Groundwater Flow Simulation Modeling
Groundwater Flow Model Application Assessment

St. Regis Paper Company Superfund Site
Cass Lake, Minnesota

Prepared for
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Contents

List of Tables

List of Figures

List of Appendices

1.0 Introduction

This report describes application of the groundwater flow model developed for the St. Regis Paper Company Site in Cass Lake, Minnesota (Site). The Site is located at the south end of the City of Cass Lake and northwest of Pike Bay (Figure 1-1). The Site groundwater flow model was developed using the U. S. Geological Survey (USGS) code MODFLOW and is described in this report as the MODFLOW Model. The extent of the MODFLOW Model grid is shown on Figure 1-2. The relationship between MODFLOW Model layers and hydrostratigraphic units in the site conceptual hydrogeologic model is illustrated in Table 1-1 (see Barr, 2015b for additional information). The material property zonation of the MODFLOW Model used in the calibration is summarized in Table 1-2 (see Barr, 2015b for additional information).

The work described in this report was performed in conformance with the Groundwater Flow Simulation Modeling Quality Assurance Project Plan (GWFSM-QAPP, [Barr, 2011c]). Terminology used in this report is consistent with the definitions provided in the glossary of the GWFSM-QAPP.

1.1 Site Background

Former wood treating operations and disposal practices resulted in the release of hazardous substances at the Site. The resulting groundwater impacts largely consist of pentachlorophenol (PCP) and polyaromatic hydrocarbons (PAHs). Results of past Site investigations and routine groundwater monitoring have shown that PCP and naphthalene (i.e., one of the PAH compounds) are effective indicators of groundwater impacts at the Site. Groundwater extraction systems were installed in the mid-1980s to pump impacted groundwater from the upper outwash aquifer to a groundwater treatment system. After treatment, the water is discharged to the channel connecting Cass Lake and Pike Bay.

The Site is divided into operable units based on the previous Site operations. The bulk of the groundwater investigation work has been conducted in Operable Units 1, 2, and 3 (OU1, OU2, and OU3, [Figure 1-1]).

1.2 Groundwater Flow Simulation Modeling Objectives

The GWFSM-QAPP was developed to guide the groundwater flow simulation modeling project to develop an accurate model of the groundwater flow system and the interaction of the extraction wells with that system. The MODFLOW Model will be used to:

1. Augment field measurements of hydraulic head to evaluate the hydraulic capture zones of the groundwater extraction systems that were installed at the former wood treating area (OU1) and the City Dump area (OU3) during the mid-1980s remedial actions or replacement wells such as W2401R. The methodology that will be used is described in Section 2.2.5.1 of the GWFSM-QAPP (Barr, 2011c). This methodology was applied to two hydraulic capture events presented in previous annual reports (Section 2). The method outlined in the GWFSM-QAPP is referred to in this report as “the modified two-dimensional approach”.

2. Simulate potential modifications to the extraction well system if such modifications are deemed necessary (see Section 2.2.5.2 of Barr, 2011c).

This focus of this report is applications of the MODFLOW Model as described in item 1 above. The MODFLOW Model and related tools, such as the MODPATH particle tracking software (Pollock, 2012), may be used in the future as described in item 2 above or for purposes in addition to those described in the current report. The specific questions such additional model uses would need to address will determine the methods employed, pertinent criteria (including relative to spatial bias between observed and simulated heads), and approaches deployed to achieve them. Descriptions of these will be provided prior to such additional model uses, for example in the form of an addendum to the GWFSM-QAPP (Barr, 2011c) or as some other project deliverable(s).

1.3 Previous Work

A list of previous work related to the regional and site hydrogeology is presented below. This work has been synthesized into the conceptual hydrogeologic model for the Site (Barr, 2015b).

1.3.1 Data Collection Efforts

The geologic and hydrogeologic conditions at the Site are described among, but not limited to, the following reports:

- Groundwater Investigation (Barr, 1982).
- Remedial Investigation/Alternatives Report (Barr, 1985a).
- Supplemental Remedial Investigation Report (Barr, 1985b).
- Groundwater Flow Model: Model Construction (Barr, 1996a); Model Calibration and Sensitivity Analysis (Barr 1996b); Predictive Simulations (Barr, 1996c).
- Technical Memorandum – Modeling Update 1 (Barr, 2006).
- Hydraulic Capture Zone Report (Barr, 2008).
- Technical Memorandum, Pre-Aquifer Test Investigation at the LLBO DRM Fish Hatchery, St. Regis Paper Company Site, Cass Lake, Minnesota (Barr, 2010).
- Revised Fish Hatchery Wells Aquifer Test Report, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota (Barr, 2011a). Referred to in this report as the Fish Hatchery aquifer testing or Fish Hatchery aquifer test. This testing was performed in the fall of 2009.
- December 2006 Aquifer Testing Report, St. Regis Paper Superfund Company Site, Cass Lake, Minnesota (Barr, 2011b). Referred to in this report as the December 2006 aquifer testing or December 2006 aquifer test.
- Vertical Aquifer Sampling Investigation Report, Operable Unit 1, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota (Barr, 2013a).

- Interim Follow-up Groundwater Quality Investigation Report, Operable Unit 3, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota (Barr, 2013b).
- NAPL Investigation Summary Report, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota (Barr, 2014b).
- Follow-up Groundwater Quality Investigation Report, Operable Unit 3, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota (Barr, 2014c).
- Technical Memorandum – Operable Unit 2 Groundwater Investigation, February-March 2014 Data Submittal (Barr, 2014d).

1.3.2 Groundwater Modeling Efforts

Hydrogeological studies by others that encompass the Site include the following:

- Hydrogeology and water quality of glacial-drift aquifers in the Bemidji-Bagley area (Stark et al., 1991).
- Hydrogeology and ground-water quality of glacial-drift aquifers, Leech Lake Indian Reservation (Lindgren, 1996).

Groundwater modeling efforts at the Site include the following:

- 1996 MLAEM model (Barr, 1996a; 1996b; 1996c).
- 2006 MODFLOW model (Barr, 2006).
- The current modeling effort.
    - As the first phase of the work outlined in the GWFSM-QAPP, a digital, three-dimensional (3-D) solids model (Solids Model) of the hydrostratigraphy within and around the Site was developed and submitted to the U.S. Environmental Protection Agency (USEPA [Barr, 2014a]). The Solids Model was approved by the USEPA with additional comments (USEPA, 2014a). The Solids Model forms the basis for the MODFLOW Model described in this report.
    - A report titled *Draft Groundwater Flow Simulation Modeling, Groundwater Flow Model Calibration Set-up, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota*, describing the set-up for the groundwater flow model calibration was submitted for stakeholder review in September, 2014 (Barr, 2014e). Stakeholder comments on the draft report were received in October, 2014 (USEPA, 2014b). The submittal described in the next bullet item incorporated revisions based on the stakeholder comments.
    - A report titled *Groundwater Flow Simulation Modeling, Groundwater Flow Model Calibration and Verification, St. Regis Paper Company Superfund Site, Cass Lake, Minnesota* documents the model calibration and verification process (Barr, 2015b). The Groundwater Flow Model Calibration and Verification Report was approved on November 2, 2015.

- The current report describes the final phase of the current modeling effort: application of the calibrated and verified MODFLOW Model to estimate hydraulic capture zones of the groundwater extraction systems in OU1 and OU3 following methods outlines in the GWFSM-QAPP for purposes of comparison with estimates made using methods applied in previous annual reports.

1.4 Report Organization

Applications of the MODFLOW Model are described in Section 2. Conclusions and recommendations based on the model applications are presented in Section 3. Appendices to this report include details on the decisions made during the groundwater-flow model application (Appendix A) and an enclosure with electronic model files and supporting information (Appendix B [Data CD]).

2.0 MODFLOW Model Application for Hydraulic Capture Zone Evaluation

Since 2006, the Site Annual Reports have used a two-dimensional approach for delineating hydraulic capture in the upper outwash aquifer using a methodology that was developed based on input from the EPA. A two-dimensional approach was outlined in the GWFSM-QAPP for future capture zone delineations. The method outlined in the GWFSM-QAPP is referred to in this report as "the modified two-dimensional approach". Consistent with the GWFSM-QAPP, data from two past hydraulic capture events were used to develop MODFLOW model instances to evaluate the applicability of a two-dimensional approach and, if applicable, to compare capture zone estimates based on this approach with those from the previous annual reports. The two hydraulic capture events considered, the evaluations performed, and the ensuing model applications are discussed in the following subsections. Additional details are provided in Appendix A.

2.1 The Hydraulic Capture Events Considered

The MODFLOW Model was applied to capture zone analysis for two hydraulic capture events from previous Annual Reports: October 2, 2009 (Barr, 2010) and April 25, 2012 (Barr, 2013c). These events were selected to illustrate applications with and without the production wells at the Leech Lake Band of Ojibwe Department of Resource Management (LLBO DRM) Fish Hatchery in operation. The model calibration included a similar range of conditions: data derived from a controlled pumping test of one of the Fish Hatchery production wells and data with both Fish Hatchery production wells idle.

In particular, the October 2, 2009 event was included in the model calibration (Barr, 2015b). Usage of a data set from the model calibration in estimating hydraulic capture is appropriate; for example, no aspect of the model calibration was directed at minimizing or maximizing any dimension of the hydraulic capture zones. Data from the April 25, 2012 hydraulic capture event were not included in the model calibration. The production wells at the LLBO DRM Fish Hatchery were inactive during the October 2, 2009 event and active during the April 25, 2012 event. It was considered desirable to include events with and without pumping of the LLBO DRM Fish Hatchery production wells in the model application evaluation. Measured pumping rates from the OU1 and OU3 groundwater extraction systems and reported pumping rates from the Leech Lake Band of Ojibwe Department of Resource Management (LLBO DRM) Fish Hatchery and other extraction wells in the nearfield model domain were used in the both simulations (Appendix A).

Figure 2-1 shows contours of simulated heads in layer 4 (representing the middle portion of the upper outwash), with symbols posted at each well used in the October 2, 2009 hydraulic capture event. This figure was presented as Figure 5-2 of the MODFLOW Model calibration and verification report (Barr, 2015b). As described in Appendix A, Section 2.1, MODFLOW settings for purposes of model calibration allow simulated heads to fall below the bottom of a given model cell. This was the case in the area labeled "A" on Figure 2-1. Contouring in this case is continuous across Area "A". The symbols indicate whether the difference between the measured hydraulic head value at a given well and the corresponding value simulated using MODFLOW (residual) met or exceeded the calibration target of ±0.078 m (±0.26 ft; Barr, 2015b). Symbols representing residuals for all wells completed in the upper outwash aquifer are posted on this figure; however, only wells with residuals exceeding the calibration target are labeled. The labels include the well names and residuals.

Surface water elevations measured at the time of the October 2, 2009 hydraulic capture event are listed in Appendix A, Table A-3. These values were used to set the heads at the boundary of boundary condition cells such as those representing Fox Creek, wetlands, Pike Bay, and Cass Lake. Due to resistance to flow between the MODFLOW Model layers representing the upper outwash aquifer (layers 3-5) and the simulated surface water features, differences will exist between simulated groundwater heads shown on Figure 2-1 and the recorded surface water elevations.

Figure 2-2 shows contours of simulated heads in layer 5 (representing the lower portion of the upper outwash), with symbols posted at each well used in the April 25, 2012 hydraulic capture event. In this model instance, layer 4 had many more dry cells than layer 5 (see Appendix A, Section 2.1), therefore contours for layer 5 are depicted in this case rather than layer 4. These data were not part of the model calibration. The recharge value for this model instance was calibrated to minimize the sum of squared residuals (Section 3.2, Appendix A). As with Figure 2-1, the symbols on Figure 2-2 indicate whether the residual at a given well met or exceeded the calibration target of ±0.078 m (Barr, 2015b). As required for use with MODPATH, in the MODFLOW instance from which modeled heads are shown on Figure 2-2, the input was such that simulated heads were not saved in the cells in the area labeled “A”; instead, the value representing dry cells was saved for those cells. Contouring in this case is therefore discontinuous across Area “A". Symbols representing residuals for all wells completed in the upper outwash aquifer are posted on this figure; however, only wells with residuals exceeding the calibration target are labeled. The labels include the well names and residuals. These residuals exhibit more spatial bias than the residuals shown in Figure 2-1. Note that the 2D methodology developed in the GWFSM-QAPP corrects for errors between measured and simulated head values, therefore spatial biases are removed prior to hydraulic capture zone estimation. See Section 3 for a recommendation on how the bias might be reduced in future applications during which the LLBO DRM Fish Hatchery production wells are pumping.

2.2 Evaluating the Applicability of a Two-Dimensional Approach

MODPATH particle tracking results based on simulated heads (uncorrected for residuals) were used to assess whether a two-dimensional approach to estimating hydraulic capture was applicable. The upper outwash aquifer is represented in the MODFLOW Model by three model layers (layers 3, 4, and 5; Barr, 2015b). A two-dimensional approach to evaluation of the capture zones of the OU1 and OU3 extraction well systems is deemed applicable if both of the following conditions are met:

1) the simulated capture zone envelopes in layers 3, 4 and 5 are similar in the areas around the extraction well systems and associated monitoring wells, and

2) if the simulated capture zones of these systems fully penetrate the upper outwash aquifer in the immediate vicinity of the extraction wells.

The following factors may lead to partial penetration of the capture zone in the upper outwash aquifer: extraction wells W404 and W406 are simulated as pumping from layers 3 and 4; the other extraction wells are simulated as pumping from layers 4 and/or 5 (see Table A-2, Appendix A).

If deviations from two-dimensionality are excessive and repeated for a model application objective, then the required adjustments to the hydraulic capture zone estimation procedure will be proposed, developed, and implemented.

Testing for Condition 1

The MODFLOW Model instances were run for the October 2, 2009 and April 25, 2012 events and particle tracking was performed on the MODFLOW model outputs (simulated heads and cell-by-cell flows) using MODPATH. The MODPATH particle tracking evaluation to determine the similarity of the simulated capture zone envelopes in layers 3, 4, and 5 (condition 1 described above), consisted of forward tracking of approximately 800 hundred particles from the midpoints of layers 3, 4, and 5 at locations upgradient of the OU1 extraction system and approximately 1100 particles midpoints of layers 3, 4, and 5 at locations upgradient of the OU3 extraction system. The resulting envelopes showing the approximate simulated extents of the hydraulic capture zones from the particle starting points forward are shown for OU1 on Figure 2-3 and for OU3 on Figure 2-4. In each case, the hydraulic capture zone envelopes in layers 3, 4, and 5 are similar in size, shape, and location; in particular the starting locations (western-most extents) in each layer are very close to one another. Differences in the pathlines downgradient of the line of recovery wells in OU1 and the three recovery well in OU3 are not considered significant; backward particle tracking would be required to determine the simulated shape of the capture zone in those areas and this was not the goal of the evaluation. Note that for the April 25, 2012 event in OU3, layer 3 is dry in area of the traces defining the northeastern extent of capture zone in layers 4 and 5, therefore the particle tracking could not be performed in layer 3 in that area (Figure 2-4). These results indicate the simulated capture zone is consistent throughout the layers representing the upper outwash aquifer in the areas through which the particle tracking occurred. Therefore, tests of condition 2 described above were applied.

Testing for Condition 2

The results discussed below are based on MODFLOW simulated-only heads and are not based on the combination of MODFLOW-simulated heads with observed heads. The MODPATH particle tracking to evaluate if the simulated capture zones in the immediate vicinity of the extraction wells fully penetrate the upper outwash aquifer (condition 2 described above), consisted of forward tracking of 500 particles from 5 elevations throughout layer 3 (the uppermost MODFLOW Model layer representing the upper outwash aquifer) along a line above the main line of extraction wells in OU1 and 1200 particles from 5 elevations throughout layer 3 along lines connecting the three extraction wells in OU3. All of the particles placed in OU1 were captured in both the October 2, 2009 and April 25, 2012 simulations (Figure 2-5). Some of particles placed in OU3 were not captured in both the October 2, 2009 and April 25, 2012 simulations (Figure 2-6). Additional detail regarding the particle tracking in OU3 is presented in Appendix A (Section 4). These results, combined with the results described in the previous paragraph indicate the modified two-dimensional approach is applicable to OU1 but may not be entirely applicable to OU3 at the rates the extraction wells there were pumped in the two events considered, but that the modified two-dimensional approach would be applicable to OU3 if the pumping rates of the extraction wells had equaled the 2015 target rates.

Based on the MODFLOW Model results, achieving the target rates is expected to result in fully-penetrating simulated capture in OU1 and OU3. Two-dimensional methods for estimating hydraulic capture are therefore expected to be increasingly applicable as extraction rates approach target rates in future hydraulic capture estimation events.

The MODFLOW Model will be used to verify that any future, proposed target rates for the OU1 and OU3 extraction well networks result in fully-penetrating capture based on the process described in this section. The current and proposed target rates will continue to be presented and discussed in Annual Reports. This process will include localized particle seeding at OU3 like that used in the 2015 Annual Report.

2.3 Two-Dimensional Hydraulic Capture Zone Evaluation

Based on the assessment described in Section 2.2, a two-dimensional evaluation of flow in the upper outwash aquifer is applicable at least in the case of OU1. For past annual reports, the evaluation has been done on a single grid encompassing both operable units (Appendix A, Section 5 and Figure A-6), therefore, the modified two-dimensional approach was used to estimate the extraction system hydraulic capture zones in order to compare the results with those from past annual reports. The methodology is summarized below and additional details on the application are presented in Appendix A.

1. A model instance of the calibrated groundwater-flow model was developed for each measurement event. Average pumping rates for the extraction wells were used based on measurements taken in the water treatment system. Pumping rates for other wells included in each MODFLOW Model instance, such as the wells at the LLBO DRM Fish Hatchery and the City of Cass Lake wells were estimated based on information from the well owners. The simulated recharge rate for the October 2, 2009 event was determined during model calibration (Barr, 2015b). The simulated recharge rate for the April 25, 2012 event was determined as described in Appendix A, Section 3.2.
2. Residuals between observed and computed water levels at wells in the upper outwash aquifer were calculated for each MODFLOW Model instance. These residuals were kriged to produce an estimate of the spatial distribution of head residual. Details on the interpolation of water levels and kriging methods are presented in Appendix A, Section 5.
3. The computed heads in MODFLOW Model layer 5 of each model instance were interpolated to the points defining the hydraulic capture zone evaluation grid used for kriging the head residual. The utility mod2smp (Watermark Computing, 2009) was used to make the interpolation. Note that mod2smp does not handle observation wells screened in multiple layers. See Appendix A, Section 4 for a discussion of methods for handling dry cells. Details on the interpolation of water levels and a discussion of the dry cells encountered during the model application are presented in Appendix A, Section 5.

4. The kriged head residuals were added to the interpolated computed heads to produce a grid of corrected heads for each event.

5. Groundwater flowpaths through the grids of corrected heads were determined using the GW Contour software package (Waterloo Hydrogeologic, 2005). The hydraulic capture zones of the extraction systems were estimated based on the groundwater flowpaths (Appendix A, Section 5.2). ParaView (Ayachit, 2015) will be used to estimate pathlines through the corrected hydraulic head grids in future events rather than GW Contour. Results for GW Contour and ParaView are compared in Appendix A, Section 6.

The hydraulic capture zone extents estimated with the modified two-dimensional approach are presented with those from past annual reports on Figures 2-7 and 2-8. The upgradient ends of the OU1 and OU3 hydraulic capture zones in Figures 2-7 and 2-8 were terminated near Highway 371, along lines approximately perpendicular to groundwater flow. The hydraulic capture zone extents estimated with the modified two-dimensional approach are similar to those presented in past annual reports in the vicinity of the extraction systems, although the downgradient extents of the hydraulic capture zone extents estimated with the modified two-dimensional approach are smaller than those presented in the past annual reports. The lateral hydraulic capture zone extents at greater upgradient distances from the extraction systems are not as similar. The orientations of the hydraulic capture zone extents at greater distances from the extraction systems based on the modified two-dimensional approach are likely more accurate than those from past annual reports, however, projection of the capture zone extents beyond the vicinity of the extraction systems and associated monitoring wells is not recommended. Proposed limits in which the capture zones would be estimated are shown with dashed lines on Figures 2-7 and 2-8. If future delineations show wider capture zones, the entire width(s) will be estimated. The upgradient extents would be as indicated, unless other extents are required by changed conditions.

3.0 Conclusions and Recommendations

Use of the MODFLOW Model and two-dimensional methods described in the GWFSM-QAPP (i.e., the modified two-dimensional approach described in this report) to estimate hydraulic capture is applicable to OU1 but may not be entirely applicable to OU3 at the rates the extraction wells there were pumped in the two events considered. However, model results indicate that the modified two-dimensional approach would be applicable to OU3 if the pumping rates of the extraction wells had equaled the 2015 target rates. Future operation and maintenance work at the site will be completed to attain pumping rates consistent with allowing the modified two-dimensional approach to be fully applicable..

Estimates of the hydraulic capture zone extents for the extraction systems in OU1 and OU3 delineated using the modified two-dimensional approach produce satisfactory results, therefore the modified two-dimensional approach should be adopted for future annual reports. Table 3-1 recapitulates the recommended steps for future hydraulic capture zone estimations.

It is recommended that the entire estimated extent of future hydraulic capture zones not be shown in future annual reports. The estimates should be limited to the vicinities of the extraction systems in OU1 and OU3. Proposed limits in which the capture zones would be estimated are illustrated with dashed lines on Figures 2-7 and 2-8. If future delineations show wider capture zones, the entire width will be estimated, but the upgradient extents would be as indicated.

The bias in hydraulic head residuals seen on Figure 2-2 would likely be reduced in magnitude if the simulated values for the LLBO DRM production well pumping rates, which were somewhat uncertain, were adjusted along with the simulated recharge rate. This procedure would improve the match between the model output and the observed conditions. Note that weekly totalizer readings were provided for both of the LLBO DRM production wells for 2015. This represents an improvement over the information regarding the pumping rates of these wells in 2012, for which a single value for the combined pumping rate of the wells was available.

It is recommended that the estimation of the three-dimensional shape of a partially-penetrating capture zone be deferred until such time as an understanding of the shape is needed for a decision related to the site. The basis for this recommendation is that details of the estimation methods will likely depend on specifics of the application. The recommendation is supported by cases of the model applications presented in this report, in which pumping at target rates that are greater than those actually achieved in OU3 would likely have produced fully-penetrating capture.

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Tables

Table 1-1 Hydrostratigraphic units (HSUs) distribution among the MODFLOW Model layers (originally presented as Table 2-1 of Barr, 2015b)

Terms of Stark et al., 1991	Terms for St. Regis Paper Company Site	MODFLOW Model Layer	Extent of Active Cells Representing this HSU
NA	Fill material	1 to 3	Site only (near field)
	Wetland deposits	1 to 3	Site only
	Intra-wetland fine sand	1, 2	Site only
	Wetland deposits	1 to 3	Site only
Unconfined drift aquifer	Upper outwash aquifer	3	Domain
		4	Domain
		5	Domain
Uppermost confining units	Upper till	6	Domain
Uppermost Confined-Drift Aquifers	Lower outwash aquifer	7	Domain
		8	OU2 only
Undifferentiated till and glacial outwash (refers in part to the lower till identified at the Site)	Lower till	7 and 8	Till zones in layers 7 and 8 may, in part, represent lower till, or wells completed in sandy units below the lower outwash (see Sections 2.4.2.7 and 3.3.1.1)

Domain – indicates hydrostratigraphic unit extends throughout the entire model domain (near and far field)

Table 1-2 Material property zonation in the MODFLOW Model (originally presented as Table 4-1 of Barr, 2015b)

Zone #	Description	MODFLOW Model Layers in which the zone occurs	Approximate Color in the Groundwater Vistas Project File
1	Fill	1, 2	
2	Intra-wetland fine sand	1, 2	
3	Wetlands deposits	1, 2, 3	
4	Peat	1, 2, 3, 4, 5	
5	Silty sand (offsite only)	1, 2, 3, 4, 5	
6	OU1 upper outwash sand	3, 4, 5	
7	OU2 upper outwash sand	3, 4, 5	
8	OU3 upper outwash sand	3, 4, 5	
9	Gravel in upper outwash	3, 4, 5	
10	Upper outwash sand (typically in the far field)	3, 4, 5	
11	Separate anisotropy zone in upper outwash	4	
12	Wetland/lacustrine deposits near Pike Bay	4	
13	Upper till in OU1 and far field	4, 5, 6, 7	
14	OU2 silty/sandy upper till	5, 6	
15	OU3 upper till	6	
16	Sandy material where upper till truncated	6	
17	Lower outwash sand, Layer 7 near field	7	
18	Lower outwash sand, Layer 7 far field	7	
19	Till in Layer 7, near field	7	
20	Till in Layer 7, far field	7	
21	Lower outwash sand in Layer 8	8	
22	Till in Layer 8	8	

Table 3-1 Outline of recommended hydraulic capture zone estimation procedures

Step	Description
1	Select the events (two per year is typical).
2	Gather pumping rate data. • St. Regis Site Extraction Wells. • LLBO DRM Fish Hatchery Wells. • City of Cass Lake Wells 4 and 5.
3	Tabulate observed hydraulic head data for upper outwash aquifer.
4	Tabulate observed surface water elevations and compare with previously simulated events.
5	Prepare MODFLOW well package (WEL), time-variant specified head (CHD) package, and river package (RIV) input files for each event – include these in a MODFLOW Model instance for each event.
6	Summarize observed precipitation data and compare with previously simulated events.
7	Estimate the recharge rate using PEST (Watermark Numerical Computing, 2005 and 2013) that minimizes the sum of squared head residuals for upper outwash monitoring wells.
8	Run MODFLOW, then apply the two-part test for the applicability of the 2D delineation methodology (based on applying MODPATH to the simulated heads and cell-by-cell flows). If fully-penetrating capture is indicated, proceed to the modified two-dimensional approach outlined below. If fully penetrating capture is not indicated, proceed as outlined below, but note the apparent lack of full penetration in the applicable report. If deviations from two-dimensionality are excessive and repeated, adjustments to the hydraulic capture zone estimation procedure will be proposed, developed, and implemented.
The modified two-dimensional approach for hydraulic capture zone estimation	
9	Interpolate the simulated heads to the grid node locations for the areas in which capture zones are to be estimated.
10	Evaluate the residuals for outliers, then establish a variogram for the accepted residual data. Apply the variogram and krige the residuals to the grid node locations for the areas in which capture zones are to be estimated.
11	Add the interpolated residuals to the interpolated heads to get corrected heads.
12	Apply the 2D particle tracking methodology to estimate the capture zone extents in the vicinity of each extraction well system.

Figures

Appendices

Appendix A

Decisions and Interpretations Made during the Groundwater Model Application and Details on the Application Results

Appendix B

Supporting Information and Electronic Files
(on compact disc)