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Appendix B

Hydrogeological Assessment Report - Updated

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SiMbA Project - Hydrogeology and Geochemistry Assessment Report

Sio Silica Corporation

Project number: 60730241

February 2025

Delivering a better world

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Executive Summary

Sio Silica Corp. intends to develop and operate an *in-situ* sand extraction operation involves extracting sand resources of the Carman Sand Member of the Winnipeg Formation, for commercial and industrial use, in southeastern Manitoba approximately 35 km east of Winnipeg. The sand resources will be used for commercial and industrial use.

This hydrogeology and geochemistry assessment report has been prepared to support the environmental assessment of the extraction component of the project, focusing on aspects that have the potential to impact the quantity or quality of groundwater in the Red River Carbonate or Winnipeg Formation aquifers. The potential for surface water quality impacts due to extraction and storage of other geologic materials (e.g. drill cuttings) was also evaluated. The method of sand extraction utilizes vertical boreholes advanced through the overburden and overlying formations to the top of the Carman Sand Member in a manner that is similar to that employed during drilling of water wells in Canada and internationally. The boreholes will be cased and grouted to isolate the overlying aquifers from the Winnipeg Formation (sandstone consisting of a very fine silica sand). Production casing will be lowered and utilized to extract the sand using pressurized air and water which may be to a maximum depth of 25 m below the top of the Winnipeg Formation Sandstone. Extraction well development will not occur within a 100 m buffer around existing homes and water supply wells. Removal of the sand will form a void in the shape of a cone extending from the bottom of the Carman Sand Member to the base of the Winnipeg Shale. The pattern of extraction cones is planned to extend laterally by successively extracting from new boreholes across the extraction area in a “room and pillar” style in accordance with the geotechnical model. The majority of groundwater that is withdrawn with the sand during the extraction process will be returned underground via the borehole from which it was extracted without the use of high pressure. This process is referred to as “re-injection”.

The bedrock aquifers are extensively developed for residential, municipal, agricultural, irrigation, commercial and industrial purposes. Groundwater is derived from a variety of overburden aquifers, but most users are supplied by the underlying bedrock aquifers of the Red River Carbonate (primarily limestone) and Winnipeg Formation Sandstone. Homeowners and businesses in the project area rely primarily on groundwater to meet water demands. Most groundwater wells in the area are completed in the shallower Red River Carbonate aquifer. The wells have been installed over a period of more than 100 years and drilling technology and capabilities have advanced over time.

Based on the results of the hydrogeological and geochemical assessment presented herein, AECOM concludes the following:

<u>Groundwater Quantity</u>

Groundwater model simulations indicate that groundwater users of the Red River Carbonate aquifer and the Winnipeg Sandstone aquifer beyond a radial distance of approximately 2.3 km from the active extraction wells are unlikely to experience any effects due to extraction activities if there is no re-injection of extracted groundwater. With the planned re-injection of groundwater, wells beyond 1.5 km from active extraction wells are not likely to be affected. Overall, groundwater quantity will be preserved within the project area due to the seasonal operation of sand extraction wells and reinjection of surplus groundwater following separation of solids. Although the spatial extent of the drawdown is anticipated to be laterally extensive, the magnitude of drawdown impacts is anticipated to be between 0.5 m and 5 m for the majority of the licensed water supply wells. Because most pumps are installed at depths of 30 m or more, and well below the static groundwater elevation, impacts of this magnitude will not likely require any mitigation.

Consistent with the results of field testing, water levels were simulated to recover relatively rapidly, with approximately 80% recovery approximately two days following the end of production at each well cluster. Groundwater levels are anticipated to return to near static water levels approximately 60 days after production ceases at each well cluster.

Two operational scenarios (0% re-injection and 42.5% re-injection) were simulated to explore the mitigative effect of reinjecting groundwater into the aquifer. With 0% re-injection of groundwater, the 0.5 m drawdown cone was simulated to extend up to 2,300 m from the active sand extraction wells in the Winnipeg Sandstone and up to 1,900 m in the Red River Carbonate. With 42.5% re-injection of groundwater, the 0.5 m drawdown cone was simulated to extend up to 1,300 m from the active sand extraction wells in the Winnipeg Sandstone and up to 1,400 m in the Red River Carbonate. This indicates that the magnitude and extent of drawdown impacts to both aquifers will be much lower when groundwater is reinjected, which is planned for extraction operations. These simulation results are consistent with the results of the 2020 field investigation that observed relatively minor drawdown in residential water supply wells, but well yield was not impacted, and impact mitigation was not required. Changes of this magnitude are not uncommon and are similar to those experienced due to natural seasonal variability.

As the majority of domestic water supply wells are completed in the Red River Carbonate (limestone), domestic water wells will be impacted to a much lesser degree by sand extraction from the underlying Winnipeg Sandstone.

Pumps installed near the piezometric surface can be lowered if the well is within the drawdown cone (i.e. within 1,300 m in Winnipeg Sandstone or 1,400 m in Red River Carbonate) associated with operating sand extraction wells or an alternative supply could be provided. Potential impacts, which would be temporary and reversible, would be limited to the period during and immediately following project operations (60 days, with approximately 80% recovery within the first two days) at each extraction well cluster proximal to each water supply well. Impacts beyond this time are anticipated to be negligible.

The project is in an area where groundwater is used for drinking water purposes and the impacts of the project on groundwater quantity should be monitored and evaluated in advance of, during and following project operations. A Water Management Plan and Groundwater Monitoring and Impact Mitigation Plan will be developed and implemented to monitor groundwater extraction/injection and water levels within the aquifer surrounding the project area and mitigate any impacts to surrounding wells.

Bedrock Geochemistry and Waste Management

Although the extraction process targets the removal of sand and groundwater, trace amounts of other unwanted material (referred to as “waste”) could also be brought to surface during the extraction process. This could include concretions (calcified sand) and bedrock cuttings, including shale fragment. Vibrating screens at the processing facility will capture these waste materials and allow them to be removed, stored and disposed at a licensed facility.

Based on the results of this hydrogeological and geochemical assessment, with the Waste Characterization and Management Plan developed in accordance with industry standard mitigation measures, material impacts to groundwater quality resulting from the above-mentioned waste materials are unlikely. Over 81% of the waste material extracted during drilling will consist of glacial sediments similar to those exposed at ground surface within the project area today. The remainder will be comprised of bedrock cuttings from the Red River Carbonate (15%) and Winnipeg Shale (4%). The Winnipeg Sandstone will be processed and sold as a commercial product and is therefore not considered to be waste.

Although evidence of pyrite has been noted laboratory testing results for the Winnipeg Shale, visual core inspection did not find any evidence of sulphide mineralization. Laboratory testing of Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone indicates the Red River Carbonate and Winnipeg Sandstone have low potential for acid generating. However, some of the Winnipeg Shale samples were classified as ‘uncertain’ due to some uncertainty with respect to adequate neutralization potential to neutralize acidity and prevent metal leaching / acid rock drainage (ML/ARD). Therefore, this very small volume of waste material will be considered a potential source of acidity. Although some trace metals reported elevated concentrations in shake flask test results, the parameters are present at low to non-detectable concentrations in groundwater suggesting they are not likely to appreciably affect water quality. Similar geologic waste has been deposited on ground surface during the advancement of nearly every water supply well drilled in southern Manitoba for over a century without any reported water quality issues caused by ML/ARD.

The Waste Characterization and Management Plan will be implemented to further characterize waste materials and direct their management to protect groundwater quality. In an abundance of caution, all waste materials will be disposed at a licensed facility. The implementation of monitoring and management measures listed in the document are expected to mitigate any potential adverse effects to groundwater quality.

Groundwater Quality

Groundwater quality is very good in the Red River Carbonate aquifer, Winnipeg Sandstone aquifer and Winnipeg Shale aquitard. However, naturally elevated concentrations of iron and manganese exceeding drinking water aesthetic criteria were reported in these aquifers as is commonly found in natural groundwater systems. Overall, material impacts to groundwater quality within the Project Area are unlikely because both the Red River Carbonate and Winnipeg Sandstone host fresh and relatively dilute groundwater. The results of geochemical modelling show that the overall quality of groundwater within the maximum footprint of the project is largely preserved. The activities associated with project operations and post-closure phases were determined to have only a minor impact on groundwater quality, and in many cases the impact was simulated to be *positive* due to reduction of concentrations of iron and manganese when oxygen is introduced into the aquifer. Interconnection between the two aquifers is a common occurrence because many drinking water wells have been screened across the Red River Carbonate and the Winnipeg Sandstone. Should project operations result in a more interconnection between the Red River Carbonate aquifer and the Winnipeg Sandstone aquifer, groundwater quality would tend to reflect conservative mixing of the two water types (i.e. limited geochemical reactions) resulting in water quality that is similar or slightly better.

The collapse of a section of the Winnipeg Shale and Red River Carbonate in the cavity formed in the Winnipeg Sandstone following the sand extraction is likely to occur. Water quality within the void may temporarily exhibit slightly elevated concentrations of selenium and manganese caused by dissolution of minerals and following the physical collapse of the overlying Winnipeg Shale and a small portion of the Red River Carbonate. The assessment and modelling of the impact of the collapse of the overlying materials on the water quality of the Winnipeg Sandstone aquifer show that the concentrations of arsenic, selenium, and uranium will decrease and remain below the Manitoba and Canadian Drinking Water Quality Guidelines. While arsenic and uranium concentrations will remain below these guidelines in the void as well, selenium concentrations will remain slightly above Manitoba water quality in the void for approximately seven years after the collapse, until they decline below the Manitoba Water Quality Standard. The lateral migration of the water quality temporarily impacted by the collapse in the void is very slow and will have a significant amount of time to stabilize (re-equilibrate) which will minimize the effect on the water quality in adjacent and downstream portions of the aquifer.

Although the injection of water containing residual dissolved oxygen will reduce concentrations of iron and manganese in the vicinity of extraction wells, it is not anticipated to induce ML/ARD reactions due to the very low to absent concentrations of minerals prone to oxidation (i.e. pyrite and pyrrhotite) coupled with low and finite concentrations of dissolved oxygen in subsurface groundwater and re-injected water. This is supported by the presence of very good water quality in both aquifers today. The vertical gradients between the two aquifers are downward and near neutral such that the magnitude of any inter-aquifer exchange during and following project operations is likely to be small.

A Waste Characterization and Management Plan and Groundwater Monitoring and Impact Mitigation Plan were developed and will be implemented to protect groundwater quality and guide responses to any potential impacts. A comprehensive vulnerability analysis demonstrated that small declines in simulated groundwater levels within the Winnipeg Sandstone as observed at the end of project operations (maximum vulnerability) result in relatively minor and local scale increases in aquifer vulnerability following the modified DRASTIC method. Even for this time period of maximum downward gradients (and hence vulnerability), there are other areas of the aquifer that have been and will continue to be more vulnerable to surface contamination as they are not protected by overlying fine-grained (low permeability) units and are associated with areas of groundwater recharge. It is noteworthy that the deep Winnipeg Sandstone aquifer will remain protected by thick and low permeability glacial sediments and separated from ground surface by the Red River Carbonate aquifer and residual intact portions of the Winnipeg Shale. As such, a Progressive Well Abandonment Plan will limit hydraulic communication between the Red River Carbonate and the Winnipeg Sandstone by plugging boreholes upon completion of sand extraction from each well.

Implementation of the monitoring and management plans discussed herein are expected to mitigate potential adverse effects on groundwater. The plans will outline follow-up adaptive management measures that will be implemented in consultation with Manitoba Conservation and Climate, Environmental Assessment Branch should there be any unforeseen adverse impacts on groundwater (i.e. beyond an acceptable threshold or regulatory guidelines).

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Appendices

1. Introduction

1.1 Initiation

AECOM Canada ULC (AECOM) was retained by Sio Silica Corp. ('Sio'; formerly CanWhite Sands Corp) of Calgary, Alberta to complete a hydrogeology and geochemistry assessment of the proposed *in-situ* silica sand extraction operation approximately 35 km east of Winnipeg, Manitoba.

1.2 Background

Sio intends to develop and operate an *in-situ* sand extraction operation in southeastern Manitoba, and approximately 35 km east of Winnipeg. The project, SiMbA, (Silica, Manitoba, Action Plan, contributing to net zero targets) will involve extraction of sand resources of the Carman Sand Member of the Winnipeg Formation for commercial and industrial use. The location of the project is shown on **Figure 1-1**. The spatial boundaries of the project are presented on **Figure 1-2**.

Silica sand is known to outcrop along some shorelines in the southern basin of Lake Winnipeg in Hecla/Grindstone Provincial Park. The Winnipeg Formation is known to also outcrop along the northern edge of the Williston Basin, between Athapapuskow and Wekusko lakes. The Winnipeg Formation occurs mostly continuously across the Williston Basin at variable depths and thicknesses. Historically, economic deposits of the silica sands of the Winnipeg Formation have been quarried from Black Island on Lake Winnipeg. The first claims for silica on Black Island were staked in 1910, but they were not developed until 1929 (Watson 1985) when materials were primarily barged to Winnipeg to make glassware. The Steel Brothers quarried up to 100,000 tonnes of silica sand per year from the Winnipeg Formation using drilling, blasting and washing to remove mineral coatings (iron oxide), kaolin and physically disaggregate the sand. The extraction of silica sand has also been investigated within the Regional Project Area historically, but economic methods for extraction were not available at the time (UMA 1967). There have been no significant environmental impacts attributed to silica sand presence or mining at any of these locations.

Sio has received direction from the Resource Development Division, Mines and Geological Survey of Manitoba that the Carman Sand Member is a Crown mineral and is under the purview of the *Mines and Minerals Act*. Sio has developed a proprietary method for sand extraction using airlift pumping methods from a series of vertical production boreholes. The method utilizes vertical boreholes advanced though the overburden and overlying formations to the top of the Carman Sand Member. The boreholes are cased and grouted to isolate the overlying aquifers from the Winnipeg Formation. Production casing is lowered and utilized to extract the sand using pressurized air and water which may be to a maximum depth of 25 m below the top of the Winnipeg Formation Sandstone to form a cone extending from the bottom of the Carman Sand Member to the base of the Winnipeg Shale. The extraction cone pattern is planned to extend laterally by successively extracting from new boreholes across the extraction area in a room and pillar style in accordance with the geotechnical model.

Homeowners and businesses in the area of the project rely primarily on groundwater to meet their water demands. Groundwater is derived from a variety of overburden aquifers, but the majority of users are supplied by the underlying bedrock aquifers of the Red River Carbonate and Winnipeg Formation Sandstone. The bedrock aquifers are extensively developed for residential, municipal, agricultural, irrigation, commercial and industrial purposes. The majority of groundwater wells are completed in the shallower Red River Carbonate aquifer, but many are also screened across the Winnipeg Sandstone Formation. Historical drilling practices and published literature (Betcher and Ferguson 2007) indicates that over 1,000 water wells (Wang et al. 2008) included in the GWDRILL database have been screened across both aquifers. Near Winnipeg, where artesian conditions persist in the Winnipeg Sandstone aquifer, it is reported that saline groundwater has migrated upward through wells interconnecting the two aquifers. The wells have been installed over a period of more than 130 years and drilling technology and capabilities have advanced over time.

The aquifers are both very productive and groundwater quality is generally good in proximity to the proposed sand extraction project. However, water quality in the Winnipeg Formation Sandstone is known to be saline approximately 70 km west of the subcrop where total dissolved solids concentrations exceeding 2 g/L immediately east of the Red River (Ferguson et al. 2007). Historical wells reportedly interconnect the sandstone and carbonate aquifers at many locations (Betcher and Ferguson 2003; Ferguson et al. 2007; Wang et al. 2008). Interaquifer exchange has reportedly influenced water quality in the Red River Carbonate aquifer in areas with underlying saline water as a result of upward flow of saline water from the Winnipeg Formation Sandstone through improperly sealed boreholes. Water quality within the Project Area is generally fresh in both the Red River Carbonate and Winnipeg Sandstone aquifers.

Sio has previously completed feasibility assessments for the project and is currently seeking regulatory approvals for extraction of the sand (pending Extraction Project *Environment Act* Proposal). The processing of the sand will occur at the processing facility (Processing Facility *Environment Act* License No. 3367). This hydrogeology and geochemistry assessment report has been prepared to support the environmental assessment of the extraction component of the project, focusing on aspects that have the potential to impact the quantity or quality of groundwater in the Red River Carbonate or Winnipeg Formation aquifers. The potential for surface water quality impacts due to extraction and storage of other geologic materials (e.g. drill cuttings) was also evaluated.

1.3 Previous Studies and Data Sources

Numerous studies have previously been conducted by provincial agencies and academic researchers in the vicinity of the project to investigate geology, hydrogeology, groundwater supply and groundwater quality. Together, they represent over 50 years of research. The following key papers were reviewed as part of this study:

- Geology:
  - McCabe, H.R. 1971. Stratigraphy of Manitoba: an introduction and review. Special Paper Geological Association of Canada 9:167–187.
  - McCabe, H.R. 1978. Reservoir potential of the Deadwood and Winnipeg formations, southwestern Manitoba. Geological Paper 78–3, Manitoba Department of Mines, Winnipeg, MB.
  - Teller J.T. and Fenton M.M. 1980. Late Wisconsinan glacial stratigraphy and history of southeastern Manitoba. Canadian Journal of Earth Science 17:19–35.
  - Matile, G.L.D and G.R. Keller. 2007. Surficial Geology of Manitoba. Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Surficial Geology Compilation Map Series, SG-MB, scale 1:1,000,000.
- Hydrogeology:
  - Render, F. W. 1970. Geohydrology of the Metropolitan Winnipeg Area as Related to Groundwater Supply and Construction. Canadian Geotechnical Journal, Vol. 7 No. 3, pp 243-374.
  - Betcher, R.N., 1986. Groundwater Availability Series – Manitoba Water Resources Branch.
  - Betcher, R., Grove, G., and Pupp, C., 1995. Groundwater in Manitoba: Hydrogeology, Quality Concerns, Management. NHRI Contribution No. CS-93017, 47 pp.
  - Cherry, A.J. 2000. A multi-tracer estimation of groundwater recharge in a glaciofluvial aquifer in southeastern Manitoba. MSc Thesis, University of Ottawa, Ottawa, ON.
  - Ferguson G. 2004. Groundwater and Heat Flow in Southeastern Manitoba: Implications to Water Supply and Thermal Energy. Ph.D. Thesis. University of Manitoba Department of Civil and Geological Engineering. Winnipeg, Manitoba.
  - Ferguson G., Woodbury A.D., Matile G.L.D. 2003. Estimating recharge beneath an interlobate moraine using temperature profiles. Ground Water 41(5):640–646.
  - Ferguson, G. A., Betcher, R. N., & Grasby, S. E. (2007). Hydrogeology of the Winnipeg Formation in Manitoba, Canada. Hydrogeology Journal, 573-587.
- Groundwater Supply:
  - Kennedy, P. L. 2002. Groundwater Flow and Transport Model of the Red River/ Interlake Area in Southern Manitoba. Master's Thesis. University of Manitoba Department of Civil and Geological Engineering. Winnipeg, Manitoba.

- Kennedy, P.L. and Woodbury, A.D. 2005. Sustainability of the Bedrock Aquifer Systems in South-Central Manitoba: Implications for Large-Scale Modelling. Canadian Water Resources Journal 30(4): 281-296.
- Wang, J., Betcher, R.N., and G.C. Phipps, 2008. Groundwater Resource Evaluation in Southeastern Manitoba. Conference proceedings of GeoEdmonton'08: 61st Canadian Geotechnical Conference and 9th Joint CGS/IAH-CNC Groundwater Conference, September 21-24, 2008, Edmonton, Canada.
- Friesen Drillers Ltd. 2015. Municipal Groundwater Well Field Investigation. NW ¼ 3-7-6 EPM. Proposed Park Road Municipal Supply Well Field Environment Act Proposal. Report for City of Steinbach, Manitoba.
- Friesen Drillers Ltd. 2019. Supplemental Municipal Groundwater Supply Rural Municipality of Springfield. Report for The Rural Municipality of Springfield, Manitoba.

- Groundwater Quality:
  - Fritz, P., Render, F.W., Brown, R.M. and R.J. Drimmie, 1975. Environmental Isotopes in the Groundwater of the Upper Carbonate Aquifer in Central Manitoba. Canadian Hydrology Symposium 1975, Winnipeg.
  - Grasby, S.E., and R.N. Betcher, 2002. Regional hydrogeochemistry of the carbonate rock aquifer, southern Manitoba. Canadian Journal of Earth Sciences 39:7 p. 1053-1063.
  - Betcher, R.N., and Ferguson, G.A. 2003. Impacts from Boreholes Interconnecting Multiple Aquifers - A Case Study of Paleozoic Aquifers in Southeastern Manitoba. 4th Annual Joint CGS-IAH Conference, Winnipeg, Manitoba, Sept. 29-Oct. 1, 2003.
  - Ferguson G., Betcher, R.N. and Grasby S.E. 2005. Water chemistry of the Winnipeg formation in Manitoba. Geological Survey of Canada Open File 4933:37.
  - Phipps, G., Betcher, R.N., and Wang, J., 2008. Geochemical and Isotopic Characterization of a Regional Bedrock/Surficial Aquifer System, Southeastern Manitoba. Conference proceedings of GeoEdmonton'08: 61st Canadian Geotechnical Conference and 9th Joint CGS/IAH-CNC Groundwater Conference, September 21-24, 2008, Edmonton, Canada.

These studies form the basis for AECOM's literature review. Together with field data collected as part of this study and provincial water supply records (well records, Water Rights Licenses/allocations, Water Use Records, etc.), these studies were used to guide development of the field investigation workplan, conceptual hydrogeological model, numerical groundwater model and geochemical assessment presented herein.

1.4 Existing Groundwater Use

A water well inventory for the study area (defined as the area encompassing the Project Site, Local Project Area and Regional Project Area) was obtained from the Groundwater Information Network (GIN) data base. The locations of all registered water wells within the study area are presented according to aquifer and water use type on **Figure 1-3** and **Figure 1-4**, respectively. A rigorous review of the well database in 2021/22 showed that there are 10,879 water wells registered within the groundwater model domain discussed in **Section 6** of this report. Of those, a total of 1,612 lie within the Regional Project Area and 406 wells are within the Local Project Area.

As shown on **Figure 1-3**, groundwater wells have been installed by private well owners and government agencies in multiple aquifers present within the groundwater model domain. According to the conceptual model stratigraphy detailed in **Section 5** there are 562 wells completed in the Quaternary Sediments, 3,845 wells installed in the Red River Carbonate, and a further 565 wells installed in the Winnipeg Sandstone. Based on discussions with Friesen Drilling, we understand that the majority of pumps are installed in wells near the bottom of the steel casing installed through overburden at depths of 30 m or more.

Groundwater is used primarily for domestic purposes, but also supports other uses. Among the total number of wells within the Regional Project Area, 1,505 water wells are licenced for domestic use, 22 for air conditioning, three (3) for industrial use, two (2) for irrigation use, 54 for livestock watering use, three (3) for municipal water supply and five (5) for other uses as shown on **Figure 1-4**. The water use was not reported for 18 wells in the Regional Project Area.

1.5 Scope of Work

AECOM previously completed a data gap analysis to inform the scope of work completed as part of this hydrogeology and geochemistry assessment. The scope of work was developed following discussions between AECOM, Sio, Friesen Drillers Ltd. and the team of consultants supporting the project.

The scope of work included the following:

- Review of available documents pertaining to project design and hydrogeological conditions in the study area.
- A comprehensive field investigation including:
  - Survey and inspections of nearby private wells.
  - Contractor oversight for drilling, installation, development and surveying of several wells.
  - Instrumentation of local groundwater monitoring network with pressure transducers and dataloggers.
  - Completion of aquifer testing including slug tests and a pumping test.
  - Collection and submission of bedrock core samples for geochemical and isotopic analysis.
  - Collection of groundwater samples for water quality and isotopic analysis.
- Desktop evaluation including:
  - Analysis of aquifer testing data to determine aquifer properties.
  - Interpretation of geochemical testing results to evaluate metal leaching and acid rock drainage (ML/ARD) potential.
  - Interpretation of water quality data including comparison to applicable water quality criteria.
  - Development of a three-dimensional conceptual geological model and numerical groundwater model to evaluate impacts of the project on groundwater quantity.
  - Completion of geochemical modelling to evaluate impacts of the project on groundwater quality.
- Documentation of the hydrogeology and geochemistry assessment in this report.

1.6 Objectives

The purpose of this Hydrogeology and Geochemistry Assessment is to:

- Investigate and document existing conditions as they pertain to groundwater flow and quality at the project site.
- Evaluate the potential for the proposed project to impact groundwater quantity, groundwater quality and users of surface water and groundwater in the vicinity of the project.
- Address concerns raised by regulatory agencies, the public, First Nations and technical reviewers.

1.7 Regulatory Setting

1.7.1 The Mines and Minerals Act

Sand extraction activities are proposed to occur within current mining claim areas issued to Sio under provisions of *The Mines and Minerals Act* or existing private claims and under borehole licences issued under Part 3 of the Drilling Regulation. The current mining claim areas that are included within the Project Site will be converted to mineral leases prior to production extraction of sand.

1.7.2 Environmental Assessment and Licensing

Manitoba's environmental assessment and licensing program is designed to minimize the environmental impact of developments. The environmental assessment process intends to identify environmental effects and develop mitigation measures to address anticipated effects. Following the environmental assessment process, a License may be issued with limits, terms and conditions, or refused. Upon approval, clear performance requirements are established following the licensing process for all stages of the project including construction, operation, maintenance and decommissioning.

This Project will be reviewed by Manitoba Climate and Conservation (MBCC) under *The Environment Act* as a “mine” which is a Class 2 development in section 3 of the Classes of Development Regulation under group 5 “*Mining*”.

Processing of the extracted sand resource at a processing facility was reviewed and granted a separate Environment Act Licence December 2021 (EAL No. 3367) under *The Environment Act* as a Class 2 development (a “manufacturing and industrial plant”) under the Classes of Development Regulation.

1.7.3 Water Rights Licensing

Manitoba’s Water Rights Licensing process intends to ensure sustainable allocation of water resources and protect the interests of licensees, existing domestic users, the general public and the environment with respect to the use or diversion of water. Manitoba’s *Water Rights Act* (the Act) gives all property owners equal access to water on a priority basis. Key objectives include:

- To ensure fair and equitable allocation of water for beneficial uses.
- To provide for optimal allocation of water within the sustainable limits of the resource base.
- To assess and license appropriate water use proposals.
- To provide clients with high quality, timely service and information.
- To ensure that the potential for negative impacts of water use projects are minimized.

Water users that use more than 25,000 L/day (4.6 US GPM) for municipal, industrial, agricultural, irrigation and other purposes must obtain a Water Rights License to extract and use groundwater under the *Water Rights Act*. Water withdrawals of less than 25,000 L/day generally do not require licensing. An environment act license is also required for groundwater withdrawals in excess of 200 dam^3/year. A groundwater exploration permit is required to drill and test groundwater wells. As part of the licensing process, the possibility of interference with other groundwater users is evaluated.

The Manitoba *Water Rights Act* prohibits connecting two aquifers within a single well completion to minimize hydraulic communication between saline and freshwater portions of drinking water aquifers. There is no known saline water present within the Project Area.

An injection permit for the return of water to the sandstone aquifer is also required.

2. Description of Proposed Development

Sio is proposing to extract silica sand and groundwater in a slurry using water well drill rigs and an airlift extraction method for processing at the proposed Vivian Sand Processing Facility to be located southwest of the hamlet of Vivian, Manitoba and approximately 35 km east of Winnipeg. The resource was characterized, and the economics of the project were assessed by Stantec (2024a; 2024b). This involved a geotechnical assessment to inform project design (Stantec 2022).

Silica sand will be extracted from the Carman Sand Member of the Winnipeg Sandstone formation, which is located below a thick layer of recent glacial sediments, the Red River Carbonate and the Winnipeg Shale. Extraction will occur during warm weather months between April and November each year. At full operation, the Project will have an estimated annual production rate of 500,000 tonnes of silica sand that will be extracted from a series of production boreholes and conveyed to the Vivian Sand Processing Facility for processing (washing and drying) via overland slurry pipe.

The groundwater portion of the extracted sand slurry that is not required for sand processing will be returned to the aquifer through the extraction wells. When the sand and water reach surface, the groundwater will be separated from the sand and immediately returned to the aquifer. The remaining sand will enter the slurry system to be transported to the Processing Facility. The amount of sand contained in the Carman Sand Member within the area covered by Sio's mining claims for this project is much more than commercially needed and only a small fraction of the sand will be extracted during the 25-year life of the project.

This hydrogeological and geochemical assessment is focused on subsurface components of the project over the first five years of operation from 2026 to 2029 as shown on **Figure 2-1**. Geotechnical aspects of this project are outside the scope of this assessment but have been completed by others. The Processing Facility was licenced by regulators under a separate *Environment Act* Licence application (EAL No. 3367).

The following sections provide additional information for each of the project components.

2.1 Components and Activities

The proposed project will consist of the following key activities and components proposed to be permitted under an *Environment Act* Licence:

- Establishment of temporary access trails to annual sand extraction areas to accommodate water well drill rigs.
- Extraction well drilling and installment of sand and water slurry piping infrastructure within each extraction well for approximately 167 wells per year, with only 25 wells in the first year.
- Construction of above-ground piping, and construction and operation of pumping stations to transport the sand and water slurry directly to the adjacent sand processing facility.
- Dismantling and relocating the above-ground piping and pumping stations to the subsequent annual sand extraction area.
- Return of excess groundwater through the extraction wells to the aquifer following appropriate treatment.
- Progressive decommissioning of annual extraction wells using a concrete cap, bentonite grout and permeable backfill layers in accordance with the *Groundwater and Water Well Act*.
- Progressive annual rehabilitation of well clusters, temporary drill rig access trails, slurry pipe routes and groundwater return pipe routes.

Figure 2-1 illustrates the location of extraction wells for Years 0 to 4. All well drilling, operation and decommissioning will be completed in accordance with the Manitoba *Groundwater and Water Well Act* and its supporting regulations, including the Groundwater and Water Well Regulation and the Well Standards Regulation.

2.2 Silica Sand Extraction Process

Silica sand extraction wells will be sequentially drilled, operated and progressively decommissioned over time. Sio anticipates extracting sand as a sand and groundwater slurry from the Carman Sand Member of the Winnipeg

Sandstone an approximate depth of 51 m to 76 m (170 ft to 200 ft) below ground surface. Up to 167 extraction wells per year will be used to extract sand from the deep sandstone formation.

Silica sand will be extracted from the deep aquifer of the sandstone geological formation using an airlift extraction method. This approach is commonly used in the water well drilling industry to advance boreholes through unconsolidated and consolidated geological formations by injecting compressed air into the bottom of a borehole to extract drill cuttings, and thereby create a borehole. The extraction method sequence of activities is described as follows:

- Establish access to the drilling location;
- Advance borehole and casing through overburden using dual rotary drilling methods;
- Install surface casing into upper portion of Red River Carbonate;
- Advance borehole through Red River Carbonate formation and underlying shale;
- Advance intermediate casing and grout borehole through shale and lower Red River Carbonate to prevent inter-aquifer mixing;
- Advance production casing through grout and extract sand from Winnipeg Formation Sandstone (Carman Sand Member) using airlift methods (and recirculated groundwater);
- Upon completion of extraction, remove production well string;
- Progressively decommission well in accordance with the Manitoba Groundwater and Water Well Act and its supporting regulations, including the Groundwater and Water Well Regulation and the Well Standards Regulation; and,
- Remove casing and progressively rehabilitate well clusters and other temporarily disturbed areas.

A schematic illustrating the silica sand extraction method is shown on **Figure 2-A**.

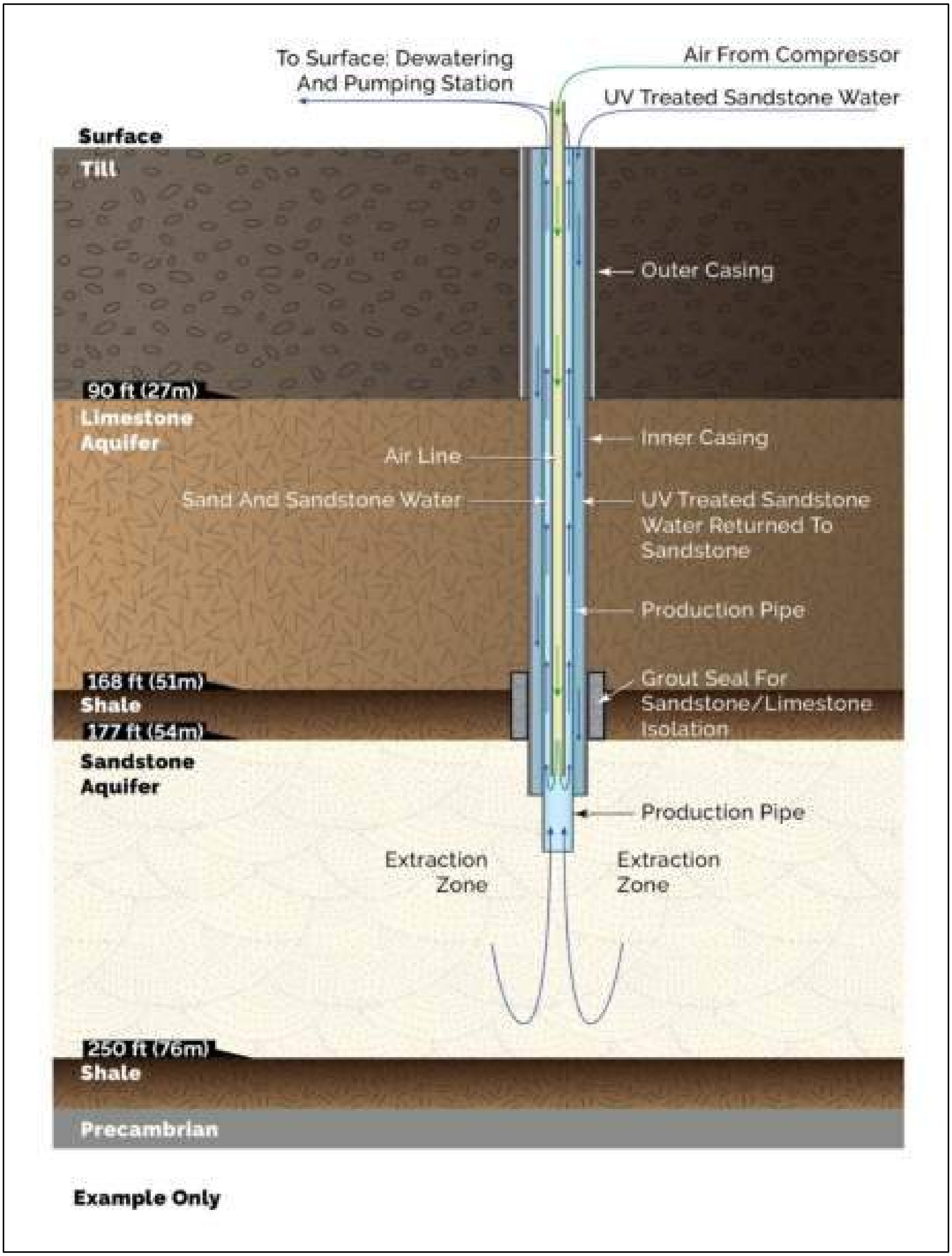

Figure 2-A: Conceptual Illustration of Silica Sand Well Extraction Method

2.3 Layout of Sand Extraction Sites

A conceptual illustration of the extraction well and well cluster layout is shown on **Figure 2-B**. During each year of sand extraction operations, extraction wells will be clustered in groups of one (1) to five (5) wells within 60 m to 70 m diameter well cluster areas. Extraction wells will be located approximately 22 m apart. To produce the initial ramp up phase of 100,000 tonnes in Year 0 to 300,000 tonnes in Year 1 (with an eventual increase to 500,000 tonnes of silica sand product annually at the Processing Facility) an average of 55 well clusters consisting of one (1) to five (5) wells each will be sequentially developed and progressively decommissioned and rehabilitated each year.

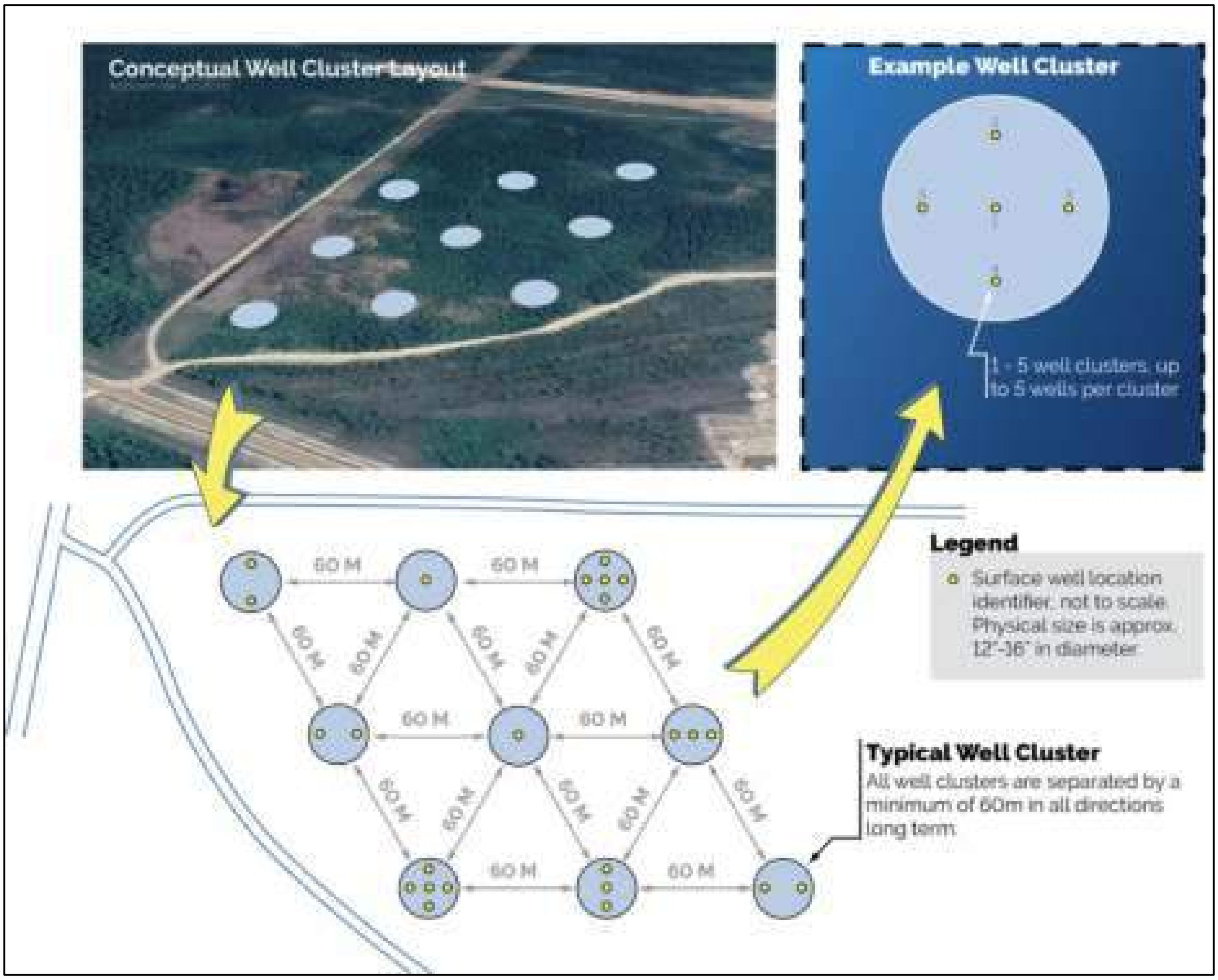

Figure 2-B: Conceptual Extraction Well and Well Cluster Layout

2.4 Groundwater Use During Sand Extraction

Each well will operate for eight (8) days and will produce from 262 m^3/day (40 GPM) to a maximum of approximately 600m^3/day (110 US GPM) of water and sand. Several wells at a given well cluster will operate at any one time, with a combined production rate of approximately 2,998 m^3/day (550 US GPM) per well cluster. Extraction from each cluster will progress according to the schedule that is tabulated in **Appendix H**.

For each extraction well, the sand and groundwater slurry will be conveyed to a dewatering screen to allow for screening and separation of sand from the majority of the groundwater. Early in the extraction process for each well, the slurry will consist primarily of solids (est. 70%) and will slowly reduce to approximately 20-30% near the end of well production. The surplus groundwater will then be passed through filtration and a ultraviolet (UV) treatment system to destroy any bacteria and returned down the outside of the production casing into the aquifer. Sio has conducted extraction testing and plans to reinject the majority of groundwater within the extraction well loop with an estimated 45 m^3/day (8.25 US GPM) lost to residual moisture (15%) content in the sand.

2.5 Materials Management

2.5.1 Waste Materials

Drill cuttings and any materials separated during pre-screening will be managed on surface in accordance with the Waste Characterization and Management Plan to mitigate any risks to surface water and groundwater quality and dust. The production schedule calls for development of 23 extraction well clusters in the first year (Year 0). Over the 5 year period, a total of 276 well clusters will be developed. Each cluster will consist of 1 to 5 wells, resulting in a total of 492 wells. Each well is anticipated to be 16” diameter through the Quaternary Sediments, 10” diameter through the Red River Carbonate and Winnipeg Shale, and 10” diameter within the Winnipeg Sandstone (production casing). The volume of drill cuttings that will be produced during operations was estimated based on an assumed thickness of 36 m for the Quaternary Sediments, 13 m for the Red River Carbonate and three (3) metres for the Winnipeg Shale as shown in **Table 2-A.**

Table 2-A. Estimated Waste Material Production by Waste Type

Lithology[1]	Assumed Thickness		Borehole Diameter		Extraction Wells	Estimated Volume of Waste[2]	
	(m)	(ft)	(m)	(inches)	(total number)	(m^3/well)	(m^3)
Quaternary Sediments	36	118	0.406	16	492	4.66	2,293
Red River Carbonate	13	43	0.254	10	492	0.66	325
Winnipeg Shale	3	10	0.254	10	492	0.15	74

Notes:

1. *Winnipeg Sandstone will not be a waste stream.*
2. *No bulking factor applied to volumes.*

2.5.2 Sand Slurry

The sand and groundwater slurry will be transported directly to the adjacent Processing Facility via slurry pipes. Pumping stations will be installed as necessary along the slurry pipe to facilitate transport of the sand and groundwater slurry to the Processing Facility. This method of silica sand extraction will minimize above-ground disturbance and eliminate the need for trucks to transport the sand. As new extraction well locations and associated piping are established in the sequential progressive sand extraction process, pumping stations will be dismantled and relocated to optimal locations to facilitate movement of the sand and groundwater slurry through the slurry pipes to the Processing Facility.

2.6 Closure and Reclamation

Following extraction, each extraction well will be progressively abandoned by backfilling with a combination of cement, bentonite and clean pea gravel or drill cuttings from the corresponding aquifer (e.g. carbonate chips) to achieve a hydraulic seal within the borehole and prevent exchange of groundwater between aquifers through boreholes. All well abandonment activities will be completed in accordance with the Manitoba *Groundwater and Water Well Act* and its supporting regulations, including the Groundwater and Water Well Regulation and the Well Standards Regulation.

3. Hydrogeological Investigation

3.1 Field Investigation Design

The field investigation was designed to collect information to fill identified data gaps and address key issues raised by the technical team, reviewers, the community, and First Nations. The field investigation was focused on characterizing hydrogeology of the Local Project Area and geochemistry within the Local Project Area and Regional Project Area. The resultant field investigation plan is presented on **Figure 3-1.** The locations of boreholes, monitoring wells and the water supply well were selected to meet the objectives of this hydrogeology and geochemistry assessment in consideration of land access and the presence of existing water supply wells that could be used as observation wells for the pumping test.

3.2 Homeowner Water Well Surveys

AECOM developed a preliminary groundwater model to estimate the extent of the drawdown cone associated with the pumping test. Modelling predicted several domestic water supply wells would be encapsulated by the 1 m drawdown cone. Sio contacted residential well owners that may be affected by pumping to determine their interest in participating in a homeowner water well survey. Residents who agreed to participate in the survey were interviewed in-person by Sio and AECOM staff, and the water well was visually inspected during a follow up meeting to confirm the well location, well construction, pump configuration, water use (e.g. domestic, livestock, irrigation, etc.), the presence of a water treatment system and document any historical issues with the well.

With the permission of the well owner, AECOM staff removed the well cap to facilitate manual measurement of the groundwater level and temporarily install a pressure transducer to monitor groundwater levels before, during and after the pumping test. AECOM also collected water quality samples from the point of consumption. Samples could not be collected directly from the well due to physical constrictions (e.g. riser pipe, pump wiring, etc.) and lack of a sampling port at the well head. Water level monitoring and water quality sampling methods are described in more detail in **Sections 3.6 and 4.2**, respectively. Water quality results are available to the residents who participated in the survey. Homeowner well surveys have not been included in this report due to privacy and confidentially reasons.

3.3 Authorization to Divert and Use Groundwater

Sio applied to Manitoba Conservation and Climate (Drainage and Water Rights Licensing Branch) to request authorization to divert and use groundwater for testing and analysis in support of this hydrogeological assessment. On November 5, 2020, Sio received letter approval to divert and use up to 16,500 m^3 of groundwater for testing from the Acting Head of the Drainage and Water Rights Licensing Branch which is provided in **Appendix A**. The field program commenced on November 9, 2020.

3.4 Drilling Investigation

Click Before You Dig Manitoba was contacted on November 9, 2020 to confirm the absence of underground utilities within the vicinity of all proposed drill locations. No utilities were identified. Therefore, additional subsurface utility clearance works (i.e. utility locate scans and daylighting) were not completed at any of the proposed drill locations.

Access to private lands was required for the 2020 investigation as two monitoring wells were located on adjacent private lands. Access agreements were negotiated on behalf of Sio prior to working on private lands using a third-party land management consulting company.

3.4.1 Monitoring Well Installation

Friesen Drillers Ltd. (Friesen) is a water well drilling contractor licensed under *The Groundwater and Water Well Act.* Friesen is located in Steinbach, Manitoba. Four (4) separate boreholes were advanced using a truck mounted Versa Drill (V-100 NG) using mud and air rotary drilling methods. Mud rotary drilling was utilized to advance through the Quaternary sediments using a 200 mm (7 7/8th inch) outer diameter (OD) tricone drill bit. Upon contact with the underlying carbonate unit, the drill rods were removed and the large tricone bit was replaced with a smaller 159 mm (6 1/4 inch OD) tricone bit. The rods were lowered downhole and the borehole was advanced approximately 0.91 m (3 ft) into the carbonate unit to create a narrow diameter "socket" at the top of the carbonate unit.

The drill rods were then removed to permit lowering of a 127 mm (5 inch) polyvinyl chloride (PVC) casing into the borehole belled end first to seat the PVC casing into the carbonate socket. The belled end of the PVC casing has an OD of 152mm (6 inch), which allows for a snug fit in the “socket”. The PVC casing came in 6.1 m (20 ft) lengths that were joined using PVC primer and glue at surface. The annulus between the overburden unit and the OD of the PVC casing was then sealed and secured using bentonite-cement grout mixed as described by Mikkelsen and Green (2003). The bentonite-cement grout was prepared using a gas-powered mixer and tremmied into the borehole using a Moyno pump and 19 mm (¾-inch) plastic tremie pipe.

After the 127mm PVC casing was installed, mud rotary drilling continued using a 120 mm (4 ¾-inch) OD polycrystalline diamond compact (PDC) Cutting Drag Bit. Upon reaching the desired depth in either the carbonate, shale or sandstone unit, the rods were removed to facilitate monitoring well installation.

Lithology was logged on-site by an AECOM hydrogeologist. Subsurface lithology is described on the borehole logs in **Appendix B**. Chip samples were collected in 3.05 m increments through the overburden unit and in 1.52 m increments through the carbonate, shale and sandstone units and stored in chip trays. Photographs of the chip trays are included in **Appendix C-2**.

Each borehole was completed as a monitoring well, with one (Bru 96-2) completed in the Red River Carbonate aquifer, one (Bru 95-9) completed in the Winnipeg Shale aquitard and two (Bru 95-6 and Bru 96-1) completed in the Winnipeg Sandstone aquifer. A detailed description of monitoring well installation methods is provided below. Monitoring well construction details are shown in the borehole logs (**Appendix B**) and summarized in the groundwater well construction details table (**Table 3-1**). Monitoring well locations are shown on **Figure 3-1**.

Only one monitoring well (Bru 96-2) was installed in the Red River Carbonate aquifer. The monitoring well was completed as an open hole monitoring well (i.e. without a well screen) in the carbonate unit by drilling to the target depth and removing the drill rods. Due to the competent nature of the carbonate unit, borehole collapse is unlikely. Therefore, installation of a screen and backfill material was not required. This completion method is common practice for wells completed in the Red River Carbonate aquifer. The monitoring well was completed by lowering solid, 51 mm (two inch) diameter flush threaded Schedule 40 PVC standpipe downhole by hand. A 127 mm diameter rubber shale trap was attached to the downhole end of the PVC pipe using a hose clamp and electrical tape. The PVC pipe and shale trap were positioned approximately 30 cm beyond the bottom of the 127 mm PVC casing and into the 120 mm OD portion of the carbonate borehole. Hydrated bentonite chips were used to create a seal above the shale trap and within the annulus between the outer 127 mm PVC casing and the inner 51 mm PVC standpipe. The well head was completed with a provincial well identification tag and a lockable 127 mm diameter PVC casing lid.

Two monitoring wells were installed in the Winnipeg Sandstone aquifer (Bru 95-6 and Bru 96-1) and one monitoring well was installed in the Winnipeg Shale aquitard (Bru 95-9). The monitoring wells were completed by using 51 mm (two inch) diameter, flush threaded, schedule 40 PVC standpipe with a 51 mm diameter 0.010” slotted PVC well screen. The annulus of each borehole was backfilled with silica sand around the well screen to form a sand filter pack. Well screens and filter packs were situated entirely within a singular hydrostratigraphic unit to avoid interconnection of hydrostratigraphic units. The remainder of each borehole was backfilled using a bentonite-cement grout mixed according to the Mikkelsen and Green (2003) method. Well heads were completed with a provincial well identification tag, lockable 127 mm diameter PVC casing lids and padlocks.

3.4.2 Water Well Installation and Development

One water well (Bru 95-7) was drilled and installed by Friesen using a truck mounted dual rotary drill rig (Foremost DR-24W). Subsurface lithology and well completion details are described in the borehole logs (**Appendix B**). Chip samples were collected in 3.05 m increments through the overburden unit and in 1.52 m increments through the carbonate, shale and sandstone units and stored in chip trays. Photographs of the chip trays are provided in **Appendix C-2**.

A surface seal was installed to a depth of 7.62 m below ground surface (bgs) using a 0.51 m diameter tricone bit and bentonite-cement grout. The borehole was advanced using a carbide-studded casing shoe (0.41 m diameter) welded-onto the outer casing, and inner drill rods outfitted with a drag bit (0.305 m diameter). After the desired depth was reached, the drill rods were removed from the borehole. The outer casing remained in place to prevent borehole collapse while the water well was installed.

The water well was completed using 0.305 m (12 inch) diameter steel casing and a 0.305 m diameter stainless-steel well screen. The pipe and well screen were supplied in 6.1 m lengths and the joints were welded together on-site. The 18.29 m long well screen consisted of three segments of stainless-steel, 15-slot, wire-wound well screen. The bottom of the well screen was sealed using a welded-on stainless-steel cap. A sand filter pack was installed around and immediately above the well screen using 0.55 mm filter sand. The well screen and sand filter pack was situated entirely within the Winnipeg Sandstone aquifer and the remainder of the borehole annulus was backfilled with bentonite-cement grout to prevent hydraulic connection with other hydrostratigraphic units. Grout was pumped into the borehole while simultaneously removing the outer casing to prevent formation collapse. This process was completed in stages to minimize grout loss into the formation. The bentonite-cement grout was prepared following the Mikkelsen and Green (2003) method using a gas-powered mixer and pumped downhole using a Moyno pump and 19 mm (¾-inch) plastic tremie pipe. The well head was completed with a provincial well identification tag, a lockable well cap and a padlock.

The water well was developed to remove drilling fluids, fine drill cuttings and thereby improve the hydraulic efficiency (connectivity) with the surrounding aquifer. The water well was developed by Friesen using both airlift and cable tool methods. Airlift development was conducted on November 24, 2020 for approximately six hours. Airlift development was completed by injecting compressed air into the bottom of the well to disturb and remove fine sediments within the well, filter pack and the formation. Water produced from the well during development was periodically collected and visually examined for suspended solids and turbidity to monitor the effectiveness of well development. Airlift development stopped when produced water was consistently clear and free of suspended sediment. Produced water was discharged to surface, contained by shallow berms, and allowed to naturally re-infiltrate to ground.

Preliminary well yield results were lower than observed elsewhere in the aquifer, and Friesen recommended additional well development be completed before proceeding with the long-term pumping test. On November 26 and 27, the well was developed using the cable tool method for a further six hours. The cable tool method involves repetitively plunging equipment downhole to agitate and suspend the sediments so they can be removed from the well. Similar to airlift development, produced water was visually examined to monitor the effectiveness of development.

3.4.3 Coring and Discontinuity Logging

Drilling at one borehole location (Bru 95-8) was conducted by Paddock Drilling Ltd. (Paddock) between November 16 and 19, 2020 using an Acker MP8 drill rig. A tricone drill bit and an HWT (11.7 cm OD) casing shoe was used to advance HW casing into the Red River Carbonate bedrock to a depth of 34.29 m bgs. After the casing was set, drilling continued using an HQ (9.58 cm OD) drill bit and triple tube drilling techniques. Core was extracted in 1.52 m runs. Lithology and discontinuities were logged from split spoons. HQ drilling continued through the Red River Carbonate, Winnipeg Shale, and into the top of the Winnipeg Sandstone unit. Due to poor recovery in the sandstone, HQ drilling ceased, and NW casing was used to advance the borehole to the target depth using a washing technique. The NW casing was temporarily left in place to prevent borehole collapse and facilitate installation of several vibrating wire piezometers (VWPs). VWP installation and borehole backfill and completion details for Bru 95-8 are discussed in detail below.

Core was logged for lithology and discontinuities. Photographs of rock cores are provided in **Appendix C-1**. Discontinuities were described according to type, angle with respect to core axis (alpha), surface shape, surface roughness, infill type, thickness rating, openness rating and overall joint condition following ISRM (1978) methods. Lithology and discontinuity details are provided in the borehole log (**Appendix B**).

3.4.4 Vibrating Wire Piezometer Installation

A vibrating wire piezometer (VWP) is a pressure transducer that is typically installed within a borehole and connected to a datalogger at surface by a cable. A mathematical transformation converts pressure readings into a water column height (m H_2O), which represents the height of the potentiometric surface above the transducer's installation depth. VWPs were connected to a datalogger and continuously monitor groundwater elevations and temperatures.

Prior to installation, VWP sensor membranes were saturated by submerging them in a pail of water for more than 24 hours in an inverted position. Once saturated, initial readings were taken with no load applied immediately before installation. These initial readings were used to apply correction factors to the post-installation readings.

On November 19, 2020, four VW-2100 (2.0 mPa range) VWPs furnished by RST Instruments Ltd. (Maple Ridge, BC) were installed at different elevations in borehole Bru 95-8 to establish a nested VWP hub. VWP sensors were secured to 25.5 mm (one-inch) diameter Schedule 80 PVC tremie pipe and lowered into the borehole until the target depth was reached. VWPs were installed in the Winnipeg Sandstone (VW4), the Winnipeg Shale (VW3), and at two different depths in the Red River Carbonate (VW2 and VW1). After the PVC tremie pipe and VWPs were confirmed to be resting at the desired depth, the borehole was grouted in tandem with removal of the NW casing. The borehole was grouted from bottom up by injecting bentonite-cement grout mixed according to the Mikkelsen and Green (2003) method using the tremie pipe.

At surface, a lockable metal waterproof box was welded on top of the HW casing to house and protect the VWP datalogger. The four VWP cables were connected to the DT2055B multichannel datalogger furnished by RST Instruments and programed to record data at 30 second intervals. Data can be downloaded using RST's DT Logger Host software. VWP installation records and RST calibration records are provided in **Appendix D**.

3.5 Surveying

AECOM completed surveying work on December 1, 2020. The equipment used was a TopCon GR5 global positioning system (GPS) receiver and base station with a Spectra Precision Geoinstruments Ranger Data Collector. The horizontal and vertical and accuracy of the equipment as deployed is conservatively estimated to be 50mm.

Surveying work involved establishing control points and surveying wells established during this hydrogeology and geochemistry assessment. Surveyed locations included the water well (Bru 95-7), the VWP nest (Bru 95-8), five monitoring wells (Bru 95-5, Bru 95-6, Bru 95-9, Bru 96-1 and Bru 96-2) and one residential well (23901). At each location, ground elevation, easting, and northing measurements were taken. Top of well standpipe elevations were also measured at well locations to allow for groundwater levels to be converted to geodetic elevations.

3.6 Groundwater Level Monitoring

Groundwater levels were measured manually and automatically using Solinst Leveloggers (pressure transducers) and VWPs (discussed above). Static groundwater levels were manually measured using an electronic water level meter. The probe was lowered down the well until the air-water interface was reached. Water levels were taken from the surveyed point marked on the well standpipe to allow groundwater levels to be converted to geodetic elevations.

Solinst Levelogger pressure transducers were lowered to known depths below the water table in monitoring wells using dedicated nylon string. Prior to the pumping test, pressure transducers were installed in the following wells to allow for continuous water level data collection before, during and after the pumping test:

- Water well (Bru 95-7)
- Select monitoring wells (Bru 95-5, Bru 95-6, Bru 95-9, Bru 96-1 and Bru 96-2)
- Select residential water wells (66124, 23901 and Unknown)

Pressure transducers recorded water level measurements at 30 second intervals and data were stored for future download and analysis. A Solinst Barologger was deployed above the water table in Bru 95-6 to monitor barometric pressure fluctuations and allow for subsequent corrections to be applied to water level data. Following completion of the pumping test on December 2, 2020, all pressure transducers were downloaded and removed from the wells. Two pressure transducers were reprogramed to record water levels at 30-minute intervals and immediately reinstalled in monitoring wells Bru 95-5 and Bru 95-6.

Groundwater level measurements were corrected to remove the influence of barometric pressure fluctuations and converted to geodetic groundwater elevations to produce hydrographs and evaluate groundwater flow. Groundwater elevations were calculated by subtracting the measured groundwater level from the surveyed top of pipe elevation. Top of pipe elevations are presented in **Table 3-1**.

3.7 Aquifer Testing

3.7.1 Single Well Response Tests

AECOM conducted single well response tests in five (5) monitoring wells to estimate aquifer/aquitard properties (e.g. hydraulic conductivity) between November 16 and 23, 2020. Testing was completed in three different hydrostratigraphic units, including the Red River Carbonate (Bru 95-5 and Bru 96-2), the Winnipeg Shale (Bru 95-9) and the Winnipeg Sandstone (Bru 95-6 and Bru 96-1). Prior to testing, each monitoring well was confirmed to have been previously developed.

Rising head and falling head slug tests were completed in wells screened in the Red River Carbonate or Winnipeg Sandstone. The static water level and depth to well bottom were measured using an electronic water level probe. A pressure transducer was set to record water level changes at half second intervals and installed in the well using nylon string. After water levels stabilized, a solid slug of known volume was inserted into the monitoring well via string to commence the falling head test. Water levels were recorded until the well had recovered at least 80% of the original water displacement. After water levels had recovered to static conditions, the slug was removed from the well to commence a rising head test. Water levels were again monitored until water levels recovered to static conditions.

A bail down test was completed in the one well screened across the Red River Shale because it was found to recharge very slowly. The static water level and depth to well bottom were measured using an electronic water level probe. A pressure transducer was set to record water level changes at half second intervals and installed in the well using nylon string. After water levels stabilized, the well was purged dry using an automated inertial pump (Hydrolift), high-density polyethylene (HDPE) tubing, and a dedicated inertial foot valve. Immediately after purging the well dry, the tubing was removed from the well and the well was allowed to recharge. Water levels were recorded until the rate of recovery was less than three millimetres per 10 minutes. Upon completion of testing, the pressure transducer was retrieved from the well, and data were downloaded and archived for analysis.

Data were analyzed using AQTESOLV Professional 4.5 software using the confined Bouwer-Rice solution. Key assumptions of the method include:

- Aquifer has infinite areal extent.
- Aquifer is homogeneous and of uniform thickness.
- Test well is fully or partially penetrating.
- Aquifer is confined.
- Flow to well is quasi-steady state with negligible storage.
- Slug is inserted or removed from the well instantaneously.

Single well response test results are summarized in **Table 3-A**. AQTESOLV analysis reports are provided in **Appendix E-1**. The hydraulic conductivity of the carbonate unit ranged from 1.5 x 10^{-5} to 3.9 x 10^{-4} m/s. The hydraulic conductivity of the shale unit was estimated to be 2.8 x 10^{-8} m/s. The hydraulic conductivity of the sandstone unit ranged from 5.2 x 10^{-5} to 6.2 x 10^{-5} m/s. These values are within the range of values reported in the literature for the subject aquifers (Render 1970; Betcher 1986; Ferguson et al. 2007; Wang et al. 2008; Friesen 2019a,b) and materials of similar origin in the case of the Winnipeg Shale (Freeze and Cherry 1979).

Table 3-A. Single Well Response Test Results

Hydro-statigraphic Unit	Well ID	Date of Test	Saturated Aquifer Thickness	Hydraulic Conductivity Test Results	Hydraulic Conductivity Geometric Mean
		mm-dd-yyyy	(m)	(m/s)	(m/s)
Red River Carbonate	Bru 95-5	11-17-2020	9.7	3.9 x 10^{-4}	7.65 x 10^{-5}
	Bru 96-2	11-20-2020	8.25	1.5 x 10^{-5}	
Winnipeg Shale	Bru 95-9	11-23-2020	2.5	2.8 x 10^{-8}	2.8 x 10^{-8}
Winnipeg Sandstone	Bru 95-6	11-16-2020	22.9	5.2 x 10^{-5}	5.68 x 10^{-5}
	Bru 96-1	11-20-2020	19.85	6.2 x 10^{-5}	

3.7.2 Pumping Test

A pumping test was conducted on the newly installed water well (Bru 95-7) to confirm the results of single well response testing, measure the properties (transmissivity and storativity) of the Winnipeg Sandstone at the rate of pumping for the proposed sand extraction operation, and assess the hydraulic connectivity between the Winnipeg Sandstone and the Red River Carbonate aquifers. The pumping test was completed between November 27, 2020 and December 2, 2020 by Friesen Drillers under AECOM oversight. The pumping test consisted of a step test and constant-rate pumping test.

A 0.15 m diameter, 1.83 m long, 40 horsepower (HP) submersible pump was temporarily installed in Bru 95-7 to complete the pumping test. The bottom of the pump motor was installed approximately 1.8 m above the top of the well screen and the pump intake was situated approximately one (1) metre above the shale-sandstone contact. Groundwater removed from the well was conveyed more than 300 m downslope of the pumping well using lay flat hose to ensure the water did not affect pumping test results. The discharge rate was measured during the pumping test using an orifice meter.

Manual water level measurements were collected in the pumping well and the newly installed monitoring wells to verify the accuracy of the pressure transducers, which were programmed to continuously record pressure head (i.e. water level) and temperature data during the pumping and recovery phases of the test. Water levels were also monitored using the four nested vibrating wire piezometers installed at Bru 95-8 and select residential wells. Atmospheric pressure was monitored for the duration of the test using a barometric pressure transducer to allow for correction of pressure transducer data.

The pumping test consisted of three phases:

- First, a step test was conducted to assist in selection of the pumping rate for constant-rate pumping test. Three different pumping rates were maintained until drawdown levels were sufficiently stable within the pumping well. The well was not allowed to recover prior to commencing the constant-rate portion of the pumping test. Evaluating the hydraulic efficiency of the pumping well was not part of the scope of work.
- Second, the water well was subjected to a period of constant-rate pumping. Professional judgement and step test results were used to select a constant-rate pumping rate that would adequately stress the aquifer without reducing the water level within the pumping well below the pump intake for the duration of the test. The duration of the constant-rate pumping test was over 72 hours. Pumping rates were modified slightly during the test to maintain water levels in the pumping well a safe distance above the pump intake as is common practice in the industry.
- Finally, upon conclusion of the constant-rate pumping phase, a recovery phase was monitored. The pump was turned off, and the rate of water level recovery was monitored until at least 80% recovery was observed in wells located within 500 m of the pumping well.

Following completion of testing and recovery, pressure transducers were removed and downloaded by AECOM staff.

3.7.2.1 Step Test

The step test consisted of four steps as summarized below:

- Step #1 was conducted at an average rate of 25.99 L/s (412 gallons per minute (GPM)) for a duration of two hours.
- Step #2 was conducted at an average rate of 25.36 L/s (402 GPM) for a duration of 2.5 hours.
- Step #3 was conducted at an average rate of 26.56 L/s (421 GPM) for a duration of 2.5 hours. This was the highest pumping rate that could be sustained for a short duration without drawing the water level down to the pump intake level.
- Step #4 was conducted at an average rate of 23.47 L/s (372 GPM) for a duration of 2.5 hours, and then transitioned directly into the long-term constant-rate pumping test (i.e. no recovery after step test completion).

3.7.2.2 Constant-Rate Pumping Test

The constant-rate pumping test data are presented on **Figure 3-2** and **Figure 3-3**. The constant-rate pumping test commenced immediately following the step test. The constant-rate pumping test consisted of a pumping period and a recovery period. The pumping period was conducted by pumping at a rate of approximately 26.56 L/s (372 GPM) for a duration of 72 hours. Slight adjustments to the pumping rate were required during the first 12 hours of pumping to maintain water levels above the pump intake. Groundwater level measurements and discharge readings were collected from the pumping well approximately once every hour, with more frequent readings at the start of pumping and again at the start of the recovery phase. Manual water level measurements were collected from the remainder of the monitoring network to supplement the continuous pressure transducer readings for the duration of pumping and recovery.

The monitoring network for the pumping test included one pumping well completed in the Winnipeg Sandstone, four (4) vibrating wire piezometers, five (5) monitoring wells completed in the and three (3) domestic water supply wells completed in the Winnipeg Sandstone, Winnipeg Shale and Red River Carbonate as shown in **Table 3-B** and in plan on **Figure 3-1**.

Table 3-B. Pumping Test Monitoring Network

Aquifer	Pumping Well	Observation Wells			
		Bru 95 Vibrating Wire Piezometer Nest	Bru 95 Monitoring Well Nest	Bru 96 Monitoring Well Nest	Domestic Water Supply Wells
Distance from Pumping Well (m)	0	89.3	338	1,211	See Below
Red River Carbonate	-	Bru 95-8-VW1 Bru 95-8-VW2	Bru 95-5	Bru 96-2	Well 23901 (660 m) Well 66124 (491 m)
Winnipeg Shale	-	Bru 95-8-VW3	Bru 95-9	-	-
Winnipeg Sandstone	Bru 95-7	Bru 95-8-VW4	Bru 95-6	Bru 96-1	Unknown Well: Obs S1 (960 m)

A total of approximately 6,880 m^3 (1,818,700 US gallons) of groundwater was pumped from the aquifer over the duration of the step test and constant-rate pumping test, which is approximately 42% of the approved volume of 16,500 m^3 (4,358,839 US gallons) under the authorization to divert and use water.

The maximum drawdown that was observed during the test was approximately 36 m. Following completion of the pumping period, the recovery period was monitored for more than 24 hours. Water levels recovered relatively quickly in the pumping well, with more than 50% recovery occurring in less than a minute and over 80% recovery in less than 30 minutes as shown on **Figure 3-2** and **Figure 3-3**. The maximum extent of drawdown in the Winnipeg Sandstone and Red River Carbonate aquifers at the end of pumping is shown on **Figure 3-4**.

3.7.2.3 Pumping Test Analysis

Confined Aquifer Solutions (No Leaky Aquitard)

Pressure transducer data were corrected for barometric pressure fluctuations in advance of data analysis. Erroneous data points resulting from episodic pressure transients were also removed with the exception of one longer term event after nine (9) hours of pumping which was due to an inadvertent adjustment of the discharge rate.

Transient water level data from the pumping well and observation wells was assessed to determine aquifer properties and evaluate the maximum extent of the drawdown cone generated by pumping. The pumping test analysis was conducted using industry-standard software (AQTESOLV Professional 4.5) using the following solutions:

- Theis (1935).
- Theis (1935) Residual Drawdown/Recovery.
- Theis (1935) Distance Drawdown.
- Cooper-Jacob (1946).

The Theis (1935) and Cooper-Jacob (1946) solutions were considered suitable for assessment of the pumping test data. Both solutions assume:

- The aquifer has infinite areal extent, is homogeneous and has a uniform thickness.
- The aquifer is confined, and water is released instantaneously from storage with decline of hydraulic head.
- The pumping well is fully penetrating.
- Wellbore storage is negligible.

For the purposes of the analysis, the Winnipeg Sandstone aquifer was assumed to have a uniform thickness of 20.14 m, which was the measured distance between the bottom of the Winnipeg Sandstone aquifer and the contact with the overlying Winnipeg Shale aquitard at the pumping well (Bru 95-7). The solutions do not consider the effects of leakage from the overlying/underlying aquitards. The results of pumping test analyses are summarized in **Table 3-C.**

Table 3-C. Pumping Test Results (Confined Aquifer)

Aquifer	Data Fit To	Analytical Solution Used	Storativity Results	Transmissivity Results	Hydraulic Conductivity Results	Hydraulic Conductivity Geometric Mean
	(-)	(-)	(-)	(m^2/s)	(m/s)	(m/s)
Winnipeg Sandstone	Pumping Well	Theis	1.2×10^{-4}	9.7×10^{-4}	4.82×10^{-5}	4.82×10^{-5}
	Observation Well	Theis	1.7×10^{-4}	2.2×10^{-3}	1.09×10^{-4}	9.52×10^{-5}
	Observation Well	Theis Distance Drawdown	1.6×10^{-4}	2.3×10^{-3}	1.14×10^{-4}	
	Observation Well	Theis Recovery	-	1.2×10^{-3}	5.96×10^{-5}	
	Observation Well	Cooper-Jacob	1.1×10^{-4}	2.2×10^{-3}	1.11×10^{-4}	

Notes:

Confined aquifer thickness: 20.14m

mgs = Below ground surface

Pumping well: Bru 95-7

Observation Points: Bru 95-6, Bru 95-8 (VW1, VW2, VW3 and VW4) and Bru 96-1

As shown in the AQTESOLV analysis reports, the pumping test data from the observation wells provide a better fit than the data from the pumping well (**Appendix E-2**). The poor fit between the type curves and measured water levels in the pumping well are interpreted to be the combined result of a borehole skin effect and turbulent head loss. Well losses commonly result from incomplete well development, hydraulic head loss across the well screen due to turbulent flow and hydraulic head losses inside the wellbore due to flow restrictions (e.g. excessively large pump for a given well diameter). In this case, the excess drawdown in the pumping well is assumed to be primarily the result of residual drilling mud in the sand pack and surrounding formation. When interpreting the results of the pumping test, emphasis was placed on evaluation of observation well data for determination of aquifer properties because they were unaffected by hydraulic head loss.

Based on analysis using the Theis and Cooper-Jacob solutions to the observation data from the observation wells presented in **Table 3-C3**, the following aquifer properties were estimated:

- Transmissivity ranged from 1.2×10^{-3} m^2/s to 2.3×10^{-3} m^2/s.
- Hydraulic conductivity ranged from 5.96×10^{-5} to 1.14×10^{-4} m/s, with a geometric mean of 9.53×10^{-5} m/s (assumed aquifer thickness of 20.14m).

- Storativity ranged from 1.14 x 10^{-4} to 1.7 x 10^{-4}.

These values are consistent with hydraulic conductivity measurements obtained from slug tests as part of this study, and measurements obtained from pumping tests and short term well yield tests conducted elsewhere in the Winnipeg Sandstone (Render 1970; Betcher 1986; Ferguson et al. 2007; Wang et al. 2008; Friesen 2019a,b).

To investigate the uncertainty in aquifer properties introduced by well inefficiency, the theoretical Theis curve was also fit to data from the pumping well. The estimated hydraulic conductivity and transmissivity values (4.82 x 10^{-5} m/s and 9.7 x 10^{-4} m^2/s, respectively) were approximately half an order of magnitude lower than the values obtained by fitting to the observation well data. The estimated storativity value (1.2 x 10^{-4}) was within the range observed when fitting to the observation point data.

The water level response in vibrating wire piezometers (Bru 95-8 VW3) and monitoring wells (Bru 95-9) installed in the shale aquitard indicates a lowering of approximately 3.5 m and 2 m at distances of 89.3 m and 338 m from the pumping well. VWPs installed in the overlying Red River Carbonate aquifer exhibited relatively small water level changes in response to pumping at location Bru 95-8 (Bru 95-8 VW1 and Bru 95-8 VW2), indicating the shale aquitard exhibits a relatively low permeability and the boreholes and wells were constructed in a manner that isolates the Red River Carbonate aquifer from the Winnipeg Sandstone aquifer. The vertical gradients near the end of the pumping test are estimated below:

- Winnipeg Sandstone (Bru 95-8 VW4) and Winnipeg Shale (Bru 95-8 VW3): ~ 1 m/m Downward
- Winnipeg Shale (Bru 95-8 VW3) and Red River Carbonate (Bru 95-8 VW2): 0.339 m/m Downward
- Winnipeg Shale (Bru 95-8 VW3) and Red River Carbonate (Bru 95-8 VW1): 0.486 m/m Downward

Downward vertical gradients of a similar magnitude were present under static conditions prior to the onset of pumping and slightly increased over the duration of the test due to the low vertical hydraulic conductivity of the Winnipeg Shale unit. Gradients of this magnitude are typically only observed in geological environments that contain low permeability materials that are sufficiently thick and spatially extensive to form an aquitard that impedes vertical groundwater flow. Overall, this information suggests the Winnipeg Shale is an effective hydraulic barrier to interaction between the two aquifers at this location.

Leaky Aquitard Solutions

The conceptual hydrogeological model includes the Winnipeg Sandstone, which is overlain by the Winipeg Shale aquitard and underlain by the Lower Shale and/or Precambrian Bedrock, which are interpreted to have a lower hydraulic conductivity than the Winnipeg Sandstone and function as aquitards. The Winnipeg Shale is overlain by the Red River Carbonate aquifer.

Because the analytical solutions presented in the previous section do not consider the effects of potential leakage from overlying and/or underlying aquitards, AECOM re-analyzed the pumping data considering the potential for recharge from overlying and/or underlying aquitards using the following solutions available within industry-standard software (AQTESOLV Professional 4.5):

- Neuman-Witherspoon (1969): Leaky recharge only from an overlying aquitard.
- Moench 1985 (Case 2): Leaky recharge from both overlying and underlying aquitards.
- Hantush-Jacob (1955) : Leaky recharge only from an overlying aquitard.
- Hantush (1960) : Leaky recharge from both overlying and underlying aquitards.
- Cooley-Case (1973): Leaky recharge from both overlying and underlying aquitards.

The results for the leaky aquitard solutions are summarized in **Table 3-D**.

Table 3-D. Pumping Test Results (Leaky Aquitard)

Aquifer	Data Fit To	Analytical Solution Used	Storativity Results	Transmissivity Results	Hydraulic Conductivity Results	Hydraulic Conductivity Geometric Mean
	(-)	(-)	(-)	(m^2/s)	(m/s)	(m/s)
Winnipeg Sandstone	Pumping Well	Neuman-Witherspoon (1969)	2.6×10^{-6}	5.4×10^{-6}	2.66×10^{-7}	8.81×10^{-6}
	Pumping Well	Moench 1985 (Case 2)	4.5×10^{-6}	8.6×10^{-4}	4.29×10^{-5}	
	Pumping Well	Hantush-Jacob (1955)	9.2×10^{-7}	3.3×10^{-4}	1.66×10^{-5}	
	Pumping Well	Hantush (1960)	9.4×10^{-7}	3.3×10^{-4}	1.69×10^{-5}	
	Pumping Well	Cooley-Case (1973)	9.6×10^{-7}	3.4×10^{-4}	1.09×10^{-5}	
	Observation Wells	Neuman-Witherspoon (1969)	9.8×10^{-6}	2.2×10^{-3}	1.09×10^{-4}	1.02×10^{-5}
	Observation Wells	Moench 1985 (Case 2)	1.8×10^{-6}	1.9×10^{-3}	9.60×10^{-5}	

Notes:

Confined aquifer thickness: 20.14m

mgs = Below ground surface

Pumping well: Bru 95-7

Observation Points: Bru 95-6, Bru 95-8 (VW1, VW2, VW3 and VW4) and Bru 96-1

Overall, the results are comparable to those produced for simple confined aquifers. Hydraulic conductivity estimates derived in consideration of one or more leaky aquitard(s) ranged from 2.66×10^{-7} m/s to 1.09×10^{-4} m/s, with a geometric mean of 1.78×10^{-5} m/s, whereas confined aquifer solutions produced results that ranged from 5.96×10^{-5} m/s to 1.14×10^{-4} m/s, with a geometric mean of 9.53×10^{-5} m/s. Furthermore, storativity values derived in consideration of one or more leaky aquitard(s) ranged from 9.21×10^{-7} to 9.83×10^{-6}, whereas confined aquifer solutions produced results that ranged from 1.14×10^{-4} to 1.7×10^{-4}. This illustrates that confined aquifer solutions that do not consider the effects of leakage from overlying and/or bottom less permeable units overestimated the magnitude of water release from elastic deformation of the sandstone unit in response to dewatering by at least one order of magnitude. However, the resultant hydraulic conductivity values for the sandstone were very similar and within the same order of magnitude.

4. Geochemical Assessment

In response to concerns expressed during community consultation activities, a geochemical assessment was undertaken to characterize existing conditions within the Project Site and evaluate the impacts of project operations. The assessment included the following components:

- An assessment of the metal leaching and acid rock drainage (ML/ARD) potential of the bedrock materials that will be encountered during operations. (**Section 4.1**)
- Characterization of existing groundwater quality in the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone. (**Section 4.2.1**)
- An assessment of the distribution of stable isotopes of oxygen and hydrogen to inform the conceptual hydrogeological model and numerical groundwater model. (**Section 4.2.2**)
- Characterization of groundwater quality in the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone prior to, during and after the constant rate pumping test. (**Section 4.2.3**)
- Geochemical and groundwater quality modelling to evaluate impacts to groundwater quality in response to project operations including the possibility of changing redox conditions, potential mixing of Red River Carbonate and Winnipeg Sandstone aquifers, and effect of the collapse of the Winnipeg Shale aquitard on water quality in the Winnipeg Sandstone Aquifer. (**Section 4.3**)

Each component is discussed in detail in the following sections.

4.1 Metal Leaching and Acid Rock Drainage (ML/ARD)

4.1.1 Existing Geochemical Conditions

The rock types and minerals encountered during exploration and mining influence solid phase and aqueous phase geochemistry. The following description of existing geochemical conditions is summarized from various sources including the Manitoba Preliminary Exploration Database (Fedikow 1995; Lapenskie 2016). This information provided the basis for designing and interpreting the samples collected in support of this geochemical assessment.

An in-depth discussion of Quaternary sediments within the region are indicate they are typically underlain by a bedrock consisting of Ordovician aged Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone over Precambrian crystalline basement (Betcher et al. 1995). The Red River Carbonate rocks usually overlie the Winnipeg Shale and the Winnipeg Sandstone, which are continuous, extensive geological unit that spans southern and central Manitoba and west into eastern and central Saskatchewan and south into North Dakota, South Dakota, Montana and Wyoming (Ferguson et al. 2007). The Winnipeg Sandstone is composed primarily of quartz-rich sandstones and mudstone which is interpreted as being deposited in deeper marine to shallow marine and possibly terrestrial environments (McCabe 1978).

Lapenskie (2016) conducted preliminary investigations into the high purity silica sand of Winnipeg Sandstone. A total of eleven (11) sand samples were collected from Seymourville, Reed Lake and Neepawa. The lithogeochemical results of samples from the Winnipeg Sandstone indicated that the purity of the silica sand is variable among samples, with silica content ranging from 61.07% to 98.89%. Sio completed two analytical programs within the Project Area between 2017 and 2019 to determine the mineralogy of the Winnipeg Sandstone locally. The results revealed that silica contents in all sand samples were above 98.4% indicating high purity.

Black shale is present as part of the Black Island Member of the Ordovician-aged Winnipeg Formation. This unit was typically deposited on top of the Winnipeg Formation, but is not present within the Project Area. It is typically composed of up to 50% pyrite nodules, which are rounded, equant to elongate, concentrically layered and 0.5 mm to 1.0 mm in diameter (Lapenskie 2016). Fedikow (1995) conducted a geochemical study of the black shale and associated rocks at the former Selkirk Silica quarry located on Black Island in Lake Winnipeg. Whole rock analysis indicated that the black shale exposed in the former Selkirk Silica quarry were classified as “metalliferous” black shale, with elevated cobalt, lead, silver and arsenic concentrations. This indicates a high potential for metal leaching to the environment. Acid Base Accounting (ABA) and shake flask extraction (SFE) tests were not conducted in the Fedikow (1995) study so results cannot be directly compared to those measured as part of this study. The Winnipeg

Shale found within the Project Area is geochemically distinct and does not contain elevated sulphides concentrations like those that are found in other areas of Manitoba.

The ML/ARD characterization program was developed to determine the potential for drill cuttings and rejects (i.e. oolites) brought to ground surface to generate ML/ARD if left exposed to air and allowed to weather for a short period of time or permanently stored on the ground surface under conditions where they will be exposed to atmospheric weathering conditions (oxygen and water) for an extended period of time.

The oxidation of sulphide minerals is the main process by which ARD is generated, and generally assumes that sulphides occur as pyrite. The oxidation of pyrite is a complex multi-step process that can be summarized by the following equation:

$$FeS_2 + 15/4O_2 + 7/2H_2O \dashrightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

This reaction is a very simple illustration of a very complex kinetic reaction catalyzed by bacteria and depends on several factors including, but not limited to, the concentration, type, form and exposure of sulphides present, concentration and supply of oxygen, temperature, moisture, etc.

As the reaction above shows, oxygen is a critical parameter for this reaction to procced. A significant amount of oxygen is needed to initiate and sustain sulphide oxidation to ultimately result in ARD after all acid neuralization potential has been depleted. However, the solubility and diffusion of oxygen in water are very low resulting in small oxygen concentrations in water compared to the air. The oxygen concentration in air is about 21 %, while its concentration in water in equilibrium with atmosphere is generally about 12 mg/L of less. Oxygen diffusion in water is more than 10,000 times lower than in the air. The low solubility and diffusion of oxygen in water is the reason than the storage of reactive mine wastes under water covers has become one the primary methods for mitigation of ML/ARD worldwide.

Deep confined aquifers distant from recharge areas (i.e. Winnipeg Sandstone Aquifer) are generally reducing or contain very low oxygen concentrations. This suggests that the formation of ML/ARD in subsurface is not anticipated to occur, because of the lack of sustained supply of oxygen independent of the sulphide content, form, type and degree of exposure.

Although, re-injected water may contain a residual amount of oxygen, its concentration will be very low, finite and insufficient to induce and sustain sulphide oxidation and acid generation in a saturated and well buffered environment. In addition, several other geochemical processes (oxidation of organic matter, iron and manganese oxidation, etc.) consume oxygen and will compete with sulphide oxidation for the limited amount of oxygen present in re-injected water. Furthermore, due to their small concentration in the shale, sulphide minerals are likely to be occluded within predominant aluminosilicates and may not be readily exposed to any residual oxygen in groundwater.

4.1.2 Rock Core Sampling for ML/ARD Assessment

Rock samples were collected to assess acid rock drainage and metal leaching potential for bedrock materials present within the Project Area at the locations shown on **Figure 3-1**. The rock types that will be disturbed during project operations include: Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone from an area that hosts productive aquifers that contain good water quality.

Samples of rock core were collected from three boreholes (Bru 121-1, Bru 146 and Bru 95-8) distributed across the Project Area (**Table 4-1**). Samples of Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone were collected from each borehole for subsequent evaluation and laboratory analysis. Core samples were collected from the Red River Carbonate and Winnipeg Shale units because the rock was competent enough to allow for recovery during drilling. Grab samples of the Winnipeg Sandstone unit were collected from bagged samples or stockpiled material obtained during rotary drilling or preliminary sand extraction tests.

Samples of Red River Carbonate and Winnipeg Shale from Bru 95-8 core were collected by AECOM staff at the time of drilling. The Winnipeg Sandstone sample associated with this location was collected from a stockpile created during a nearby sand extraction test at Bru 95-3. Boreholes Bru 121-1 and Bru 146 were drilled as part of historical investigations. Samples of Red River Carbonate and Winnipeg Shale were collected from core boxes stored in Sio’s core storage facility in Steinbach, and the samples of Winnipeg Sandstone associated with these locations had been previously collected and submitted by others to ALS Environmental Laboratories (ALS).

Photographs of the rock samples submitted for geochemical analysis are provided in **Appendix C-3**.

4.1.3 Laboratory Analysis

A total of nine (9) samples were submitted to ALS for the following analyses:

- Rietveld X-ray Diffraction (XRD): Qualitative x-ray powder diffraction was conducted to determine the mineralogical composition of the rock samples.
- Aqua Regia Digestion followed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS): This analysis was conducted to determine "whole rock" concentrations of metals, samples were subjected to bulk geochemical analysis after digestion with *aqua regia* ($HCl + HNO_3$). This digestion is routinely used for analysis of trace metals to allow quantification of the potential reservoir of leachable metals. It also allows comparison of concentrations of selected metals with average crustal abundance data for similar rock types (MEND 1997) to determine if they are depleted or enriched in the rock. The digestion does not completely dissolve resistant minerals such as quartz, spinels, zircon, rutile, ilmenite, chromite, or some silicates. Thus, the concentrations of certain major rock-forming constituents including aluminum, calcium, magnesium, potassium, sodium, iron, zirconium, chromium, uranium, thorium, and vanadium may be under-reported by this method.
- Shake Flask Extraction (SFE): This analysis was conducted to identify parameters potentially prone to leaching in the field by meteoric water. Samples are continuously shaken for 24 hours at 3:1 liquid to solids ratio by weight with reverse osmosis deionized (RODI) water. Gentle agitation is provided to ensure continuous exposure of all surfaces and mixing of the rinse solution. Twenty-four hours is a nominal residence time. The leachate solution is extracted and analyzed for general parameters (pH and hardness) and dissolved metals by ICP-MS. A distilled water blank is carried through the procedure and analyzed for pH as a control sample. SFE provide very conservative estimates of metal release because the setup of the experiment (i.e. crushed sample, highly oxidizing conditions, continuous shaking, etc.). These laboratory conditions generally result in worse water quality than would be observed under site conditions.
- Acid-Base Accounting (ABA): This analytical package included analysis of total sulphur (LECO method) with sulphur speciation via hydrochloric acid and sodium carbonate (sulphate sulphur), sulphide sulphur (difference), inorganic carbon (via LECO); paste pH; and modified Sobek Neutralization Potential (NP). ABA is a series of laboratory tests designed to estimate a rock's acidification potential (AP) and neutralization potential (NP). The AP of a rock is the total capacity of that rock to generate acid if all of its acid-generating minerals react to completion during weathering. Similar to the definition of AP, the NP of a rock is its total capacity to neutralize acid if all its carbonate and reactive aluminosilicate minerals react to completion. Both AP and NP are expressed in units of tons of calcium carbonate equivalent per 1,000 tons of material (t $CaCO_3$/kt) to allow direct comparisons. Corrections must be made when the respective minerals are not all pyrite or calcite.

4.1.4 Quality Assurance/Quality Control

Laboratory results were evaluated for quality assurance and quality control criteria. Evaluation of laboratory results indicated that:

- Sulphate-sulphur results were less than or equal to total sulphur results, within a 30 percent (%) margin.
- Neutralization potential was consistent with Fizz Rating in all samples.
- Neutralization potential was consistent with carbonate content (r^2 = 0.9).
- Total sulphur values were higher than sulphate-sulphur values when detected at concentrations higher than 10 times the detection limit.
- Duplicate samples were not collected due to collection of fewer than 10 samples for geochemical assessment purposes.
- Laboratory analysis included blank samples and control reference materials in each analytical batch, and results were within the tolerance ranges established by the laboratory (Appendix F-1).

The results of the QA/QC evaluation indicate the analytical results are suitable for the intended purposes (i.e. a screening evaluation of ML/ARD potential).

4.1.5 Results

The results of the laboratory testing outlined above were assessed to determine the types of minerals present in the samples (XRD), the concentrations of elements relative to average crustal abundance (Near-Total Recoverable Elemental Analysis), the potential for rock types to generate acid rock drainage (ABA) and the potential for metal leaching (dissolution) under simulated conditions using shake flask extraction (SFE). The results are discussed in the subsequent sections. The laboratory report is provided in **Appendix F-1**.

4.1.5.1 Types and Occurrence of Minerals

Table 4-2 presents the results of the XRD analysis, including the relative amounts of crystalline phases normalized to 100%. The mineralogy reports in **Appendix F-1** provide the ideal formula for the minerals and Rietveld refinement plot for the nine (9) samples.

I. Red River Carbonate

The most dominant minerals across the sample set of Red River Carbonate were, in order of decreasing abundance: calcite (79.1 weight percent (wt)% to 80.4 wt%, median 79.2 wt%), ankerite (a calcium-iron-magnesium and manganese-rich carbonate) (10.9 wt% to 13 wt%, median 11.8 wt%), k-feldspar (3.3 wt% to 4.2 wt%, median 3.6 wt%), quartz (3 wt% to 3.7 wt%, median 3.2 wt%), and illite/muscovite (1.0 wt% to 1.4 wt%, median 1.0 wt%).

Sulphide and Oxide Mineralogy:
Sulphide minerals which are the primary source of acidity were not identified through XRD analysis in samples of Red River Carbonate.

The iron oxide mineral, hematite, was identified in trace amounts in all three samples from drill core advanced in the Red River Carbonate.

Carbonate Mineralogy:
Carbonate minerals present in the samples generally provide readily available neutralization potential. Calcite was identified as the dominant carbonate mineral in all three samples collected from drill core. Siderite and ankerite were identified in all three samples.

II. Winnipeg Shale

The most dominant minerals across the sample set of Winnipeg Shale were, in order of decreasing abundance: illite/muscovite (31.1 wt% to 54.4 wt%, median 35.3 wt%), k-feldspar (26.3 wt% to 35.3 wt%, median 26.5 wt%), quartz (0.4 wt% to 32.4 wt%, median 11.3 wt%), kaolinite (3.6 wt% to 18.4 wt%, median 4.0 wt%), and calcite (0.3 wt% to 2.7 wt%, median 0.5 wt%).

Sulphide and Oxide Mineralogy
Pyrite was identified as a sulphide mineral in two out of three samples collected from drill core advanced through the Winnipeg Shale. These samples contained 0.6 wt% and 1.3 wt% pyrite in Bru121-1-36.57 to 37 and Bru 95-8_49.39 to 49.79, respectively.

The iron oxide mineral, hematite, was identified in trace amounts in two out of three primary samples from drill core. The iron oxy-hydroxide mineral, goethite, was identified in sample Bru 95-8_49.39 to 49.79 and accounted for 5.1 wt% of the sample.

Anatase and rutile, titanium oxide minerals, were detected in all three shale samples.

Carbonate Mineralogy
Calcite was identified in all three samples collected from drill core advanced in the shale formation. These samples contained between 0.3 wt% to 2.7 wt% calcite with a median of 1.78 wt% calcite. Dolomite was identified in trace amounts in one sample, accounting for between 0.9 wt% of the total sample.

Ankerite was observed in two out of three samples. Siderite was observed in sample Bru 121-1_36.57 to 37.00 and accounted for 0.3 wt% of the sample.

III. Winnipeg Sandstone

The most dominant minerals across the sample set of Winnipeg Sandstone were, in order of decreasing abundance: quartz (97.3 wt% to 98.7 wt%, median 98.3 wt%), kaolinite (0.2 wt % to 0.9 wt%, median 0.8 wt%), albite (0.4 wt% to 0.9 wt%, median 0.7 wt%), siderite (0.1 wt to 0.9 wt%), calcite (0.2 wt%). Siderite and calcite were detected in two out of three samples. Samples contained brown colored concretions which were likely amorphous iron oxide minerals that were not detectable by XRD analysis due to their non-crystalline structure. Trace amounts of α-Fe (Ferrite) were measured in two of the Winnipeg Sandstone samples.

Sulphide and Oxide Mineralogy:
No sulphides or oxides were identified through XRD analysis.

Carbonate Mineralogy:
Trace calcite was identified in Bru 95-3 and Bru146_189-194 samples collected from the Winnipeg Sandstone and each mineral accounted for 0.2 wt% of the sample. Trace dolomite mineral was identified only in Bru-95-3 sample. Trace siderite, an iron carbonate mineral, was also detected in two sandstone samples, Bru121-1_174-179 and Bru146_189-194. The dissolution of siderite initially consumes acidity, however, in oxygenated conditions, the subsequent oxidation and hydrolysis of the released iron produces equivalent acidity. Therefore, there is no net neutralization under aerobic conditions as result of siderite dissolution.

4.1.5.2 Near-Total Recoverable Elemental Analysis

Table 4-3 presents total recoverable concentration results for the nine (9) samples. To estimate the elemental enrichment in the collected samples, the laboratory concentrations of total metals were compared to the following references to highlight elements that may be of possible environmental interest (MEND 1997):

- Carbonate
- Shale
- Sandstone

Concentrations are compared to crustal abundance to evaluate whether trace elements of potential concern are present in samples at concentrations that are elevated compared to concentrations normally found in rock and soil of similar type. An enrichment factor of five times the average crustal abundance was used to identify those metals that are elevated relative to concentrations typically found in those rock types elsewhere on the earth's crust that may be of possible environmental importance.

I. Red River Carbonate

Table 4-3 presents near-total recoverable concentration results of the three (3) samples of drill core recovered from the Red River Carbonate. In these samples, the following elements were present at concentrations more than five times the crustal abundance screening criteria for carbonate sedimentary rocks:

- Cobalt: All three samples exceeded screening criteria.
- Lanthanum: One out of three samples (Bru 95-8_40.16 – 40.65) exceeded screening criteria.
- Selenium: Two out of three samples (Bru 146_36.82 – 37.13 and Bru 95-8_40.16 – 40.65) exceeded screening criteria.

II. Winnipeg Shale

Table 4-3 presents total recoverable concentration results of the three (3) samples of drill core recovered from the Winnipeg Shale. Sulphur content in two samples (Bru 121-1_36.57 – 37.00 and Bru 95-8_49.39 – 49.79) were an order of magnitude higher than the other samples, indicating the increased metal concentrations observed in these two samples of Winnipeg Shale are associated with sulphide minerals (i.e. pyrite). In these samples, the following elements were present at concentrations more than five times the crustal abundance screening criteria for shale sedimentary rocks:

- Selenium: One out of three samples (Bru 121-1_36.57 – 37.00) exceeded screening criteria.
- Silver: One out of three samples (Bru 121-1_36.57 – 37.00) exceeded screening criteria.
- Uranium: One out of three samples (Sample Bru 121-1_36.57 – 37.00) exceeded screening criteria.

Previous geochemical investigations of black shale have found that antimony, cobalt, molybdenum, nickel, silver, and sulphur concentrations were most elevated (Fedikow 1995). However, all these trace metal concentrations in Winnipeg Shale from the Project Area were below average crustal abundance criteria, and concentrations were typically one to two orders of magnitude lower than those in Black Island Shale. This clearly indicates that the Winnipeg Shale found within the Project Area has metals concentrations that are significantly lower than the Black Island Shale.

Based on field observations and a review of photographs of the solid samples, the shale material encountered within the Project Area is characterized as fine-grained, moderate to highly fractured and greyish to bluish grey in color. In some locations the shale is found to be red. Disseminated sulphides or visible minerals were not observed in any of Winnipeg Shale samples collected from the Project Area. The appearance of the Winnipeg Shale and relatively low metals concentrations indicate that shale observed on Black Island is quite different from that observed in the Project Area.

III. Winnipeg Sandstone

Table 4-3 presents total recoverable concentration results of the three (3) grab samples recovered from the Winnipeg Sandstone. In these samples, the following elements were present at concentrations more than five times the crustal abundance screening criteria for sandstone sedimentary rocks:

- Copper: One out of three samples (Bru 95-3) exceeded screening criteria.
- Niobium: One out of three samples (Bru 95-3) exceeded the screening criteria, but the concentration was 0.06 ppm and only marginally above the detection limit of 0.05 ppm.

Correlation with Other Constituents

Correlation coefficients between constituent concentrations and concentrations of iron, aluminum, manganese and organic matter are provided in the last four columns of **Table 4-4**. The highly positive correlation between sulphur and iron (i.e. 0.93) indicates that iron concentrations may be primarily related to the presence of sulphide minerals (i.e. pyrite) and/or iron oxy-hydroxide minerals. In addition, the high correlation (>0.75) between trace metals tellurium and titanium and organic carbon suggest that these metals may be complexed or coprecipitated and/or adsorbed on organic matter. Moreover, some trace elements, including chromium, cobalt, gallium, hafnium, indium, lithium, molybdenum, niobium, scandium, sulphur, tellurium, thorium, tin, titanium, vanadium, zinc and zirconium are strongly (>0.75) correlated with iron. The high correlations with iron suggest that these metals may be contained in pyrite minerals present in some samples or complexed or coprecipitated and/or adsorbed on oxyhydroxide minerals. Selenium, terbium, thallium, thorium, tin, titanium and tungsten and uranium are strongly correlated with aluminum. The oxyhydroxide mineral phases were not identified by XRD due to their non-crystalline nature but were observed in hand specimens.

These correlations suggest that the iron and organic matter may play a key role in controlling trace metal mobility. Under acidic conditions, iron oxy-hydroxide can dissolve and release adsorbed trace elements. Trace elements could also be released from organic matter under oxidizing conditions (i.e. exposure to atmospheric oxidation).

4.1.5.3 Acid Base Accounting

The risk of acid generation was determined based upon the calculated Neutralization Potential Ratio (NPR) described by MEND (2009). NPR ratio is defined by the neutralization potential (NP) divided by the acid potential (AP). MEND (2009) recommends the following classification:

- NPR > 2: Sample is considered non-potentially acid generating (Non-PAG).
- 2 > NPR > 1: Uncertain. Test is inconclusive.
- 1 > NPR: Sample is considered potentially acid generating (PAG).

Figure 4-1 illustrates carbonate NP plotted against the modified Sobek NP. Samples plotting along the 1:1 correlation line show that the source of modified Sobek NP in these samples is dominantly carbonate minerals. In general, carbonates can provide effective neutralization potential that is readily available to neutralize acidity. Deviation from the 1:1 correlation line indicates other minerals are contributing to the modified Sobek NP, such as fast-reacting aluminosilicate minerals. The modified Sobek method is a relatively aggressive method which can dissolve fast-reacting silicate minerals in addition to readily available carbonate minerals.

I. Red River Carbonate

Acid Potential

Acid generation potential for all three (3) samples of Red River Carbonate ranged from 1.3 t $CaCO_3$/kt to 2.2 t $CaCO_3$/kt (median 1.6 t $CaCO_3$/kt). Total sulphur concentrations ranged from 0.04 wt% to 0.07 wt% (median 0.05 wt%). Sulphur speciation results indicate that samples contained concentrations of sulphate and sulphide species that were less than detection limits (i.e. <0.01 wt%).

Results from all samples were plotted on a scatter plot of total sulphur (wt%) vs sulphide sulphur (wt%) (**Figure 4-2**). The results did not conform to the 1:1 correlation line, which indicates that the sulphur content was primarily not the result of sulphide or sulphate species.

Neutralization Potential

Modified Sobek neutralization potential (NP) for all Red River Carbonate samples ranged from 820 t $CaCO_3$/kt to 868 t $CaCO_3$/kt (median 821 t $CaCO_3$/kt). Total inorganic carbon as carbon dioxide (as CO_2) ranged from 0.39 wt% to 39.6 wt% (median 39.6 wt% as CO_2) in Red River Carbonate samples. Carbonate neutralization potential in all samples range between 887 kg $CaCO_3$/T to 900 kg $CaCO_3$/T (median 900 kg $CaCO_3$/T).

Figure 4-1 presents the carbonate NP vs. modified Sobek NP. The samples generally plot close to the 1:1 correlation line, indicating that the source of modified Sobek NP in these samples is dominantly carbonate minerals.

Acid Generation Potential

Figure 4-3 presents a scatter plot of AP (t $CaCO_3$/kt) vs NP (t $CaCO_3$/kt). NPR ratios for all samples ranged between 394.55 to 630.77 (median 513.13). Calculated NPR results are significantly greater than 2 for all samples. This results in the samples being classified as non-PAG according to the criteria presented by MEND (2009). The combination of XRD and ABA results indicates that calcite is available to neutralize acidity in all three samples. Low total sulphur concentration in all three limestone samples contributes to low acid potential and results in a high NPR ratio (**Table 4-4**).

II. Winnipeg Shale

Acid Potential

Acid generation potential for all three (3) samples collected from shale ranged from 2.2 t $CaCO_3$/kt to 20 t $CaCO_3$/kt (median 7.2 t $CaCO_3$/kt). Total sulphur concentrations ranged from 0.07 wt% to 0.64 wt% (median 0.23 wt%). Sulphur speciation results indicate that samples contained concentrations of sulphate species from 0.01 wt% to 0.12 wt% (median 0.06 wt%) and concentrations of sulphide species below detection (<0.01 wt%).

Results from all samples were plotted on a scatter plot of total sulphur (wt%) vs sulphide sulphur (wt%) (**Figure 4-2**). The results plot below the 1:1 correlation line, which indicates that the sulphur content was dominated by sulphates or sulphur species other than sulphides.

Neutralization Potential

Modified Sobek neutralization potential (NP) for all shale samples ranged from 5 t $CaCO_3$/kt to 25 t CaCO3/kt (median 10 t CaCO3/kt). Total inorganic carbon as carbon dioxide (as CO_2) ranged from 0.2 wt% to 1.3 wt% (median 0.3 wt% as CO_2) in shale samples. Carbonate neutralization potential in all samples ranged from 4.17 kg CaCO3/T to 30 kg CaCO3/T (median 5.83 kg CaCO3/T).

Figure 4-1 presents the carbonate NP vs. modified Sobek NP. The samples generally plot along the 1:1 correlation line, indicating that the source of modified Sobek NP in these samples is dominantly carbonate minerals.

Acid Generation Potential

Figure 4-3 presents a scatter plot of AP (t $CaCO_3$/kt) vs NP (t $CaCO_3$/kt). NPR ratios for all samples ranged between 1.25 to 2.27 (median 1.39). Calculated NPR results are between 1 and 2 for two samples (Bru 121-1_36.57 to 37.00 and Bru 95-8_49.39 to 49.79), and samples would be classified as uncertain according to the criteria presented in MEND (2009). The third sample (Bru 146_49-86 to 50.29) had an NPR value of 2.27 which is slightly higher than 2. Although sulphide sulphur concentrations were below the detection limit (<0.01 %) in all shale samples, the XRD mineralogy detected pyrite in two shale samples (Bru 121-1_36.57 – 37.00 and Bru 95-8_49.39 – 49.79). The combination of mineralogy and acid base accounting results indicate that pyrite is present is both samples with uncertain acid generation potential (Bru 121-1_36.57 to 37.00 and Bru 95-8_49.39 to 49.79) and could contribute to acid generation. Calcite minerals are available in all three samples, but it is present in low concentrations (<2.7 wt%). Comparison to the total sulphur concentration confirms that the highest total sulphur is detected in the two samples classified as having uncertain acid generation potential (Bru 121-1_36.57 to 37.00 and Bru 95-8_49.39 to 49.79) (**Table 4-4**).

However, AP is calculated by assuming all detected sulphur (wt.%) produces the same acidity per mole of S as pyrite (FeS_2) or pyrrhotite (Fe1-xS). This can overestimate the AP and result in incorrect classification of samples. This is particularly true for this case, where most of the sulphur appears to be present as sulphate indicating the parent sulphide minerals may have largely been oxidized by weathering processes over time. Therefore, the actual AP in the Winnipeg Shale may be much lower than the NP. The limited carbonate-NP data suggested there were sufficient carbonate minerals present to neutralize the majority of the potential acidity in the samples of Winnipeg Shale. Additional sampling and ongoing monitoring are required to expand the data set and directly observe behaviour of the Winnipeg Shale under simulated or actual field conditions.

III. Winnipeg Sandstone

Acid Potential

Acid generation potential for all three (3) samples collected from the Winnipeg Sandstone ranged from below detection limits (<0.3 t $CaCO_3$/kt) to 0.6 t $CaCO_3$/kt (median 0.3 t $CaCO_3$/kt). Total sulphur concentrations ranged from below the detection limit (< 0.01 wt%) to 0.02 wt% (median 0.0.1 wt%). Sulphur speciation results indicate that samples contained concentrations of sulphate species at or below the detection limit (0.01 wt%) to 0.02 wt% and concentrations of sulphide species below detection (<0.01 wt%).

Results from all samples were plotted on a scatter plot of total sulphur (wt%) vs sulphide sulphur (wt%) (**Figure 4-2**). The results were below with the 1:1 correlation line, which indicates that the sulphur content was largely due to the presence of sulphates or other species of sulphur.

Neutralization Potential

Modified Sobek neutralization potential (NP) for all samples of Winnipeg Sandstone ranged from 3 t $CaCO_3$/kt to 6 t CaCO3/kt (median 4 t $CaCO_3$/kt). Total inorganic carbon as carbon dioxide (as CO_2) ranged from 0.2 wt% to 0.3 wt% (median 0.3 wt% as CO_2). Carbonate neutralization potential in all samples ranged from 4.17 t $CaCO_3$/kt to 7.5 t $CaCO_3$/kt (median 7.5 t $CaCO_3$/kt).

Figure 4-1 presents the carbonate NP vs. modified Sobek NP. The samples generally plot along the 1:1 correlation line, indicating that the source of modified Sobek NP in these samples is dominantly carbonate minerals.

Acid Generation Potential

Figure 4-3 presents a scatter plot of AP (t $CaCO_3$/kt) vs NP (t $CaCO_3$/kt). The calculated NPR results are between 10 and 13.33 (median 10), and samples would be classified as non-PAG according to the criteria presented in MEND (2009). One NPR value was calculated using AP values that were below detection limits (< 0.3 t $CaCO_3$/kt) and were replaced by the detection limit value. The combination of mineralogy and acid base accounting results indicate that sulphide minerals are not present in any of the samples from the Winnipeg Sandstone, which is consistent with the low sulphide sulphur (i.e. below detection limit) and AP (<0.7 t $CaCO_3$/kt). Dolomite minerals are available in one sample but they are present in low concentrations (<0.2 wt%) (**Table 4-4**).

4.1.5.4 Shake Flask Extraction (SFE)

The SFE results for dissolved concentration from the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone are presented in **Table 4-5**. The SFE analytical results were compared to the groundwater guidelines and standards indicated in **Table 4-A** in **Section 4.2.2.4** of this report. This comparison is meant only to serve as a reference to interpret and contextualize results, and to highlight potential additional contaminants of concern that may be of environmental interest. The SFE test is considered an aggressive test given that a small mass of crushed sample is in contact with and constantly “washed” by the same aliquot of deionized water for a given period of time. This process may result in artificially elevated concentrations of various parameters that may approach solution saturation when they would be less likely to occur under field conditions. The SFE analysis reflects laboratory conditions and cannot be used to accurately predict leachable metal concentrations under field conditions.

I. Red River Carbonate

The results from the SFE tests for the Red River Carbonate samples are presented in **Table 4-5**. In general, the patterns of the constituent concentrations in the SFE leachates were consistent with the results of near-total recoverable metals analyses, with the exception of aluminium and lanthanum. In one of the Red River Carbonate samples, lanthanum was present at concentrations above the five times average crustal abundance screening criteria but was not detected in SFE leachate. Aluminium concentrations were below the fives times average crustal abundance screening criteria but had elevated concentrations in the SFE leachate in all three samples of Red River Carbonate. Dissolved concentrations of the following elements were higher than the reference guidelines and standards in samples of the Red River Carbonate:

- Aluminium: All three samples marginally exceeded the CCME FAL Acute Guidelines (i.e. 0.005 – 0.1 mg/L) for dissolved aluminium.
- Selenium: All three samples exceeded the applicable guidelines and standards for dissolved selenium. Two samples (Bru 121-1_24.38 - 24.83 and Bru 146_36.82 - 37.13) exceeded the CCME FAL Chronic Guidelines (i.e. 0.001 mg/L). One sample (Bru 95-8_40.16 - 40.65) exceeded three applicable guidelines including CCME FAL Acute Guidelines (i.e. 0.001 mg/L), FIGQG Agricultural (i.e. 0.001 mg/L) and MWQSOG MAC (i.e. 0.01 mg/L).
- Mercury: All three samples exhibited concentrations of dissolved mercury below the detection limit. Whether mercury exceeds the CCME FAL Chronic Guidelines(i.e. 0.000026 mg/L) in these samples is uncertain because mercury results were not detected at the laboratory detection limit of 0.00005 mg/L.

II. Winnipeg Shale

The results from the SFE tests for the Winnipeg Shale samples are presented in **Table 4-5**. In general, the patterns of the constituent concentrations in the SFE leachates were consistent with the results of near-total recoverable metals analyses, with the exception of arsenic, selenium and silver. In one of the Winnipeg Shale samples, silver was present at concentrations above the five times average crustal abundance screening criteria but was not detected in SFE leachate. Selenium concentrations were above the fives times average crustal abundance screening criteria in one sample (Bru 121-1_36.57 - 37.00) which had elevated concentrations in SFE leachate from all three samples of Winnipeg Shale. Dissolved concentrations of the following elements were higher than the reference guidelines and standards in samples of the Winnipeg Shale:

- Arsenic: One sample (Bru 121-1_36.57 - 37.00) exceeded seven applicable guidelines including the CCME FAL Chronic Guideline (i.e. 0.005 mg/L), CCME Livestock and MWQSOG Livestock (i.e. 0.025 mg/L), MWQSOG MAC (i.e. 0.01 mg/L), FIGQG Agricultural (i.e. 0.005 mg/L) and CDWQ MAC (i.e. 0.01 mg/L) for dissolved arsenic. The exceedances of the drinking water guidelines were very marginal (less than 5 times). None of the groundwater quality samples exceeded drinking water guidelines (see **Section 4.2**), indicating that the release of arsenic in SFE is due to the aggressivity of the SFE experiment.
- Selenium: All three samples exceeded the applicable guidelines for dissolved selenium. One sample (Bru 146_49.86 - 50.29) exceeded CCME FAL Chronic Guidelines (i.e. 0.001 mg/L). The other two samples (Bru 121-1_36.57 - 37.00 and Bru 95-8_49.39 - 49.79) exceeded two or more applicable guidelines. One sample (Bru 121-1_36.57 - 37.00) exceeded multiple guidelines including CCME FAL Chronic (i.e. 0.001 mg/L), CCME Livestock and MWQSOG Livestock (i.e. 0.05 mg/L), CCME Irrigation and MWQSOG Irrigation (i.e. 0.02 - 0.05 mg/L), FIGQG Agricultural (i.e. 0.001 mg/L), MWQSOG MAC (i.e. 0.01 mg/L) and, CDWQ MAC (i.e. 0.05 mg/L). Sample Bru 95-8_49.39 - 49.79 exceeded CCME FAL Acute and Chronic (i.e. 0.001 mg/L), FIGQG Agricultural (i.e. 0.001 mg/L) and MWQSOG MAC (i.e. 0.01 mg/L). The exceedances of drinking water guidelines were very marginal, except in one sample (Bru 121-1_36.57 - 37.00). It is likely that selenium is more prone to release from the crushed shale samples, which have a finer texture and a higher surface area to volume ratio for the release of constituents between from the solid. Selenium is generally present as oxyanions and more mobile under oxidizing conditions prevailing during the SFE tests. Dissolved selenium exists mostly as the selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) anions under alkaline and oxidizing conditions, like the environment. Groundwater conditions at the site are reducing and selenium is expected to be in the least soluble form. It is therefore likely to precipitate out of the solution. The aquifer chemistry shows that selenium is below the detection limit (< 0.00005 mg/L) in most water quality samples from all three units (see **Section 4.2**). The

highest concentration measured was 0.00091 mg/L, an order of magnitude lower that the MWQSOG MAC, indicating that the release of selenium in SFE is due to the aggressivity of the SFE experiment.

- Uranium: One sample (Bru 121-1_36.57 - 37.00) exceeded seven applicable guidelines for dissolved uranium including CCME FAL Chronic Guidelines (i.e. 0.015 mg/L), CCME FAL Acute (i.e. 0.033 mg/L), MWQSOG Irrigation and CCME Irrigation and FIGQG Agricultural (all three are 0.01 mg/L) and MWQSOG MAC and CDWQ MAC (0.02 mg/L). Like arsenic and selenium no exceedance of the drinking water guidelines was reported for uranium (see **Section 4.2**).
- Mercury: All three samples exhibited concentrations of dissolved mercury below the detection limit. Whether mercury exceeds the CCME FAL Chronic Guidelines (i.e. 0.000026 mg/L) in these samples is uncertain because mercury results were not detected at the laboratory detection limit of 0.00005 mg/L. Mercury was also below the detection limit in all water quality samples.

III. Winnipeg Sandstone

The results from the SFE tests for the Winnipeg Sandstone are included in **Table 4-5**. In general, the patterns of the constituent concentrations in the SFE leachates were not consistent with the near-total recoverable metal results. In one sample (Bru 95-3), copper and niobium concentrations were present at concentrations above the five times average crustal abundance screening criteria for sandstone, but they were not detected in SFE leachate. Aluminium concentrations were below the fives times average crustal abundance in all three samples but had elevated concentrations in SFE leachate from all three samples of Winnipeg Sandstone. Iron and selenium concentrations were below the fives times average crustal abundance screening criteria but had marginally elevated concentrations in SFE leachate from one sample each. Dissolved concentrations of the following elements were higher than the reference guidelines and standards in samples of the Winnipeg Sandstone:

- Aluminium: All three samples exceeded the CCME FAL Guidelines (i.e. 0.005 – 0.1 mg/L) for dissolved aluminium.
- Iron: One out of three samples (Bru 95-3) exceeded five applicable guidelines for dissolved iron concentrations including CCME FAL Chronic Guidelines (i.e. 0.3 mg/L), FIGQG Agricultural and MWQSOG AO and CDWQ AO (all three are 0.3 mg/L).
- Selenium: One out of three samples (Bru 121-1_174 to 179) exceeded the applicable guidelines and standards for dissolved selenium and marginally exceeded CCME FAL Chronic Guidelines and FIGQG Agricultural (all three 0.001 mg/L). Selenium generally does not appear to be a contaminant of potential concern for the Winnipeg Sandstone even under the aggressive SFE procedure and under neutral pH site conditions as indicated above and the single marginally elevated concentration may be related to the presence of fragments of the Winnipeg Shale in the sample.
- Mercury: One out of the three samples (Bru 95-3) exhibited dissolved mercury concentrations below the detection limit. The other two samples were not analyzed by the laboratory for dissolved mercury. Whether mercury exceeds the CCME FAL Chronic Guideline (i.e. 0.000026 mg/L) in these samples is uncertain because mercury results were not detected at the laboratory detection limit level of 0.00005 mg/L in the sample from Bru 95-3 and it was not analyzed in the other two samples.

4.1.6 Summary of Metal Leaching and Acid Rock Drainage Results

In total, nine (9) rock samples were collected from the drill cores and included three (3) samples each of Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone at three (3) locations (Bru 121-1, Bru 146 and Bru 95-8). All nine (9) samples were submitted for geochemical characterization including XRD mineralogical analysis, near-total recoverable elemental analysis using aqua regia method, ABA and SFE. The groundwater quality results discussed in **Section 4.2.2** are representative of existing water-rock interactions in the subsurface and should be evaluated together with the solid phase data to supplement the discussion and analysis of ML/ARD testing results.

All samples of Red River Carbonate and Winnipeg Sandstone have calculated NPR values significantly greater than 2, and those samples are classified as non-PAG according to definitions in MEND (2009). Two samples collected from the Winnipeg Shale had calculated NPR values below 2 (1.25 to 1.39) and they are classified as uncertain acid generation potential. The third sample of Winnipeg Shale was classified as non-PAG. Although mineralogy results indicated that pyrite is present in two of the three the samples from the Winnipeg Shale, ABA test results suggest that it is not conclusively acid generating. As discussed in **Section 4.1.3**, the accuracy of the mineralogy or AP measurements should be validated through additional sampling during extraction operations. This will help address the discrepancies between mineralogy and ABA test results and confirm the quantity and behaviour of sulphide minerals in the Winnipeg Shale. Until this information is available and has been assessed, waste derived from the Winnipeg Shale should be considered PAG, managed conservatively, and disposed of in accordance with the Waste Characterization and Management Plan.

SFE results indicated that the rock types display varied metal leaching potential. Dissolved aluminium was elevated in the Red River Carbonate and Winnipeg Sandstone. Aluminum is a major constituent of aluminosilicate rocks, is generally present in most environments due to weathering and is commonly elevated in SFE test results. Selenium was identified as marginally elevated in samples of Red River Carbonate, Winnipeg Shale and one sample of Winnipeg Sandstone, except in one sample where the concentration was significantly higher than the guidelines. . Arsenic and uranium were identified as also marginally elevated in one sample of Winnipeg Shale. However, arsenic, selenium and uranium concentrations in groundwater were below or close to detection limits. This indicates that these constituents were released due the crushing and constant shaking of the sample in a highly oxidizing setting during the SFE tests and that their solubilities under natural site conditions are low. Whether mercury was a potential contaminant of concern in all samples was uncertain because most of the results exhibited concentrations below the detection limit. Based on ML/ARD tests results, wastes derived from the Winnipeg Shale, Red River Carbonate and Winnipeg Sandstone should be managed conservatively in accordance with the Waste Characterization and Management Plan.

The acidity released from the oxidation of low sulphur material like the project wastes in a favorable environment (abundant oxygen, moisture and microorganism) can be easily neutralized by several rock forming minerals including carbonates and aluminosilicates. Carbonate minerals such as calcite are particularly very effective in neutralizing the acidity released according to the following reaction.

$$4CaCO_3 + 4H_+ \rightarrow 4Ca^{2+} + 4HCO_3^-$$

The process of neutralization increases the pH reducing metal solubility and causing metal precipitation and co-precipitation.

Because drill cuttings and rejects from the project brought to surface will include significant carbonate minerals due to the thick limestone aquifer and oolites found in the sandstone, there is a significant reservoir of neutralizing capacity in the project wastes that will inhibit or buffer ARD. Additionally, the current project plan is to collect and haul all project wastes to an accredited facility for disposal. The occurrence of ARD in subsurface is also not plausible due to anoxic and saturated subsurface conditions coupled with low and finite sulphide concentrations in the Winnipeg Shale, Red River Carbonate and Winnipeg Sandstone. In summary, the potential for ARD related environmental effects due to the project are very low.

The Winnipeg Shale found at the site is commonly mistakenly considered similar to the Black Shale found in other parts of the province such as Black Island Shale on Lake Winnipeg. Our data show that the highest sulphur concentration in the Winnipeg Shale at the site was 0.64 %, while a Black Shale sample collected from Black Island returned a total sulphur concentration of 20.8% (unpublished data). This clearly demonstrates that the Winnipeg Shale found at the site is geochemically very different from the Black Island Shale.

4.2 Aqueous Geochemistry

The dissolved constituents in groundwater provide a record of the minerals encountered as water moves through an aquifer. Thus, water chemistry can be used to trace the movement of groundwater and evaluate the origin of the water types. In this section, stable isotopes and groundwater quality were evaluated to assess the water geochemistry of the carbonate, shale and sandstone in the Project Area.

4.2.1 Existing Groundwater Quality

Water quality in the Red River Carbonate and Winnipeg Sandstone aquifers is the result of a complex history that includes entrainment of old basin brines and subsequent halite dissolution, subglacial recharge of and infiltration of modern precipitation based on an extensive evaluation of water quality and stable isotopes (Grasby and Betcher 2002). In the Red River Carbonate aquifer, groundwater quality reflects a mixture between subglacial recharge and either basin brines or recent recharge (Ferguson et al. 2007). The Winnipeg Sandstone aquifer has freshened more slowly than the overlying Red River Carbonate aquifer due to spatial variability in modern recharge and the lower permeability of the Winnipeg Sandstone relative to the Red River Carbonate aquifer. Groundwater quality in the sand and gravel aquifers that comprise the Quaternary Sediments is not well characterized but is thought to be relatively fresh as water is primarily derived from recent meteoric recharge. However, the aquifer is known to contain elevated concentrations of iron and sulphate in some locations.

Water quality in the aquifers is generally fresh in the eastern and central portions of southeastern Manitoba including the area surrounding the Project Site. However, water quality further west is known to be saline in the Winnipeg Sandstone and brackish in the Red River Carbonate where the two aquifers may be interconnected or receive lateral saline recharge from the Williston Basin near the Red River. Water quality is generally the most saline near the Red River Floodway, where concentrations of total dissolved solids are known to exceed 1,000 mg/L. This may reflect lateral eastward migration of saline water from the Williston Basin in the vicinity of the Red River, which is thought to be the boundary between fresh and saline water in the Red River Carbonate aquifer (Grasby and Betcher 2002). Water quality in the Red River Carbonate is thought to be affected by upwelling saline water from the underlying Winnipeg Sandstone at some locations.

One notable exception is the area surrounding the Birds Hill Complex, which is comprised of coarse textured glaciofluvial sediments that allow for recharge of significant quantities of fresh modern precipitation. The overall freshening of the aquifer from east to west and radially outward from the Birds Hill Complex was described by Render (1970). Betcher (1995) identified a freshwater zone in the Winnipeg Sandstone aquifer extending from the eastern subcrop of the Winnipeg Formation across most of the study area. The western boundary of the freshwater lens is thought to migrate northward at a rate of approximately 10 m/year (Betcher 1986) as basin brines continue to be flushed from the aquifer. The Red River Carbonate aquifer is known to be influenced by spatially distributed recharge through the overlying glacial sediments, whereby gypsum dissolution results in elevated sulphate concentrations in the underlying carbonate aquifer (Grasby and Betcher 2002).

Groundwater chemistry ranges from Mg-Ca-HCO_3 type groundwater to Na-K-Cl-SO_4 type groundwater exhibiting higher concentrations of total dissolved solids (Phipps et al. 2008). The majority of the study area exhibits good water quality of Mg-Ca-HCO_3 type groundwater, with slightly higher concentrations of sulphate to the west, and Na-Mg-HCO_3-Cl type groundwater to the south. The water quality in the Red River Carbonate and Winnipeg Sandstone aquifers has been previously evaluated based on water quality data from the groundwater observation well network maintained by Manitoba Sustainable Development.

Concentrations have been noted to exceed Maximum Allowable Concentrations (MAC) for barium in areas of southeast Manitoba and are discussed in detail by Underwood and Ferguson (2008). It is speculated that this is related to interconnection of the Winnipeg Sandstone and Red River Carbonate resulting in changes in barite solubility (Betcher et al. 2003). The majority of nitrate concentrations in the study area are low, but locally elevated concentrations have been reported in the Red River Carbonate aquifer near Dugald (Friesen 2019). Elevated concentrations of arsenic, fluoride and uranium have also been found in groundwater within the study area. Arsenic concentrations are typically below 0.025 mg/L but may be elevated in proximity to shales. Fluoride concentrations have also been found to be elevated (1-2 mg/L) within the study area and may be related to mixing between saline and fresh waters (Betcher et al. 2003) and are notably higher in the Winnipeg Sandstone.

Stable isotopes of oxygen and hydrogen have been used extensively to investigate the hydrogeology and water quality of the Sandilands area, Red River Carbonate aquifer and Winnipeg Sandstone aquifer in southeastern Manitoba. The local meteoric water line and evaporation line have been empirically derived. Information from chlorofluorocarbon (CFC) tracer studies has been used to estimate groundwater recharge rates (Cherry 2000) and stable isotopes has been used to identify end mixing members for the purposes of evaluating water quality (e.g. Ferguson et al. 2007; Phipps et al. 2008).

4.2.2 Stable Isotopes of Hydrogen and Oxygen

4.2.2.1 Rock Core Sampling for Vapour Analysis

A total of nineteen (19) rock core samples were collected from the Red River Carbonate and Winnipeg Shale units encountered at Bru 95-8. Core samples were collected in 0.10 m increments and markers were placed in the core box. Drilling mud was scraped from the outside of the core samples using a metal spatula. Core was not washed during the process to avoid cross-contamination by waters of different isotopic signature.

These rock samples were then collected in medium-sized Ziploc™ Freezer bags with the headspace evacuated, then placed in a second large-size Ziploc™ Freezer bag with the headspace evacuated. Samples were stored in a Styrofoam cooler under standard chain of custody procedures and transported to the University of Saskatchewan Aqueous Geochemistry Lab within two days of sampling. In the lab the medium-sized Ziploc™ bags were blown up with dry air (air passed through a drierite™ column) and the core and headspace allowed to equilibrate in the bag for four days before analysis. Samples were analyzed using the DVE-LS method described in Wassenaar et al. (2008) and Hendry et al. (2015) and a Picarro-2120i cavity ringdown spectrometer.

Two laboratory standards of known isotopic composition (certified calibration done by the USGS) were prepared and analyzed every four samples to allow for normalization of results and isotopic drift correction. A third laboratory standard was prepared and analyzed every 12 samples as a check standard to ensure results were within acceptable limits. Accuracy and precision of $\delta^{18}O$ and $\delta^{2}H$ measurements using this method are ±0.4 and 2.1‰, respectively. The laboratory noted that the reported isotopic composition of the Winnipeg Shale should be interpreted with caution due to the possibility for interference by organic compounds contained within the shale.

4.2.2.2 Water Sampling for Aqueous Analysis

Drilling fluid samples were collected at regular intervals during each day of drilling to characterize the isotopic signature of the drilling fluids and evaluate the potential for analytical interference. Five (5) water samples were collected directly from the water truck utilizing a bypass valve during drilling. The water truck was filled daily from a water well at the Friesen yard. Samples were placed in HDPE bottles without any headspace and sealed for transport to University of Saskatchewan under standard chain of custody (COC) procedures.

A total of seven (7) groundwater samples were collected from pumping well Bru 95-7 before and during the 72-hour pumping test to evaluate any changes in isotopic signature over time in response to induced horizontal and vertical gradients. The primary purpose of these samples was to evaluate changes in groundwater contributions from the Winnipeg Sandstone and Winnipeg Shale during pumping. Samples were placed in HDPE bottles without any headspace and sealed for transport to University of Saskatchewan under standard COC procedures. Laboratory reports are provided in **Appendix F-2.**

Water samples were analyzed using a Picarro 2130i cavity ringdown spectrometer coupled with a Leap Technologies PAL HTC-xt autosampler. Three USGS calibration standards are analyzed every 10 samples, two for normalization of results and isotopic drift correction and one as a check standard. Accuracy and precision of $\delta^{18}O$ and $\delta^{2}H$ measurements using this method are ±0.3 and 2.0‰, respectively.

4.2.2.3 Depth Profile of Hydrogen and Oxygen Isotopes

A total of 31 samples collected from different depths and hydrostratigraphic units were analyzed for stable isotopes of oxygen and hydrogen. Values are relative to Vienna standard mean ocean water (VSMOW). Stable isotope analytical results are presented in **Table 4-6**. The δD and $\delta^{18}O$ values are presented with depth on **Figure 4-4** in reference to the boundaries of hydrostratigraphic units.

In the Red River Carbonate, δD and $\delta^{18}O$ generally exhibit a consistent pattern, with values ranging from -96.85‰ to -104.57‰ and -13.14‰ to -10.90‰, respectively. Both δD and $\delta^{18}O$ have higher values at the shallowest depth and then become more depleted with increasing depth. δD values appear to exhibit more variability with depth compared to δ18O.

In the transition zone between Red River Carbonate and Winnipeg Shale, both δD and $\delta^{18}O$ values exhibit strong variations (**Figure 4-4**). For instance, δD are most depleted at the contact between the Red River Carbonate and the Winnipeg Shale and increase with depth. In contrast to δD, $\delta^{18}O$ are the most enriched at the contact between the Red River Carbonate and the Winnipeg Shale and decrease with depth. This contrasting pattern may reflect a seawater source that has subsequently mixed with meteoric recharge as noted by others (Grasby et al. 2000; Hendry et al. 2014). The $\delta^{18}O$ values are highest near the centre of the Winnipeg Shale (up to -8.23‰) and consistent with the range of values presented in Ferguson et al. (2007) for basin brines, which exhibit $\delta^{18}O$ values of -3‰ to +4‰ in the Williston Basin and may point to ongoing diffusion of brines from the Winnipeg Shale to the overlying Red River Carbonate and underlying Winnipeg Sandstone along concentration gradients. The anomalously low value of $\delta^{18}O$ (-12.61‰) is coincident with an anomalously elevated $\delta^{2}H$ (-108.01‰) and an observed sand seam observed at a depth of 50.6 m. Aside from this anomalous sample, the isotopic profile through the Winnipeg Shale is consistent with one that would be generated by slow outward diffusion of brine. Pleistocene-aged water has been demonstrated to have a uniform $\delta^{18}O$ value of -25‰ in the clay-rich lacustrine clays deposited below Lake Aggasiz (Ramenda et al.

1994), imparting an estimated air temperature of 16°C. The isotopic profile through the shale exhibits $\delta^{18}O$ values between -12.61‰ and -8.23‰, and these waters appear to have become entrapped when temperatures were cooler than observed during the Pleistocene.

Multiple water samples (i.e. S1 through S7) were collected from the Winnipeg Sandstone during the pumping test at Bru 95-7. δD and $\delta^{18}O$ were generally stable, with values ranging from -107.40‰ to -105.80‰ and -14.76‰ to -14.14‰, respectively. Water samples in the Winnipeg Sandstone generally had more depleted δD values than those in the Red River Carbonate but were enriched relative to those observed in the Winnipeg Shale. Water samples in the Winnipeg Sandstone were more depleted in $\delta^{18}O$ than those observed in either the Red River Carbonate or the Winnipeg Shale.

4.2.2.4 Local Meteoric line and Local Evaporation Line

The δD versus $\delta^{18}O$ plot (**Figure 4-5**) shows changes in the water isotope composition with water groups along the meteoric water line, giving an overall sense of water isotope composition within the local water sources over the vertical profile. The plot also allows for identification of any non-conservative mixing processes due to water-rock reactions.

Precipitation and other waters that have not undergone evaporation (such as most groundwaters) generally fall along a local meteoric water line (MWL) having a slope of about 8. As shown on **Figure 4-5**, water samples collected from the Winnipeg Sandstone have a relatively uniform isotopic composition and become more depleted with increased pumping time. However, the majority of the water samples from the Red River Carbonate and Winnipeg Shale are relatively enriched in δD and $\delta^{18}O$ compared to those in the Winnipeg Sandstone. More pronounced deviation is observed in water samples collected from the Winnipeg Shale. The deviation from the MWL indicates the presence of kinetic fractionation during the evaporation, and the extent of deviation is strongly dependent on temperature, salinity, wind speed and humidity (Clark and Fritz, 1997). Meteoric waters that have undergone evaporation display systematic enrichment in both δD and $\delta^{18}O$, resulting in divergence from the MWL along evaporation lines having slopes of less than 8. Based on the isotope fractionation in the Red River Carbonate and Winnipeg Sandstone, the local evaporation line (LEL) was defined as:

δD = 2.12 δ18O - 75.2 ‰ (R^2 = 0.77)

Most of the water samples from the shale are enriched in both δD and $\delta^{18}O$ and fall below the evaporation line, which indicates the possibility of analytical interference by organic compounds in the shale. This deviation could also be interpreted in terms of climatic conditions and the presence of additional geochemical processes (i.e. mineral-water interactions) other than evaporation during sediment deposition and diagenesis. However, the changing isotopic composition along with pumping indicates that pumping did not result in an appreciable downward movement of water from the Red River Carbonate across the Winnipeg Shale and into the Winnipeg Sandstone.

As noted in Ferguson et al. (2007), fresh waters in the Winnipeg Formation plot along the Gimli Meteoric Water Line and have $\delta^{18}O$ values ranging from -12‰ to -24‰ suggesting groundwater recharge occurred under a wide range of climatic conditions. The values decrease to around 16‰ to -18‰ and are typically lowest near the freshwater/saline water interface near the Red River. These low values have been attributed to subglacial recharge when temperatures were colder than present. Phipps et. al. (2008), conducted isotope analysis for groundwater sampling from over 50 observation and monitoring wells across southeastern Manitoba area. All of these wells are screened in Quaternary Sediments, Red River Carbonate and Winnipeg Sandstone. Therefore, there was no reference stable isotope data available for the Winnipeg Shale. Results of this study indicate that isotope data from the Red River Carbonate and Winnipeg Sandstone within the Project Area are generally consistent with the results of previous investigations, and indicate that groundwater in the carbonate was recharged under a variety of climatic conditions that are also slightly different from those affecting the isotopic composition of the Winnipeg Sandstone within the Project Area. These differences can likely be explained by differences in regional groundwater flow velocities and the fact that the Red River Carbonate may be directly influenced by more recent meteoric recharge from the overlying glacial sediments.

4.2.3 Groundwater Quality

4.2.3.1 Monitoring Well Development

Monitoring wells were developed to remove fluids used during drilling and fine drill cuttings. Monitoring well development was completed between November 13 and 24, 2020, shortly following well installation. Monitoring wells were developed using an automated inertial pump outfitted with dedicated inertial footvalves and tubing. During development, a YSI ProDSS (digital sampling system) was used in the field to monitor water quality parameters including:

- Temperature
- Conductivity
- Specific conductance
- pH
- Dissolved oxygen (DO)
- Oxidation-reduction potential (ORP)
- Salinity
- Turbidity

Monitoring wells screened in the Red River Carbonate and Winnipeg Sandstone units were developed until:

- A minimum of one wellbore volume was removed from the well.
- Water purged from the well was relatively clear.
- Field parameters as noted above stabilized.

The monitoring well screened in the Winnipeg Shale was developed by purging the well dry twice. Further development could not be completed at the time of the field program due to slow well recovery.

4.2.3.2 Groundwater Sampling and Laboratory Analysis

Groundwater samples were collected from nine (9) locations across the Project Area to characterize baseline groundwater quality within the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone. Water quality samples were collected before, during and after the pumping test to assess effects of the pumping test and continued well development on water quality. Two groundwater samples were collected from each well before pumping commenced and after pumping stopped. One additional water sample was collected from the pumping well (Bru 95-7) during the pumping test. One additional groundwater sample was collected from Bru 95-9 three months after pumping test (i.e. February 2021) to further characterize groundwater quality in the Winnipeg Shale.

Groundwater samples were collected from the water well after it was developed using the pumping test equipment by opening a gate valve at the well head. One sample was collected immediately after the 72-hour pumping test commenced, a second sample was collected during pumping, and the final sample was collected immediately before the pumping test ended.

Groundwater samples were collected from the monitoring wells using an automated inertial pump (Hydrolift) and dedicated inertial foot valves and tubing. Groundwater samples from select residential water wells were collected from a point of consumption within the house (e.g. tap in kitchen). Samples could not be collected directly from the residential water wells because downhole equipment and wiring obstructed sampling equipment.

A YSI ProDSS was used to monitor the following field parameters: temperature, conductivity, specific conductivity, pH, DO, oxidation-reduction potential (ORP), salinity and turbidity. Samples were filtered and preserved in the field accordingly to laboratory specifications. Samples were collected in laboratory supplied bottles and were delivered to the ALS laboratory (ALS) in Winnipeg. Samples were subsequently analyzed by ALS, a Canadian Association for Laboratory Accreditation (CALA) certified laboratory, following industry standard practices for QA/QC.

Groundwater samples were submitted for analysis of the following parameters:

- Physical tests (alkalinity, hydroxide, bicarbonate, carbonate, dissolved organic carbon (DOC), specific conductivity, pH, total dissolved solids (TDS), total suspended solids (TSS), turbidity and hardness)
- Anions and nutrients (chloride, fluoride, nitrate, nitrite, ammonia, sulphate and sulphide)
- Dissolved metals

The following additional parameters were also analyzed at the water well:

- Biological oxygen demand (BOD); Chemical oxygen demand (COD)
- Polycyclic aromatic hydrocarbons (PAHs);

- Phenols
- Petroleum hydrocarbons (i.e. benzene, toluene, ethylbenzene and xylenes)

Water quality data were compared against applicable criteria and are presented in **Table 4-7** and **Table 4-8**. Laboratory analytical reports are provided in **Appendix F-3**. **Figure 4-6** and **Figure 4-7** present general water chemistry (conductivity, TDS, alkalinity, hardness, sodium, potassium, chloride, sulphate) in the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone. The terms “Pre-test”, “Mid-test” and “Post-test” refer to the timing of water sample collection in relation to the pumping test.

4.2.3.3 Quality Assurance/Quality Control

One duplicate sample was collected from Bru 96-2 during the site visit in November 2020. The analytical results and calculated relative percent difference values (RPD) are presented in **Table 4-7**. RPDs are not to be calculated for parameters where one or both sample concentrations are below the laboratory method detection limit (MDL).

Comparison of the analytical results for the blind field duplicate pair indicates that RPDs for all inorganic parameters were below the allowable limit of 30% when both concentrations were above the MDL, except for total phosphorus. Overall, groundwater field duplicates showed good precision for most parameters. Therefore, groundwater analytical results are considered to be representative of field conditions and suitable for the intended purposes of this report.

4.2.3.4 Regulatory Criteria

Groundwater analytical results were compared to the following groundwater guidelines and standards (based on guidance from Manitoba Sustainable Development Information Bulletin of June 2016 “Assessment Criteria for Groundwater”), as a screening assessment based on potential groundwater exposure pathways (**Table 4-A**). All guidelines/standards indicated below have been applied to groundwater analytical results presented in **Table 4-7** and **Table 4-8**.

Table 4-A. Groundwater Standards and Guidelines Assessment

Standard / Guideline	Rationale
Exposure Pathway - Discharge to Groundwater	
Canadian Drinking Water Quality (CDWQ, updated in February 2024 Version)	Applied as a screening tool as water supply wells and private wells in the vicinity of the Project Area may use the aquifer for drinking water.
Manitoba Water Quality Standards, Objectives, and Guideline (MWQSOG, Tier III) for the protection of Drinking Water	
Canadian Council of Ministers of the Environment (CCME), Water Quality Guidelines for the Protection of Agriculture Water - Irrigation Water Use	The Project Area is located on agricultural land.
Canadian Council of Ministers of the Environment (CCME), Water Quality Guidelines for the Protection of Agriculture Water - Livestock Water Use	
Federal Interim Groundwater Quality Guidelines (FIGQC) for the Protection of Agriculture	
Exposure Pathway - Discharge to Surface Water	
Canadian Council of Ministers of the Environment (CCME), Water Quality Guidelines for the Protection of Aquatic Life	Screening tool to assess if groundwater from the site is applicable to discharge to surface water.
Manitoba Water Quality Standards, Objectives, and Guideline (MWQSOG,Tier II) for the protection of Aquatic life and Wildlife	

4.2.3.5 Summary of Groundwater Exceedances

Table 4-9 summarizes the parameters that exceeded applicable screening criteria. CCME and MWQSOG have both long-term (chronic) and short-term (acute) water guidelines for protection of aquatic life. The exceedances of both the long-term and the short-term acute are highlighted in the analytical tables (**Table 4-8)**. However, only short-term exceedances are present in the summary table (**Table 4-9**), which is considered appropriate for the purposes of this report and in the context of the frequency of sampling.

Groundwater quality in all samples met CDWQ for all parameters, except turbidity, iron and manganese. The CDWQ for iron and manganese in drinking water is an aesthetic objective (AO) to protect against staining and unpleasant taste but is not considered to be toxic at these concentrations. The field turbidity values were generally above 20 NTU, and well above the treatment limit ranges (0.1 to 1 NTU). CDWQ recommended that water entering the treatment distribution system have turbidity levels of 1.0 NTU or less. The common sources for elevated turbidity in natural water are clays, silts and metal precipitates. In addition, sulphide concentrations in Bru 95-5 exceeded MWQSOG of 0.05 mg/L. Sulphide concentrations in all other water samples remained low or below detection limits. Similar to iron, the MWQSOG for sulphide in drinking water is an aesthetic objective, it is not a widespread issue and is not considered to be a concern.

Fluoride concentrations in all water samples exceeded FIGQC for agricultural use. Fluoride is a naturally occurring trace element found in low concentrations in nature and is present in most geologic environments. Based on the provincial groundwater quality survey conducted by Manitoba Sustainable Development, elevated fluoride concentrations are generally observed in the Winnipeg Sandstone aquifer in parts of south-eastern and west-central Manitoba. Fluoride concentrations in all water samples met CDWQ MAC of 1.5 mg/L.

Sulphide concentrations at multiple locations may have exceeded FIGQC for agricultural use of 0.002 mg/L because the FIGQC guideline is lower than the laboratory detection limit of 0.019 mg/L.

Boron concentrations in Bru 96-1 ranged from 0.605 to 0.692 mg/L, which marginally exceeded CCME, FIGQG and MWQSOG guidelines for agricultural use. Dissolved iron and zinc concentrations at some locations also marginally exceeded FIGQC for agriculture. Molybdenum concentration in Bru 95-9 exceeded CCME and MWQSOG guidelines for agricultural use but remained low for the rest of the locations.

Fluoride and iron concentrations exceeded CCME for aquatic life at multiple locations. Dissolved copper and zinc concentrations exceeded CCME for aquatic life.

Groundwater quality in all water samples met all applicable guidelines for protection of livestock.

4.2.3.6 Groundwater Characterization

Piper trilinear diagrams were used to visually compare water chemistry of each sample and evaluate the potential for mixing among water types. These plots include two triangles, one for plotting cations and the other for plotting anions. The major cations and anions fields are combined to show a single point in a diamond-shaped field. Chemical components consist of three cation species (calcium, magnesium, and sodium plus potassium) and three anion species (chloride, sulfate, and carbonate plus bicarbonate) or groups of species. These ions account for the electrical charge balance in most natural waters. Values are plotted on a diagram by converting cation and anion concentrations to milliequivalents per liter (meq/L) and then calculating relative percentages of cation and anion species or groups of species. It should be noted that water samples with very different concentrations of total dissolved solids, but with the same relative proportions of cation and anion species plot at the same position on the diagram.

All water samples collected during the field investigation were plotted on a Piper diagram in **Figure 4-8**. Sample locations and the lithology of the hydrostratigraphic unit from which it was collected are the basis for identifying the water type for each sample. There are six water composition types:

- Type 1: Ca-HCO_3: Freshwater dominant
- Type 2: Na-Cl-SO_4: Saline water dominant
- Type 3: Mixed Ca-Na-HCO_3: Mixing between Type 1 and Type 2, with higher carbonate proportion
- Type 4: Mixed Ca-Mg-Cl: Mixing between Type 1 and Type 2, with higher chloride proportion
- Type 5: Ca-SO_4: Gypsum dominant

- Type 6: Na-HCO_3: Alkali carbonate dominant

In addition to water type, the origin of groundwater is also assessed based on total dissolved solids (TDS) values. Hem (1985) developed a system to classify salinity of water using TDS concentrations as follows:

- Brines: >35, 000 mg/L
- Saline Waters: 10,000 – 35,000 mg/L
- Brackish Waters: 2,000 – 10,000 mg/L
- Fresh Water: <2,000 mg/L

TDS in all groundwater samples ranged from 217 to 489 mg/L, indicating the groundwater is fresh. Groundwater in the Red River Carbonate unit generally had the lowest TDS values (i.e. <300 mg/L). Slightly elevated TDS values (300 – 500 mg/L) were observed in Bru 95-9, which was screened in the lower permeability Winnipeg Shale.

As shown on **Figure 4-8**, water chemistry was variable in groundwater samples across the Project Area and included Type 1 (Ca-HCO_3), Type 3 (Mixed Ca-Na-HCO_3) and Type 6 (Na-HCO_3). These water samples exhibited a higher portion of bicarbonate (HCO_3) and calcium (Ca) and a low TDS concentration (<1,000 mg/L), indicating fresh water.

Based on a review of the water quality data, specific findings and interpretations are summarized below:

- **Red River Carbonate**:
  - Groundwater in the Red River Carbonate typically plotted on the left-hand side of the Piper quadrangle in the Type 1 (Ca-HCO_3) facies. This is typical of groundwater in areas in contact with carbonate rocks, where the fresh meteoric water charged with carbon dioxide from the soil zone reacts with the carbonate host rock or with carbonate-rich materials overlying the bedrock, resulting in dedolomitization reactions along the flow path (Plummer et al. 1990). Groundwater is characterized by circumneutral to slightly alkaline pH (7.54 – 7.91) and moderately elevated conductivity (395 to 543 µS/cm), hardness (112 to 268 mg/L) and TDS (217-277 mg/L). Major ions include sulphate, sodium, calcium, magnesium, potassium and chloride concentrations are generally below 50 mg/L, indicating overall good water quality.
  - Private wells (23901 and 66124) were screened in the Red River Carbonate, and water quality is characterized by higher sodium (i.e. 134-138 mg/L) and low calcium and magnesium (<0.2 mg/L) concentrations, and therefore plotted on the bottom of the Piper quadrangle in the Type 6 Na-HCO_3 facies. TDS at these locations remained below 500 mg/L. The elevated sodium and low calcium/magnesium concentrations are likely due to the use of a water softener (i.e. water softener salt), which is primarily composed of sodium chloride. Without application of the water softener, groundwater in these two private wells would likely be similar to water samples from the carbonate or sandstone units and plotted in Type 1 or Type 3 facies.
  - Sulphide concentrations were below detection limit for all samples, except for Bru 95-5 (Post). The sulphide concentration in Bru-95-5 (Post) exceeded both FIGQG Agricultural and MWQSOG AO guidelines. Sulphate concentrations in all samples remained low (<20 mg/L).
  - Nutrients including ammonia, nitrate and nitrite exhibited low concentrations, and met all applicable guidelines. Fluoride concentrations in all water samples were marginally above FIGQG Agricultural of 0.12 mg/L but below the applicable drinking water guidelines. Dissolved organic carbon (DOC) concentrations in water samples were relatively low, and ranged from 1.45 mg/L to 3.65 mg/L.
  - Dissolved metals concentrations were generally low and met the applicable guidelines except for iron. Iron concentrations in Bru 95-5 (Pre and Post) water samples marginally exceeded CDWQ AO and FIGQG Agricultural guidelines.
- **Winnipeg Shale:**
  - Groundwater samples collected from the Winnipeg Shale (Bru 95-9) plotted on the left-hand side of the Piper quadrangle in the Type 1 (Ca-HCO_3) and Type 6 (Na-HCO_3) facies. TDS concentrations in the shale samples were generally higher than those in the Red River Carbonate and Winnipeg Sandstone, but well below 1,000 mg/L.

- It is suspected that the sample collected immediately before the end of the pumping (i.e. plotted in Type 6) was not representative of groundwater in the Winnipeg Shale due to extremely high alkalinity concentration of 1,230 mg/L. Moreover, this water sample had the highest observed TDS, conductivity, chloride, sulphate, potassium and DOC concentrations. It is AECOM's opinion that the sample collected prior to the end of the pumping test was influenced by grouting during well installation. Grouting can impact water quality temporarily in the area around the borehole until the grout has set. An additional groundwater sample was collected at Bru 95-9 three months after the pumping test, and water quality results indicated it had proportions of major ions that were comparable to the pre-test sample and plotted in the Type 1 facies.
- Water quality in the Winnipeg Shale unit was otherwise characterized by circumneutral to slightly alkaline pH (7.54 to 7.75), moderately elevated conductivity (471 to 515 µS/cm), hardness (204 to 211 mg/L) and TDS (269 to 302 mg/L). Major ions including sulphate, sodium, calcium, magnesium, potassium and chloride concentrations were generally low and consistent with those in the Red River Carbonate. TSS in the Winnipeg Shale ranged from 186 to 1,150 mg/L and may have been influenced by residual fine materials including clays and silts following drilling.
- Sulphide concentrations were below detection limits for all samples. The overall low sulphide and sulphate concentrations in the shale samples indicates that water quality is not influenced by the weathering of sulphide minerals or gypsum and is not impacted by ML/ARD.
- Nutrients including ammonia, nitrate and nitrite exhibited low concentrations and met all applicable guidelines except fluoride and dissolved organic carbon. Fluoride concentrations in all water samples were marginally above FIGQG Agricultural of 0.12 mg/L but below the applicable drinking water guidelines. Dissolved organic carbon (DOC) concentrations were higher in the Winnipeg Shale than in the Red River Carbonate or Winnipeg Sandstone, and ranged from 1.75 to 7.03 mg/L.
- Dissolved metals concentrations were generally low and met the applicable guidelines, except for cadmium. Iron concentrations in one water sample exceeded the FIGQG Agricultural guideline.

- **Winnipeg Sandstone:**
  - Water quality collected in the Winnipeg Sandstone (Bru 96-1 and Bru 95-7, and private well "unknown") plotted on the left-hand side of the Piper quadrangle in the Type 1 ($Ca\text{-}HCO_3$) and Type 3 ($Ca\text{-}Na\text{-}HCO_3$) facies. They are characterized by circumneutral to slightly alkaline pH (7.72 – 8.5), and moderately elevated conductivity (428 to 594 µS/cm), hardness (110 to 238 mg/L) and TDS (239 - 358 mg/L).
  - Major ions including sulphate, sodium, calcium, magnesium, potassium and chloride concentrations were generally consistent with those in the Red River Carbonate, except for Bru 96-1. TDS, conductivity, sodium, chloride and sulphate concentrations were most elevated in Bru 96-1, indicating water quality was slightly worse.
  - Sulphide concentrations were below detection limit for all samples, except for Bru 95-7. Sulphide concentrations in Bru 95-7 Post exceeded FIGQG Agricultural guideline of 0.002 mg/L. Sulphate concentrations remained low (<10 mg/L) in Bru 95-7 and slightly elevated in Bru 96-1 (~30 mg/L). The overall low sulphide and sulphate concentrations and the circumneutral pH indicates that water quality is not influenced by the weathering of sulphide minerals or gypsum and is not impacted by ML/ARD.
  - Nutrients including ammonia, nitrate and nitrite exhibited low concentrations and met all applicable guidelines. Fluoride concentrations in all water samples were marginally above FIGQG Agricultural of 0.12 mg/L but below the applicable drinking water guidelines. Boron concentrations in Bru 96-1 (Pre and Post) marginally exceeded the FIGQG Agricultural guideline of 0.5 mg/L. Dissolved organic carbon (DOC) concentrations in water samples were generally lower than those in the Red River Carbonate and ranged from 0.5 to 2.89 mg/L.
  - Dissolved metals concentrations were generally low and met the applicable guidelines, except for zinc. Zinc concentrations in Bru 95-6 and Bru 95-7 marginally exceeded FIGQG Agricultural guideline of 0.01 mg/L.
  - Bru 95-7 (pre and post) were sampled for PAHS, PHCs and BTEX and reported concentrations below detection limits for these parameters.

Overall, water chemistry in Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone is generally comparable and classified dominantly as $Ca\text{–}Mg\text{–}HCO_3$ water type. The overall low TDS (<500 mg/L) indicates groundwater in the

Project Area is fresh. This is consistent with previous investigations, regional aquifer characterization studies and water source mapping (Grasby and Betcher 2002; Phipps 2008). The Project Area is near the Sandilands area, where the highland form local recharge areas (Simpson et al. 1987; Betcher et al. 1995).

All water samples collected in the carbonate, shale and sandstone units met applicable drinking water criteria. However, treatment or filtration should be considered due to the high turbidity values. Groundwater in all groundwater samples exceeded CCME and/or FIGQG for fluoride, which is very common for sedimentary rocks.

4.2.3.7 Impact of Pumping Test on Water Quality

In order to assess the impact of pumping on water quality, Relative Percent Differences (RPDs) were calculated between the "Pre" and "Post" samples collected at each location for select analytes as shown in **Table 4-10**. General water quality parameters (i.e. conductivity, hardness, alkalinity, bicarbonate), major ions and dissolved metals (i.e. boron, iron, manganese, molybdenum and zinc) which exceeded the applicable guidelines were selected for RPD calculations. Parameters that have calculated RPDs greater than +/- 30% are considered to have changed (positively or negatively) as a result of the pumping test. It is possible that well completion methods and additional well development influenced water quality between sampling events.

In the Red River Carbonate, water quality at Bru 95-5 exhibited more pronounced changes than at Bru 96-2, with five (5) out of 22 calculated RPD values changing by more than 30%. Of these five parameters, only one (dissolved iron) had a positive RPD value of 32%, indicating slightly increased concentrations following the pumping test. Bru 96-2 is located approximately 900 m east of the pumping well (Bru 95-7), where pumping had a negligible effect on groundwater levels. Water quality at Bru 96-2 was relatively stable before and after the pumping test, with one parameter (DOC) having an RPD value greater than 30%. It is likely that continued well development associated with sampling is responsible for the relatively subtle water quality changes at Bru 96-2. Water quality at Bru 95-5 generally improved after the pumping test as indicated by a large proportion of negative RPD values. However, sulphide and zinc concentrations increased slightly from below detection limits to values just above detection limits. Bru 96-2 is located approximately 900 m east of the pumping well (Bru 95-7), where pumping had a negligible effect on groundwater levels. Water quality at Bru 96-2 was relatively stable before and after the pumping test, with one parameter (DOC) having an RPD value greater than 30%.

Bru 95-7 is a water supply well screened in the Winnipeg Sandstone and water quality remained relatively stable or slightly improved during the pumping test. Water quality showed decreased sulphide, manganese, zinc and molybdenum concentrations. Similar to Bru 95-5, iron concentrations in Bru 95-7 increased 2-3 times during the pumping test, which is inferred to be the result of continued well development and removal of drilling fluids.

Bru 95-6 is located close to Bru 95-7 and within the drawdown cone induced by the pumping test in the Winnipeg Sandstone. During the pumping test, water quality degraded slightly with 14 out of 22 parameters having positive RPD values. Four parameters including DOC, manganese, molybdenum and zinc had positive RPDs values greater than 40%. The consistency between DOC and metal concentrations may indicate that these metals are bounded or form a complexation with DOC.

Bru 96-1 is located approximately 900 m east of Bru 95-7 and is completed in the Winnipeg Sandstone. Water quality at Bru 96-1 remained relatively stable during the pumping test. Five (5) out of 22 selected parameters had RPD values greater than 30%. Similar to Bru 95-6, DOC, manganese, molybdenum and zinc had positive RPD values greater than 40%.

Bru 95-9 is screened in the Winnipeg Shale unit and water quality changed significantly during the pumping test, with nine out of 22 parameters having RPD values greater than 100%. However, as discussed earlier in **Section 4.2.3.6**, the water sample collected near the end of pumping is not considered to be representative of groundwater in the Winnipeg Shale due to interference by water impacted by cement-bentonite grout chemistry. The water sample collected in advance of the pumping test exhibited water quality that was similar to the additional sample collected three months after the pumping test, indicating consistency of water quality.

Overall, water quality remained relatively similar over the duration of the pumping test. While concentrations of some parameters increased in response to continued well development, the majority of parameters decreased in response to pumping indicating the possible benefits of well and aquifer development.

4.3 Geochemical / Groundwater Quality Modelling

Geochemical modelling was undertaken using PHREEQC (Parkhurst and Appelo 1999) to evaluate the impact of project operations on water quality. PHREEQC is an industry-standard geochemical modelling code that allows identification and quantification of chemical reactions and simulation of one-dimensional transport processes involving solid minerals and aqueous and gaseous phases. PHREEQC is often used for mine water predictive studies because of the ease with which it can be used to mix waters and specify equilibrium controls.

4.3.1 Groundwater Quality in Response to Changing Redox Conditions

Operational processes including sand extraction and reinjection of excess groundwater could introduce groundwater containing low concentrations of oxygen into the subsurface. This has the potential to affect both redox conditions and groundwater chemistry. PHREEQC (version 3.1.4 with the minteq.v4 database) was utilized to evaluate the effect of changing redox conditions and mineral equilibrium controls on groundwater chemistry. The model was developed to evaluate the overall impact of reinjection of oxygenated water on groundwater quality.

Groundwater samples were collected from Bru 95-5, Bru 95-9 and Bru 95-7 prior to completion of the pumping test and were considered to be representative of groundwater quality in the Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone, respectively.

PHREEQC simulations assumed that groundwater was fully exposed to oxygen and became oxidizing after it was pumped out of the aquifer. Therefore, the groundwater collected from the Red River Carbonate (Bru 95-5), Winnipeg Shale (Bru 95-9) and Winnipeg Sandstone (Bru 95-7) were modeled to be in equilibrium with atmospheric CO_2 and O_2, with the partial pressure of carbon dioxide (PCO_2) set at $10^{-3.5}$ and $PO_2 = 10^{-0.67}$, respectively. The initial redox condition (pe) for each water type was calculated using the field measured ORP for each sample. This is an unlikely worst-case scenario, because during project operations, extracted water will re-injected back into the aquifer immediately after treatment and it will not be exposed to the atmosphere long enough to fully equilibrate with the partial pressure of oxygen in the atmosphere. However, simulation results are useful for understanding the potential magnitude of change in geochemistry and water quality if oxygen concentrations were very high. Although the simulations are a simplification of actual processes, the results can be used to investigate potential geochemical conditions during and following sand extraction operations.

Semi-quantitative XRD is not capable of determining the presence of non-crystalline and/or amorphous compounds. As such, selected groundwater samples were allowed to equilibrate with atmospheric conditions in the PHREEQC equilibrium modelling software to determine which minerals are anticipated to precipitate out of solution. PHREEQC results indicated that the amorphous mineral phases including ferrihydrite $Fe(OH)_3$ and diaspore (AlOOH) are near saturation or slightly supersaturated in water from all three units (i.e. Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone) and can be considered solubility controls for iron and aluminum concentrations.

Other iron and aluminum oxides, including goethite and gibbsite, are more crystalline forms and less likely to reach equilibrium status within a reasonable timeframe. Although dissolved iron and manganese concentrations were present in groundwater, iron and manganese carbonate minerals including siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$) were undersaturated in all three groundwater samples. Due to the high concentrations of calcite (i.e. 80 wt.%), water from the Red River Carbonate was also assumed to be in equilibrium with calcite. It should be noted that these calculations are representative of oxidizing conditions only. Although trace metals including arsenic, copper, and selenium tend to be adsorbed to these amorphous mineral phases, the adsorption process was not considered in PHREEQC simulations. Therefore, the predicted water quality results under oxidizing conditions are conservative with respect to simulated dissolved trace metal concentrations.

The simulated water quality and saturated indexes of mineral phases including calcite ($CaCO_3$), siderite ($FeCO_3$), rhodochrosite ($MnCO_3$), manganite (MnOOH), ferrihydrite (FeOOH), strontianite ($SrCO_3$), diaspore (AlOOH) and gypsum ($CaSO_4$) is shown in **Table 4-11**. Parameters including pH, alkalinity, major ions and selected dissolved metals (aluminum, arsenic, fluoride, iron, manganese, molybdenum and zinc) are presented. The predicted results for chromium, cadmium, copper, lead, mercury, nickel and selenium were not presented because their initial concentrations in all three water samples were below detection limits. The impact of redox conditions on water quality was assessed by comparing the simulated concentration of modeled parameters in each source of water (i.e. Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone) with existing water quality and calculating the relative percent difference as shown in **Table 4-11**. Parameters that have calculated RPDs greater than +/- 50% were considered to be impacted by the redox conditions.

As shown in **Table 4-11**, simulated pH in all three water samples increased approximately 12% -16% under simulated operating conditions. This is because the system was simulated as open to atmospheric conditions, which typically have a lower partial pressure of carbon dioxide than a closed system such as a confined aquifer. When groundwater is pumped to the surface, excess carbon dioxide will be released to the atmosphere resulting in an increase in pH and a decrease in alkalinity.

"Pe" is parameter used to measure redox potential. Higher pe values usually indicate oxidizing conditions and lower pe values are indicative of reducing conditions. As discussed above, the pe values in existing groundwater samples were calculated based on field measurements of ORP and ranged from 2.44 to 3.2. Under the simulated conditions, pe values were simulated to be greater than 13, indicating oxidizing conditions in groundwater.

Under slightly alkaline pH and oxidizing conditions, ammonia concentrations were simulated to be zero, as ammonia is only stable under relatively reducing conditions in groundwater. Iron and aluminum oxides including ferrihydrite and diaspore were simulated to precipitate out of the solution and result in a decrease in iron and aluminum concentrations in groundwater. As shown in **Table 4-11**, the simulated dissolved iron and aluminum concentrations in all three units were very low and almost negligible under simulated conditions. Manganite (MnOOH) was simulated to become over saturated due to the forecast oxidizing conditions in groundwater, and dissolved manganese concentrations are anticipated to be lower as a result of precipitation reactions. Although trace metals including arsenic, molybdenum and zinc tend to be adsorbed to these amorphous mineral phases, the adsorption process was not included in PHREEQC. As stated above, simulation results are therefore conservative for these dissolved trace metal concentrations. Under oxidizing conditions, most fluorides are present as inorganic F^- or associated with calcium and sodium which are very water soluble. Therefore, changing redox conditions are not forecast to impact fluoride concentrations.

Carbonate minerals including gypsum ($CaSO4 \cdot 2H_2O$), siderite ($FeCO_3$), rhodochrosite ($MnCO_3$) and strontianite ($SrCO_3$) were simulated to remain unsaturated. Therefore, increasingly oxidizing conditions will tend to further reduce iron, manganese and aluminum concentrations, but have minor impact on sulphate and strontium in groundwater.

Besides iron and manganese, calcium concentrations in Bru 95-5 decreased by over 90% from 50.7 mg/L to 5.19 mg/L following re-equilibration of calcite in groundwater with atmospheric pressure. Off gassing of carbon dioxide results in super saturation of groundwater with respect to calcium and subsequent precipitation of calcite.

4.3.2 Groundwater Quality in Response to Mixing of Waters from Red River Carbonate and Winnipeg Sandstone Aquifers

It is possible that project operations will result in increased hydraulic communication between the Red River Carbonate and the Winnipeg Sandstone within the Project Area due to fractures and borehole annuli that may extend across the Winnipeg Shale aquitard. Degradation of the Winnipeg Shale could lead to a more interconnected aquifer system comprising the Red River Carbonate aquifer and the underlying Winnipeg Sandstone aquifer. Water quality samples collected from each aquifer were utilized as end mixing members. PHREEQC geochemical modelling software was used to simulate the effect of this by mixing groundwater from the Red River Carbonate and Winnipeg Sandstone in various proportions. The "MIX" keyword in PHREEQC allows the mixing of an unlimited number of solutions at user defined proportions. The simulations calculate the equilibrium distribution of each species in the mixture. It should be emphasized that there is no molar transfer of the minerals allowed between each simulation.

The resultant water chemistry was simulated based on the assumed mixing ratio between groundwater derived from the Red River Carbonate and the Winnipeg Sandstone. PHREEQC simulated a mixed water chemistry by assigning normalized mixing fractions ranging from 0.1:0.9 to 0.9:0.1. The sum of mixing fractions was 1.0 in all cases. The exchange of groundwater between the two aquifers will be determined by the vertical hydraulic conductivity of the zone separating the aquifers, the vertical groundwater gradient and the spatial extent of any zones exhibiting altered hydraulic properties as a result of project operations. It is important to acknowledge groundwater exchange between the two aquifers has been occurring naturally via natural spatially distributed flow across with Winnipeg Shale under a hydraulic gradient, via groundwater flow through boreholes or wells that interconnect the aquifers and via borehole annuli that are poorly sealed across the Winnipeg Shale.

The vertical groundwater gradients between the Red River Carbonate and Winnipeg Sandstone aquifers are spatially and temporally variable, so two mixing scenarios were evaluated:

- Upward groundwater flow from the Winnipeg Sandstone to the overlying Red River Carbonate in areas where an upward gradient is present.
- Downward groundwater flow from the Red River Carbonate to the underlying Winnipeg Sandstone in areas where a downward gradient is present.

The methods and results of each simulation are discussed in detail below.

4.3.2.1 Scenario 1: Simulated Groundwater Quality in Red River Carbonate Due to Upward Flow of Groundwater from Winnipeg Sandstone

This scenario simulates the net effect of upward groundwater flow from the Winnipeg Sandstone to the overlying Red River Carbonate aquifer. Mixed water was assumed to be in equilibrium with calcite. The system is closed, so the pCO_2 was calculated rather than specified as a boundary condition. The simulated results were compared to CDWQ MAC and AO as shown in **Table 4-12**.

As indicated in **Table 4-12**, metal concentrations in the mixed water were generally low and met the applicable guidelines, except for manganese and iron. Iron concentrations marginally exceeded the CDWQ AO of 0.3 mg/L in all simulated water, except for water containing less than 20% of the Red River Carbonate end member. Dissolved manganese concentrations in the Winnipeg Sandstone were approximately 20 times higher those in the Red River Carbonate. As a result, the simulated manganese concentrations increase with an increasing proportion of groundwater derived from the Winnipeg Sandstone, and simulated water quality exceeded CDWQ AO of 0.02 mg/L when the mixing fraction of water derived from the Winnipeg Sandstone was greater than 70%. This reflects the naturally elevated concentrations of manganese in the Winnipeg Sandstone.

Concentrations of alkalinity, chloride, calcium, magnesium, arsenic, iron, uranium and strontium concentrations progressively decreased with an increasing proportion of groundwater derived from the Winnipeg Sandstone because concentrations of these parameters are generally lower in the Winnipeg Sandstone unit. Simulated dissolved zinc concentrations gradually increased from <0.001 mg/L to 0.01 mg/L, but remained well below the CDWO AO of 5 mg/L.

4.3.2.2 Scenario 2: Simulated Groundwater Quality in Winnipeg Sandstone Due to Downward Flow of Groundwater from Red River Carbonate

This scenario simulates the net effect of downward groundwater flow from the Red River Carbonate to the underlying Winnipeg Sandstone. The system is closed, so the pCO_2 was calculated rather than specified as a boundary condition. No mineral equilibrium was specified for this case because quartz is the predominant mineral in the Winnipeg Sandstone, and it is not likely involved in any geochemical reactions that occur over a reasonable timeframe. The simulated results are compared with CDWQ MAC and AO as shown in **Table 4-13**.

As indicated in **Table 4-13**, metal concentrations in the mixed water were generally low and met the applicable guidelines, except for manganese and iron. Iron concentrations in the Winnipeg Sandstone were low, but water quality was simulated to marginally exceed CDWQ AO of 0.3 mg/L when the mixture contained over 30% of Red River Carbonate end member reflecting the naturally elevated concentrations of iron in the Red River Carbonate aquifer. The simulated dissolved manganese concentrations decreased with the increasing proportions of groundwater derived from the Red River Carbonate, and only exceeded CDWQ AO of 0.02 mg/L when the proportion of water derived from the carbonate was below 30%.

Concentrations of sulphate, sodium and zinc concentrations were simulated to progressively decrease with increasing proportions of groundwater from the Red River Carbonate where concentrations of these parameters are generally lower.

Simulated calcium concentrations ranged from 36.4 mg/L to 49.3 mg/L and were generally lower than those in Scenario 1. This is because calcite is the controlling mineral in the Red River Carbonate aquifer, and it is allowed to precipitate out of solution when it is saturated with respect to calcite.

The simulated upward and downward mixing of the Red River Carbonate and Winnipeg Sandstone aquifers indicate no material effect on the water quality of both aquifers, because both aquifers contain fresh water (TDS <500 mg/L and the majority of chemical constituents and metals are below the detection limit), and there are no reported exceedances of the Canadian and Manitoba guidelines for the protection of drinking water MAC, except for turbidity and fluoride.

The porewater extracted from the Winnipeg Shale was not included in the assessment, because the Winnipeg Shale is an aquitard and only contains a very small volume of water within a low permeability matrix. Winnipeg Shale porewater is also fresh (TDS <500 mg/L and most chemical constituents and metals are below the detection limit) with only reported exceedances of the Canadian and Manitoba guidelines for the protection of drinking water MAC for turbidity and fluoride. The maximum concentrations of arsenic, selenium and uranium in Winnipeg Shale porewater were low (0.0018, 0.00091 and 0.00121 mg/L, respectively) and five to ten times lower than the Canadian and Manitoba guidelines for the protection of drinking water MAC. As such, the mixing of a small volume of fresh water from the Winnipeg Shale with the Winnipeg Sandstone aquifer is not anticipated to affect the water quality in the latter.

4.3.3 Impact of Shale Collapse on Water Quality in Winnipeg Sandstone Aquifer

Sand extraction and the subsequent localized collapse of a section of the Winnipeg Shale and a small portion of the overlying Red River Carbonate near extraction wells will result in a series of underground cavities in the Winnipeg Sandstone that will temporarily be void of solids and will replenish with groundwater following completion of extraction activities at a given well location. Groundwater from the Winnipeg Shale aquitard, Red River Carbonate aquifer and Winnipeg Sandstone aquifer is anticipated to flow into and fill the void with groundwater. A significant amount of sand derived from the Winnipeg Sandstone aquifer is also expected to migrate into the cavity as was documented by sonar surveys following extraction activities. Geochemical modelling was conducted to determine the impact of localized shale collapse on the water quality in the Winnipeg Sandstone. The assessment included a conservative mixing model to predict the water quality in the cavity (impacted water) and a reactive transport model to understand the evolution of the impacted water and predict transport of constituents of potential interest (COPI) from the cavity to downgradient areas.

4.3.3.1 Model Input Data

An average water quality for each of the three units were generated from existing data to represent the water quality in the Red River Carbonate aquifer, Winnipeg Sandstone aquifer and Winnipeg Shale aquitard. An average of SFE leachate data was calculated to represent water quality released from the Winnipeg Shale aquitard, Red River Carbonate aquifer and Winnipeg Sandstone aquifer as a result of the physical collapse. This represents a worst-case scenario, because the SFE is conducted under highly oxidizing vigorous laboratory conditions as discussed above (**Section 4.1.3**).

A residual oxygen concentration of 5 mg/L was assigned to the SFE water quality to represent the maximum concentration of dissolved oxygen that dissolves into the groundwater prior to re-injection. As indicated in **Section 4.3.1**, groundwater extracted from the Winnipeg Sandstone will be re-injected into the aquifer immediately after extraction, removal of the sand, and treatment of the water. As such, the residual groundwater will not be exposed to the atmosphere long enough to fully equilibrate with atmospheric oxygen.

A mixing ratio was developed based on the geotechnical assessment of the collapsed cavity and its size. A mixing ratio of 97%, 2% and 1% of Winnipeg Sandstone aquifer water, Red River Carbonate Aquifer water and Winnipeg Shale porewater, respectively, was used to combine site water quality and SFE leachate data to determine the water quality in the cavity (impacted water).

4.3.3.2 Assumptions

To develop the reactive transport model the following assumptions were made:

- All Winnipeg Shale (3m) above the Winnipeg Sandstone aquifer and unstable portions of Red River Carbonate (i.e. lowermost 2m) will collapse into the cavity.
- Sand and water in the Winnipeg Sandstone aquifer will flow into the void immediately after the sand extraction. This process was documented by side scan sonar surveys following pilot extraction tests.
- Metal concentrations will be primarily impacted by advection, dispersion, and diffusion. It was assumed that geochemical attenuation processes were not active. Minerals precipitation (calcite, selenite) due to saturation or changing redox conditions were disabled so that all metal species remained in solution. Therefore, this assessment is very conservative as calcite could sequester aqueous arsenic through co-precipitation, and selenite precipitation could decrease aqueous selenium concentrations. Surface reactions such as adsorption were also assumed to be inactive in this model further contributing to the conservativeness of this assessment. Under oxic conditions and pH higher than 3.5-4, iron and manganese oxides and oxyhydroxide readily precipitate out of solution. Iron and manganese oxides and oxyhydroxides commonly sequester and co-precipitate metals. The

concentrations of arsenic would be most affected by this process due to its affinity for iron, and simulated arsenic concentrations are likely conservatively high.

4.3.3.3 Model Setup

A reactive transport model was constructed using the "X1t" 1D reactive transport modelling program included in Geochemist's Workbench Pro (Bethke, 2022). X1t utilizes a finite difference approach and can simulate speciation, redox/cation exchange reactions, mineral dissolution/precipitation, and contaminant transport by groundwater flow via advection, dispersion, and diffusion processes. The purpose of the model was to investigate the impact of the collapse on groundwater quality within the extraction cone, and downgradient portions of the Winnipeg Sandstone aquifer.

A Conceptual Geochemical Model was developed for the Site and indicated that the key factors likely to impact the water quality in the Winnipeg Sandstone Aquifer following the shale collapse are mixing of the fresh waters and natural dilution (**Figure 4-9**). The oxidation of sulphide to the level that they would impact water quality is unlikely due to the very low sulphide concentration in the Winnipeg Shale and the low and finite dissolved oxygen concentration in the subsurface. The Winnipeg Sandstone is dominated by quartz, which is essentially inert, so mineral reactions are unlikely to play a substantive role in metal attenuation. Thus, mineral precipitation reactions were suppressed in the model. Under this constraint, phase changes are negligible, and aqueous solutes can only undergo dilution due to advection, dispersion, diffusion, and redox changes. This approach is very conservative because significant metal(loid)s attenuation reactions such as the co-precipitation of metal(loid)s with iron and manganese oxides, oxyhydroxides and calcite which reduce metals(loid)s concentration in solution are inhibited.

A domain with the length of 1.4 km comprising of twenty-five 50 m cells (**Figure 4-9**) was considered for the model. The height and width of the cells were considered as 25 and 50 m, respectively. The height of the cells was based on the combined approximate height of the collapsed cavity and the width and length of the cells reflect an estimated diameter of the void space (i.e., extraction cone) of 50 m. The model domain was designed with a single extraction cone near the beginning of the flow path so that groundwater quality within and downstream of the extraction cone could be investigated. It is worth mentioning that given the model set is based on concentrations and the areas of Winnipeg Shale collapse (with marginally elevated selenium concentrations in water) are much smaller than the Winnipeg Sandstone aquifer (with clean groundwater diluting the lower quality water resulting from the shale collapse), the model domain dimensions do not affect simulated results.

Groundwater flow through the modelling domain was set from right to left, based on the orientation of the conceptual geochemical model, and aligned with the regional groundwater flow system. A groundwater flow rate of 0.002 m/day was considered in the model according to the average linear velocity of groundwater in the area of the extraction cone, as derived from groundwater modelling investigations presented herein (**Section 5.8.3)**. A longitudinal dispersivity of 4.0 m was assigned based on the average of the range (0.4 to 7.5 m) of longitudinal dispersivity reported in the literature for similar aquifers (Bjerg, 2008). In addition, a sensitivity analysis of the modelling results to longitudinal dispersivity was conducted using the lowest and the highest values reported in the literature. A diffusion coefficient of 1.0×10^{-6} cm^2/s was used in all simulations. The porosity of the domain was set to 18%, reflecting the porosity of fine sand (Freeze and Cherry, 1979). The model duration was set to 10 years.

The simulation began with two initial fluids assigned to the model domain: one fluid represented groundwater in the Winnipeg Sandstone aquifer, and the other fluid represented the impacted water in the collapsed cavity as described in **Section 4.3.3.1** (**Table 4-14**). Cell 6 of **Figure 4-9** represents a single extraction cone and contained the mixed impacted groundwater. All remaining cells (Cells 1-5 and 7-25) contain the initial fluid that represents Winnipeg Sandstone groundwater. The same fluid recharges the domain from the right (upgradient) side of the model (Cell 1). The concentration of oxygen in the simulation was set by the mixing of site water quality and SFE data as described in **Section 4.3.3.1**. Moreover, the sensitivity of simulated water quality to variable concentrations of dissolved oxygen was evaluated using values ranging from 4 to 12 mg/L dissolved oxygen.

4.3.3.4 Simulated Water Quality

Model results showed that selenium, arsenic, and uranium concentrations in groundwater within the extraction cone are initially slightly elevated compared to average water quality in the Winnipeg Sandstone Aquifer but their concentrations remained below their respective CDWG MAC Guidelines (0.05 mg/L) at all times. This is because the collapse of the Winipeg Shale occurs instantaneously at the start of the simulation, and concentrations subsequently decrease over time as a result of advection, mechanical dispersion, and diffusion (**Figure 4-10** and **Figure 4-11**). Only selenium was initially marginally elevated above the MWQSOG MAC (0.01 mg/L) but is subsequently decreased to levels below the MWQSOG MAC at year 7 (**Figure 4-10)**. After 10 years, concentrations of these metal(loid)s decreased by more than 50% as a result of hydrodynamic dispersion. The evolution of the concentrations is illustrated in **Figure 4-10** and **Figure 4-11**. **Figure 4-10** shows changes in selenium, arsenic, and uranium concentrations over time in cells 6, 8, 10, and 12 of the model domain representing the center of extraction cone, and 50 m, 100 m, 150 m downgradient of the center of the extraction cone, respectively.

As depicted in **Figure 4-10**, metal(loid) concentrations in cells downgradient of the extraction cone increased slowly over time, as their concentrations in the extraction cone decreased due to advective groundwater flow. Varying the longitudinal dispersivity had a marginal impact on metal(loid)s concentrations after 10 years suggesting that the bulk advective flow of groundwater is a more important driver of mixing than longitudinal dispersion (**Figure 4-12**). Varying concentrations of dissolved oxygen also had no effect on the concentrations of selenium, arsenic and uranium, because mineral precipitation reactions were suppressed. Allowing mineral precipitation and dissolution proceed and increasing the concentration of dissolved oxygen would likely result in the oxidation and hydrolysis of iron and manganese and the dissolution of calcite leading to co-precipitation of selenium, arsenic and uranium out of the solution. This could further improve the water quality in the void and areas downgradient of the extraction cone. The oxidation of pyrite found in the Winnipeg Shale may occur if concentration of dissolved oxygen increase, but the rates of the reaction would be limited by the low pyrite content. Furthermore, the acidity released during oxidation of any pyrite would be immediately neutralized by the abundant calcite present in the collapsed Red River Carbonate fragments. Under anaerobic conditions (low concentrations of dissolved oxygen), uranium and selenium are relatively immobile and selenium would be expected to precipitate out of the solution in its reduced form (i.e., selenite).

5. Conceptual Hydrogeological Model

A conceptual hydrogeological model was developed based on extensive literature review and the results of the AECOM field investigation. The following sub-sections describe the various components of the conceptual hydrogeological model.

5.1 Climate

The Ostenfeld, Manitoba climate station (Climate ID 503B0NE) is located approximately 13 km southeast of the Project Site and is the closest climate station to the Project Area. The station is located at 49°49'00.000" N and 96°29'00.000" W at an elevation of 274.3 masl. **Table 5-A** provides the 30-year Canadian Climate Normals for this station from 1981 to 2010. The climate at the Local Project Area is expected to be very similar. The climate in the area is continental and shows variability in response to seasonal fluctuations in temperature and precipitation. Long cold winters and short warm summers characterize the weather in this region.

Canadian Climate Normals for Ostenfeld, Manitoba indicate average annual precipitation is 635 mm, with 512 mm falling as rain and 123 cm falling as snow during winter months. The wettest month is August and the driest month is February. Average temperatures are 2.7 °C. The coldest month is January (-16.7°C) and the warmest month is July (18.9 °C). Evapotranspiration is estimated to be 450 mm annually in southern Manitoba (Environment Canada 1982).

Table 5-A. Canadian Climate Normals (1981 to 2010) for the Ostenfeld, Manitoba (Environment Canada 2020)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature													
Daily Average (°C)	-16.7	-12.5	-5.5	4.0	11.3	16.3	18.9	18.0	12.1	4.9	-4.9	-13.4	2.7
Daily Maximum (°C)	-11.4	-7.0	0.0	10.5	18.4	22.8	25.3	24.7	18.2	10.1	-0.7	-8.7	8.5
Daily Minimum (°C)	-22.0	-18.0	-11.0	-2.6	4.3	9.8	12.5	11.2	5.9	-0.4	-9.1	-18.1	-3.1
Precipitation													
Rainfall (mm)	0.1	2.0	11.4	20.3	69.7	104.1	104.5	81.1	63.9	42.4	11.0	1.7	512.2
Snowfall (cm)	25.9	15.3	13.7	10.1	1.4	0.0	0.0	0.0	0.1	6.7	22.4	27.1	122.7
Precipitation (mm)	26.0	17.3	25.1	30.4	71.1	104.1	104.5	81.1	64.0	49.1	33.4	28.7	634.9

5.2 Topography and Drainage

The project is situated in the Boreal Plain Ecozone and the landscape is a composite of nearly level to gently rolling plains consisting largely of gently undulating morainal till deposits and level to depressional glaciolacustrine sediments (Smith et al. 1998). The Regional Project Area is relatively flat and located in proximity to where thick lacustrine clays were deposited in ancestral Lake Agassiz. From the lacustrine flats in the west, the ground surface elevation rises to the east toward the Sandilands Glacial Complex comprised of upland glacial sediments. The Project Area is situated on the Interlake Plain between the Sandilands Area in the east and the Red River to the west. Ground surface elevations range from approximately 255 masl to 295 masl within the Project Site.

Several streams drain the Regional Project Area. They generally originate near the topographic high in the Sandilands and flow west or northwest toward the Red River, Red River Floodway or Lake Winnipeg (Wang et al. 2008), which form the natural groundwater and surface water discharge area as shown on **Figure 5-1**. Streams include the Brokenhead River in the eastern portion of the Regional Project Area, Cooks Creek in the central portion of the Regional Project Area and the Seine River near the southern boundary of the Regional Project Area. Several small natural surface water features are present in the area including a relict small lake located northwest of Ostenfeld and several wetlands.

5.3 Well Inventory

A groundwater well inventory was completed in December 2020 to identify the groundwater users in proximity to the Project Site, Local Project Area and Regional Project Area. Information was primarily derived from the Canadian Federal Government Groundwater Information Network (GIN 2020) database, with individual well records available from Manitoba Conservation and Climate Groundwater Drill Record Database. As is common with well databases, the accuracy of well locations is often limited by the lack of field validation and historical use of land parcel identifiers rather than coordinates derived using more accurate global positioning systems. The majority of the wells in the GIN database are plotted at the centroid of the referenced section or quarter section and may be plotted up to 600 m from the actual location of the well in extreme cases (distance from centre to corner of a quarter section). New wells are frequently installed and commissioned so it is important to regularly update well users and verify the location of wells by way of windshield survey if a higher degree of accuracy is required for the analysis.

Information pertaining to the well locations, aquifer in use and the use of the water (e.g. domestic, municipal, commercial, industrial, agricultural, irrigation, etc.) was compiled and presented on **Figure 1-3** (by aquifer) and **Figure 1-4** (by water use type). Some of the wells are part of an extensive groundwater observation well network maintained by Manitoba Sustainable Development. The wells are typically installed in pairs, with one well completed in the Red River Carbonate and one well completed in the Winnipeg Sandstone within the Regional Project Area. The observations wells are routinely monitored for groundwater elevations and groundwater quality. The well inventory was used in combination with information derived from the literature to construct a three-dimensional geologic model.

The distribution of groundwater wells is discussed in detail in **Section 1.4**. Most wells are completed in the Red River Carbonate aquifer, with the remainder completed in the Quaternary Sediments or the Winnipeg Sandstone aquifer. Wells completed in the Red River Carbonate aquifer range from 13 m to 60 m in depth, with groundwater levels generally within 15 m of ground surface. Wells completed in the Winnipeg Sandstone aquifer range from 39 m to 75 m in depth, with groundwater levels generally within 10 m of ground surface. Sio provided additional information including exploration borehole logs and test well logs across parts of the Project Site.

5.4 Surficial Geology

Surficial geology has been mapped at a scale of 1:500,000 (Matile and Keller 2004) and at 1:100,000 (Matile 2004) within the Regional Project Area as shown on **Figure 5-2**. Quaternary sediments dominate the surficial geology of southern Manitoba. During the late Wisconsinan Glaciation, the Laurentide and Keewatin Ice Sheets advanced across Manitoba from the northeast and northwest respectively (Teller and Fenton 1980). The ice overlying southern Manitoba is estimated to have been approximately 1,500 m thick (Peltier 1994). Near the end of the Wisconsinan Glaciation, several glaciofluvial complexes were formed in the vicinity of the boundary between the Canadian Shield and the Williston Basin sediments, including the Sandilands Interlobate Moraine, the Belair Moraine and the Birds Hill glaciofluvial complex, and a large northwest-southeast trending buried esker north of the Sandilands moraine on the margins of the Regional Project Area.

In the Regional Project Area, these sediments include:

- Organic Deposits: These sediments consist of pead and muck up to 5 m thick in the form of wetlands including fens, bogs, swamps and marshes.
- Alluvial Sediments: These sediments are generally present along channels incised by postglacial rivers and streams. They consist of sand and grave, silt, clay and organic materials, and are up to 20 m thick. They are derived from channel and overbank deposits from modern streams including the Brokenhead River, Hazel Creek and Seine River.
- Proximal Glaciofluvial Sediments: These sediments consist of sand and gravel up to 20 m thick. The deposits are complex and may consist of belts with single or multiple esker ridges and kames as well as thin undulating deposits laid down in proximity to glacial ice and meltwater. These sediments are primarily present near and east of Vivian and in the south-central portions of the study area near and east of Ste-Geneviève. The Sandilands Interlobate Moraine is comprised of these glaciofluvial sediments in the southeastern portion of the study area.

They are also found in a localized deposit known as the Birds Hill Glaciofluvial Complex in the northwestern portion of the study area.

- Till: These sediments consist of calcareous silt diamicton up to 75 m thick that are largely derived from Paleozoic dolomite and limestone. Some of the sequences are variable in texture with depth and are often covered by thin (<1 m) veneers of glaciolacustrine and glaciofluvial sediments. Till is found at surface east of Glass and may underlay other sediments across the study area.
- Marginal Glaciolacustrine Sediments: These sediments consist of sand and gravel up to 20 m thick formed by waves at the margin of glacial Lake Aggasiz. tills and glaciofluvial sediments deposited during the Wisconsinan Glaciation, glaciolacustrine sediments deposited by proglacial lakes and alluvium and organic sediments deposited during the Holocene. These are found in isolated locations across the study area east of Glass.
- Offshore Glaciolacustrine Sediments: These sediments consist of clay, silt and minor sand up to 20 m thick. They are very low relief massive and laminated deposits deposited offshore in the deep waters of glacial Lake Agassiz. The upper surface is commonly scoured by icebergs. These are present in the western portion of the study area between Anola and the Red River. These deposits are found at surface in a continuous layer west of Anola, and in isolated and localized deposits over the remainder of the study area.

The role of these units in the hydrogeology of the region is discussed in detail in Betcher (1986), Betcher et al. (1995), Betcher and Ferguson (2003), Ferguson (2004), Ferguson et al. (2007) and Wang et al. (2008). These features indicate that large quantities of subglacial water would have been present along the subcrop belt of the Red River Carbonate and Winnipeg Sandstone aquifers during the last glaciation (Ferguson et al. 2007), and recent meteoric recharge in the Sandilands Area and across the project footprint are important contributors to the water balance of the aquifer system.

5.5 Bedrock Geology

The Project Site is located within the eastern border of the Western Canadian Sedimentary Basin (WCSB) or the Williston Basin. The stratigraphic sequence is presented in Figure 5-A and the stratigraphy encountered within the Regional Project Area is highlighted in the red boxes.

Bedrock geology is presented on **Figure 5-3**. Precambrian igneous and metamorphic rocks form the basal geologic unit within the study area and consist of granite and tonalite gneiss. Precambrian bedrock outcrops or subcrops east of the Regional Project Area and the community of Elma located near the Whitemouth River. West of that location, the Winnipeg Sandstone, Winnipeg Shale and Red River Carbonate form the uppermost bedrock units. Although it is not well constrained with drilling intercepts, the Precambrian basement rock is estimated to be nearly 200 m below ground surface the western portion of the study area (Matile and Keller 2011).

The Winnipeg Formation overlies the Precambrian basement. It is an Ordovician aged sandstone consisting of a very fine silica sand that is poorly consolidated to unconsolidated. It is reported to be composed of weakly cemented marine silica sandstones and interbedded marine shales (McCabe 1978). The Winnipeg Sandstone is interbedded with siliceous to mildly calcareous shales in the upper portion of the formation that are reported to be of middle to late Ordovician age (Ferguson et. al. 2007). Moderately to well-cemented sandstones are occasionally encountered in the middle and upper portions of Winnipeg Formation. The lower section of the Winnipeg Formation consists of shale. The Winnipeg Formation is not present beyond the eastern margin of the Williston Basin and is up to 30 m thick at the western boundary of the study area near the Red River. Within the Regional Project Area, the Winnipeg Formation is approximately 15 to 30 m thick and dips downward to the west at a grade of 0.6%.

The Winnipeg Formation has been subdivided into stratigraphically distinct units with subdivisions generally consisting of a lower sandstone unit (Black Island Member) and overlying units consisting of sandstone and shale layers (Icebox Member). A third unit (Carman Sand Member) is a clean very-fine-to-medium-grained sandstone zone that is up to 30 m thick in the upper portion of the Winnipeg Formation in Southeastern Manitoba. This feature extends from south of Brandon, Manitoba to the subcrop below the Sandilands Area (Ferguson et. al. 2007). Sio drilled over 45 boreholes between 2017 and 2022 to characterize local lithology and inform a Preliminary Economic Assessment (Stantec 2024a; Stantec 2024b). They found the Carman Sand Member was typically uncemented, well sorted, well rounded, and fine- to medium-grained, with a consistent thickness ranging from 20 m to 30 m.

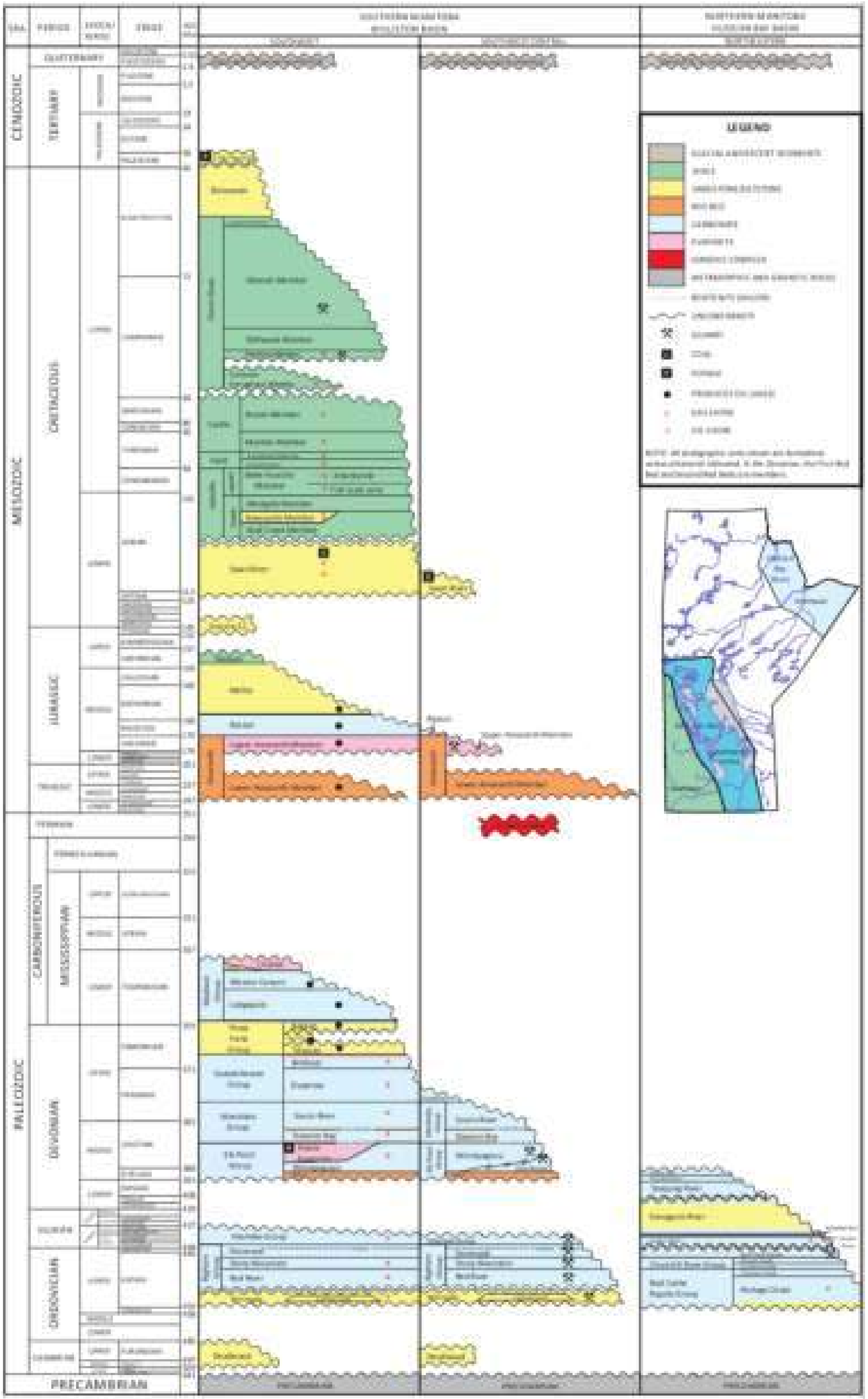

Figure 5-A. Stratigraphic Column of Williston Basin (modified after Grasby and Betcher 2002)

The Carman Sand Member is overlain by shale (Winnipeg Shale) that varies in colour from emerald green to dark brown or red. Some of the literature assigns the shale to the Red River Formation, while others indicate it is part of the Winnipeg Formation. For the purposes of this report, the shale at the base of the Red River Formation is referred to as the Winnipeg Shale. Within the Local Project Area, the thickness of this shale was found to be on the order of 3 m thick, but the literature reports the thickness may vary from 1 m to 24 m (Stantec 2024b). This unit is thought to consist of interbedded marine shales that serve as an effective aquitard (Betcher et al. 1995). The shale unit is not well understood as it has not been consistently mapped and most groundwater wells and boreholes terminate before they intersect the shale. Field observations from cuttings and bedrock core suggest the shale is variably weathered and has been reduced to high plasticity clay minerals in some areas.

The Winnipeg Shale is overlain by a thick sequence of Ordovician carbonate rocks (limestone and dolostone) of the Red River Formation, which subcrops throughout much of the study area. It is composed of a basal dolomitic sequence and mantles by carbonate-evaporite deposits that have subsequently been exposed to weathering and preferential dissolution. This has resulted in a relic rock mass that is variably weathered ranging from extensive to minor fracturing and dissolution resulting in a vuggy fabric that in turn affect the permeability of the rock mass (Render 1970). It consists of carbonates with alternating shale intervals, and the Winnipeg Shale forms its base. These carbonates are thickest in the western portion of the Regional Project Area and have been eroded to the east beyond the edge of the subcrop. The thickness is over 100 m west of the Red River (Wang et. at., 2008) but is less than 50 m thick within the Local Project Area.

5.6 Hydrostratigraphy

The regional hydrostratigraphy has been intensively studied and presented in numerous research papers as shown in **Figure 5-B**. The approximate extents of the current study area are highlighted in red. The groundwater flow system within the study area consists primarily of meteoric water, but relic basin brines are present just east of the Red River (Ferguson et al. 2007). West of the Red River, brines flow eastward from the Williston Basin and discharge primarily to the Red River.

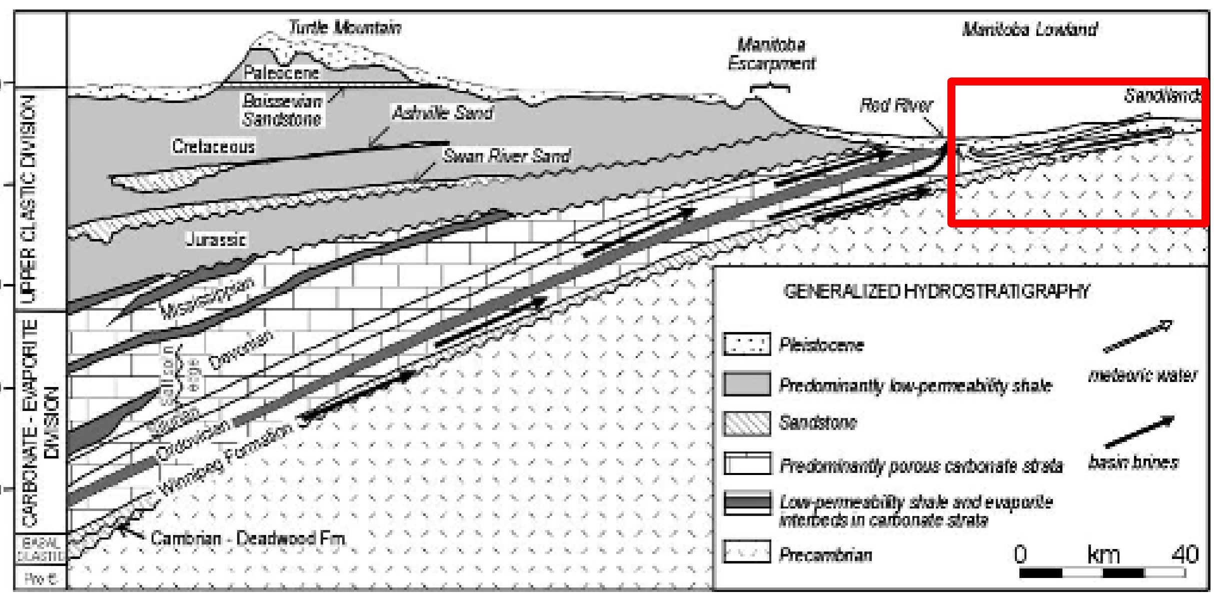

Figure 5-B. Geological Cross-Section of Southeastern Manitoba (after Simpson et al. 1987; Ferguson et al. 2007)

Lithological descriptions from water supply wells and borehole logs were classified according to major hydrostratigraphic units and interpolated to surfaces using the implicit Radial Basis Function (RBF) method within Leapfrog™ Works. The resulting 3D geological model is shown on **Figure 5-4** and was used as input to the numerical groundwater model developed in **Section 6**.

Based on a review of the scientific literature, groundwater studies conducted in the region (e.g. Render 1970; Betcher 1986; Rutulis 1986; Kennedy 2002; Betcher and Ferguson 2003; Ferguson et al. 2007; Wang et al. 2008; Friesen

2019) and the results of geological and hydrogeological field investigations provided by Stantec (2019), the geologic framework of the Model Domain was subdivided into the following hydrostratigraphic units:

- Quaternary Sediments (Subdivided into coarse, medium, and fine grained)
- Red River Carbonate (Aquifer)
- Winnipeg Shale (Aquitard)
- Winnipeg Sandstone (Aquifer)
- Precambrian Bedrock / Lower Shale (Aquitard)

The top of each hydrostratigraphic surface was interpreted from GIN borehole data and they are shown together with isopachs of the overlying unit on **Figure 5-5** (Red River Carbonate), **Figure 5-6** (Winnipeg Shale), **Figure 5-7** (Winnipeg Sandstone) and **Figure 5-8** (Precambrian Bedrock / Lower Shale).

5.6.1 Quaternary Sediments

Topography forms the upper surface of the Quaternary Sediments as illustrated on **Figure 5-1**. The isopach illustrating the thickness of the Quaternary Sediments is shown on **Figure 5-5.**

Within the model domain coarse grained quaternary deposits make up the majority of the package of unlithified sediments overlying bedrock in the Sandilands Area and Birds Hill Glaciofluvial Complex. These areas have been the focus of several studies and are believed to be the primary sources of recharge to the bedrock aquifers (Cherry 2000; Kennedy and Woodbury 2005; Ferguson et al. 2007). However, a preliminary water balance developed by Wang et al. (2008) suggests that vertical recharge outside of these regions must also be significant. Outside of these locations coarse grained material is present as lenses within a generally finer grained matrix of till-like material. Clay-rich to gravel-rich till and glaciolacustrine deposits are the dominant Quaternary sediments in the Regional Project Area (**Figure 5-2**). The thickness of unlithified sediments overlying bedrock in Southern Manitoba is thought to generally be approximately 30 m (Friesen 2015).

While aquifers are present in coarse grained glacial sediments in some locations within the broader region, they are generally discontinuous. Typical well yield for the sand and gravel aquifers ranges from less than 0.1 L/s to more than 10 L/s. Water quality ranges from very poor to excellent (Rutulis 1986).

5.6.2 Red River Carbonate

The upper surface of the Red River Carbonate is illustrated on **Figure 5-5**. The isopach illustrating the thickness of the Red River Carbonate is shown on **Figure 5-6.**

Two major hydrostratigraphic units (upper and lower) are distinguished in the literature within the Red River Carbonate aquifer. According to Render (1970) the major aquifer underlying the Regional Project Area occurs in the top 15 to 30 m of the Paleozoic limestones and dolomites. The aquifer is partially confined due to the overlying glacial drift and underlying less pervious carbonate rock. A relatively minor aquifer occurs in the bottom 7.5 m to 15 m of the Red River Carbonate along the contact with the Winnipeg Shale.

The upper carbonate aquifer is characterized by a network of fractures, joints and bedding planes and intensive dissolution which provide substantial permeability to the aquifer. The transmissivity values of the upper carbonate aquifer range from 28 m^2/day to 2,840 m^2/day and the storage coefficient varies from 1×10^{-6} to 1×10^{-3} (Render 1970). The lower carbonate aquifer has lower permeability due to less frequent interception of fracture sets and groundwater flow is reduced. The maximum probable transmissivity of this aquifer was estimated by Render (1970) to be less than 62 m^2/day. The upper and lower carbonate aquifers are more pronounced in regions where the Red River Carbonate is thickest. In the Regional Project Area, which is less than 10 km from where the Red River Carbonate pinches out (**Figure 5-B** and **Figure 5-3**), the upper and lower carbonate aquifers may be grouped into a single hydrostratigraphic unit, which in this study is referred to as simply the Red River Carbonate.

5.6.3 Winnipeg Shale

The upper surface of the Winnipeg Shale is illustrated on **Figure 5-6.** The isopach illustrating the thickness of the Winnipeg Shale is shown on **Figure 5-7.**

The Winnipeg Shale is a relatively thin aquitard which separates the Red River Carbonate aquifer above from the Winnipeg Sandstone aquifer below (Wang et al. 2008). The Winnipeg Shale is not well characterized for its hydraulic properties in the literature, likely due to it not being a target for groundwater extraction. The Winnipeg Shale is extensively weathered to clay and shows a strong blue color in the bottom half of its thickness at some locations suggesting limited access to oxygen.

Several boreholes within the Regional Project Area and groundwater model domain do not report the presence of shale, even where it appears on the geologic map and cross sections. Given the long history of groundwater exploration and development in this area, it is possible that these units were not split out as the upper (Red River Carbonate) and lower (Winnipeg Sandstone) aquifers were historically viewed as one groundwater resource. The presence of an aquitard may not have been viewed as important information historically because the shale is not one of the aquifers targeted by water well drillers. Historical drilling methods may not have observed a relatively thin unit. Even contemporary drilling methods employed to install many of the recent wells (i.e. air rotary, dual rotary or mud rotary) do not produce cuttings that are easily logged due to homogenization as they travel upward through the borehole to surface.

Sedimentary sequences are typically deposited in laterally continuous layers and most boreholes report the presence of the Winnipeg Shale, and it is AECOM's interpretation that the Winnipeg Shale is continuous across the study area from the edge of the Williston Basin at the Sandilands subcrop westward (i.e. where it is mapped on the regional geology maps). This interpretation is consistent with most of the literature reviewed for this study.

5.6.4 Winnipeg Sandstone

The upper surface of the Winnipeg Sandstone is illustrated on **Figure 5-7.** The isopach illustrating the thickness of the Winnipeg Sandstone is shown on **Figure 5-8.**

The Winnipeg Sandstone aquifer has been extensively studied over a period of approximately 50 years. The aquifer extends to the Sandilands Area and terminates at a subcrop as shown on **Figure 5-3**. Here, the aquifer is recharged by fresh water from the Sandilands Area. The Carman Sand Member of the Winnipeg Formation is an anomalous east-west trending zone of clean very fine to medium-grained sandstone that is up to 30 m thick (Betcher 1986; Betcher et al. 1995). It extends from south of Brandon to the eastern outcrop area within the Regional Project Area and extends approximately 240 km (Ferguson et al. 2007). The Winnipeg Sandstone aquifer provides an economic source of fresh water to a significant number of groundwater users in the Regional Project Area but is not utilized as heavily as the Red River Carbonate, largely owing to its deeper depth and the associated expense of drilling to this aquifer. The western portion of the aquifer becomes brackish and then saline near the Red River due to remnant basin brines and lateral recharge of saline water from the Williston Basin. As a consequence, the shallow Red River Carbonate aquifer is the primary potable groundwater source in the western portion of the study area near the Red River and the City of Winnipeg.

5.6.5 Lower Shale / Precambrian Bedrock

The upper surface of the Lower Shale / Precambrian Bedrock is illustrated on **Figure 5-8**, which is the basal hydrostratigraphic unit.

Due to the limited number of borehole intercepts, the lowest hydrostratigraphic unit considered in this study area is a combination of two lithological units: the Lower Shale of the Winnipeg Formation, and the Precambrian Bedrock that forms the lowermost bedrock unit present in the study area. Both of these units are inferred to exhibit similar hydraulic properties and are likely to form a basal aquitard at the base of the Winnipeg Sandstone. The hydraulic properties of the Lower Shale and Precambrian Bedrock have not been well characterized within the Regional Project Area. There are no known deeper aquifers targeted for fresh water in the Regional Project Area.

5.7 Hydraulic Conductivity

Hydraulic conductivity results are compiled from available literature documenting academic research (Kennedy 2002; Ferguson 2004), municipal water supply studies (Friesen 2015; 2019) and regional aquifer studies (Ferguson et al. 2007; Wang et al. 2008) in **Table 5-1**. The two aquifers most relevant for the SiMbA Project (Red River Carbonate and Winnipeg Sandstone) are both well characterized with several hydraulic conductivity and statistical analysis having been conducted for each.

The dominantly glacially deposited Quaternary sediments are heterogeneous and could be divided into several sub-hydrostratigraphic units to characterize the flow system in more detail. In relation to the other hydrostratigraphic units important to this study, the Quaternary sediments function as an upper aquitard that confines the Red River Carbonate and limits infiltration or recharge to the Red River Carbonate aquifer. The coarse-grained Quaternary sediments found in the Sandilands Area exhibit a hydraulic conductivity between 8.2 x 10^{-6} m/s and 2.4 x 10^{-4} m/s (Cherry 2000) which facilitates recharge to the underlying aquifers. The fine-grained Quaternary Sediments in the Sandilands Area have a measured hydraulic conductivity range of 8.3 x 10^{-9} m/s to 6.8 x 10^{-6} m/s (Cherry). The clay rich glaciolacustrine deposits present in the Interlake Region have a hydraulic conductivity range of 8.2 x 10^{-10} m/s to 1.6 x 10^{-7} m/s (Pach 1994, Domenico and Schwartz 1990 cited in McMillan and Woodbury 2000).

The Red River Carbonate has measured hydraulic conductivities ranging between 1.5 x 10^{-5} m/s (AECOM) and a value that is higher than 8 x 10^{-4} m/s (only a geometric mean of 8 x 10^{-4} m/s is reported by Wang et al. (2008). The hydraulic conductivity of the Red River Carbonate is dependant on the frequency and aperture of fractures in the bedrock which can lead to considerable variability at the local scale.

The hydraulic conductivity of the Winnipeg Shale is not well characterized in the literature. During the field program conducted by AECOM for this study analysis of a rising head test showed the Winnipeg Shale to have a hydraulic conductivity of 2.8 x 10^{-8} m/s.

Hydraulic conductivity estimates are available for a number of locations in the Winnipeg Sandstone. Pumping tests conducted on 20 wells during the early 1980s gave hydraulic conductivities ranging from 1.1 x 10^{-3} m/s to 3.6 x 10^{-6} m/s, with 16 of these 20 tests giving values between 1 x 10^{-4} m/s and 1 x 10^{-6} m/s (Ferguson et al. 2007). These tests were conducted in either sandstone intervals or over the entire Winnipeg Formation (Betcher 1986).

5.8 Groundwater Flow

Betcher (1986) mapped regional groundwater flow in the aquifer based on water level and salinity data from water and oil wells and deduced that two large scale flow systems were present:

1. A regional system flowing to the east or northeast from recharge areas in the northern United States.
2. An intermediate system in southeastern Manitoba with groundwater recharging along the outcrop area beneath the Sandilands Moraine, south east of the Regional Project Area and flowing to the west and north toward the Red River and Lake Winnipeg. More recent studies (Wang et al. 2008) postulated that spatially distributed recharge through the glacial sediments was an important component of the water balance for the groundwater aquifers in the area based on a preliminary water balance assessment.

These two flow systems converge near the Red River and are deflected to the north. Regional groundwater discharges to the Red River, Red River Floodway and Lake Winnipeg although some discharge to overlying sediments occurs where erosional features have cut through the overlying Red River Carbonates and the upper shale.

5.8.1 Groundwater Recharge

Previous studies have found that the majority of groundwater recharge in southeastern Manitoba is derived from infiltration through the relatively coarse textured deposits of the Sandilands Interlobate Moraine, Birds Hill Glaciofluvial Complex and localized esker deposits (Betcher 1986; Kennedy 2002; Wang et al. 2008). Recharge rates in the Sandilands area have been found to range from 1.4 x 10^{-9} m/s (37 mm/year) to 5.5 x 10^{-9} m/s (504 mm/year) using tritium and chlorofluorocarbon dating methods (Cherry 2000). Ferguson (2004) estimated recharge rates using thermal modelling techniques and found them to range from 1.2 x 10^{-9} m/s (44 mm/year) to 1.6 x 10^{-8} m/s (173 mm/year).

Wang et al. (2008) estimated that the total lateral recharge from the Sandilands Area to be 1,863,000 m^3/year, which was estimated to be 7.2% of the estimated groundwater usage at the time and location of the study in 2008. This led to the conclusion that vertical recharge throughout the remainder of the flow system was of greater importance than it was previously thought to be.

Except for the Birds Hill Complex, the remainder of the area is covered by glacial till and glaciolacustrine deposits that exhibit lower permeability. Kennedy (2002) developed and calibrated a regional numerical groundwater model of a portion of the study area. Recharge in the Interlake and Birds Hill regions was implemented as a fitting parameter in the model, and results reported to be 1.0 x 10^{-8} m/s (315 mm/year) for the Birds Hill Complex, and 2.0 x 10^{-10} m/s (6 mm/year) for the Interlake region.

5.8.2 Groundwater Elevations and Gradients

Groundwater elevations in the Quaternary Sediments are shown on **Figure 5-9** and range from in excess of 320 masl in the Sandilands Area to less than 230 masl near the Red River based on groundwater elevations reported in the GIN database. Within the Project Site, reported groundwater elevations are highly variable and range from 230 masl to 290 masl. Groundwater elevations in this unit are anticipated to be quite variable locally due to variability in texture and the possible presence of localized and perched aquifers. Furthermore, the data source itself typically contains water levels measured shortly after drilling. In permeable aquifer systems, groundwater levels will recover to static conditions relatively quickly, but in finer grained sediments (like those that may be present in the study area) slow well recovery and it may take days to months for static groundwater elevations to be achieved.

Groundwater elevations in the Red River Carbonate aquifer are shown on **Figure 5-10** and range from in excess of 300 masl near the southeastern limit of the study area where the aquifer subcrops in the Sandilands Area, to less than 200 masl in the extreme northwestern portion of the study area near the Red River based on groundwater elevations reported in the GIN database. Within the Project Site, reported groundwater elevations are relatively consistent and range from 260 masl to 280 masl.

Groundwater elevations in the Winnipeg Sandstone aquifer are shown on **Figure 5-11** and range from in excess of 320 masl at one location in the aquifer near the subcrop below the Sandilands Area to less than 180 masl between Anola and Winnipeg based on groundwater elevations reported in the GIN database. It is likely that measured groundwater elevations have not been corrected for density effects related to brackish to saline water. Calculated equivalent freshwater heads would be higher in areas of saline water quality. Within the Project Site, reported groundwater elevations are highly variable and range from 240 – 280 masl, with the lowest elevations near the town of Anola where there are more municipal and domestic groundwater supply wells that may have locally lowered groundwater elevations.

An extensive observation well network has been established by the Government of Manitoba to monitor groundwater elevations and groundwater quality in the Red River Carbonate and Winnipeg Sandstone aquifers across the study area. Vertical gradients during the winter (January 1) and summer (July 1) of 2020 are calculated for four (4) well pairs in proximity to the Project Site and presented in Table 5-B.

Measured groundwater elevations and calculated vertical gradients for three (3) well pairs are plotted over time from January 2006 until January 2021 on **Figure 5-12** (G05SA003 / G05SA013), **Figure 5-13** (GO5SA014 / GO5SA015) and **Figure 5-14** (GO50J175 / GO50J163). Groundwater flow is generally from southeast to northwest in the vicinity of the Project Site and the well pairs shown on the figures listed above are arranged from upgradient to downgradient along a groundwater flow path.

As shown on **Figure 5-12** (G05SA003 / G05SA013), southeast of the Project Site groundwater elevations fluctuated between 272.03 masl and 273.77 masl in the Red River Carbonate between 2006 and 2021 and groundwater elevations in the Winnipeg Sandstone fluctuated between 272.28 masl and 273.85 masl. Groundwater elevations in the Winnipeg Sandstone were predominantly above those reported for the Red River Carbonate aquifer between 2007 and approximately January 2017 on dates when groundwater elevations from both wells were available. This indicates prevailing upward groundwater flow from the Winnipeg Sandstone to the Red River Carbonate over that period of time. Since the late summer of 2018, groundwater elevations in both aquifers have been similar and vertical gradients have since been near-neutral (i.e. neither upward nor downward), indicating a possible change in the water balance of the Winnipeg Sandstone aquifer. It is unclear if any new wells interconnecting the Red River Carbonate and Winnipeg Sandstone were installed near the observation well that may have affected water levels and vertical gradients.

As shown on **Figure 5-13** (GO5SA014 / GO5SA015), within the Project Site groundwater elevations fluctuated between 267.88 masl and 270.98 masl in the Red River Carbonate between 2006 and 2021 and groundwater elevations in the Winnipeg Sandstone fluctuated between 267.61 masl and 268.07 masl. Groundwater elevations in the Red River Carbonate were consistently above those observed in the Winnipeg Sandstone between 2007 and approximately January 2021. This indicates prevailing downward groundwater flow from the Red River Carbonate to the Winnipeg Sandstone. Since the summer of 2017, groundwater elevations in the Red River carbonate aquifer appear to have decreased, thereby reducing the magnitude of the vertically downward groundwater flow. The difference between water levels in the two aquifers suggests they are not highly interconnected in the immediate vicinity of these observation wells.

Table 5-B. Vertical Gradients Between Red River Carbonate and Winnipeg Sandstone (2020)

Monitoring Station Name	Well Name	Easting (m)	Northing (m)	Well Completion Interval	Well Depth (m bgs)	Measured Groundwater Elevation (masl)		Vertical Gradient (Upward / Downward)	
						Winter	Summer	Winter	Summer
G05SA003	101888	688076.0	5515444.0	Red River Carbonate	30.5	273.65	273.65	-0.002 (Neutral)	0.0009 (Neutral)
G050SA013	138719	688076.0	5515501.0	Winnipeg Sandstone	41.5	273.67	273.64		
G05SA014	138721	681166.0	5523650.0	Red River Carbonate	36.6	269.53	269.58	0.069 (Downward)	0.072 (Downward)
G050SA015	138722	681167.5	5523644.4	Winnipeg Sandstone	61.0	267.84	267.82		
G050J163	113299	673065.0	5525169.0	Red River Carbonate	27.4	259.00	258.96	0.040 (Downward)	0.046 (Downward)
G050J175	138723	673068.9	5525144.6	Winnipeg Sandstone	67.1	257.39	257.14		
G050J177	138728	666504.8	5525923.6	Red River Carbonate	30.2	248.20	248.00	0.034 (Neutral)	0.002 (Neutral)
G050J176	138725	666507.4	5525948.9	Winnipeg Sandstone	78.6	248.09	247.90		

Notes: Groundwater elevations measured January 1, 2020 (Winter) and July 1, 2020 (Summer). Vertical gradients calculated between well screens.

As shown on **Figure 5-14** (GO50J175 / GO50J163), within the Project Site groundwater elevations fluctuated between 257.50 masl and 259.83 masl in the Red River Carbonate between 2006 and 2021 and groundwater elevations in the Winnipeg Sandstone fluctuated between 255.69 masl and 258.11 masl. Groundwater elevations in the Red River Carbonate were consistently above those observed in the Winnipeg Sandstone between 2007 and approximately January 2021. Furthermore, the magnitude of the downward gradient remained relatively stable, indicating downward groundwater flow from the Red River Carbonate to the Winnipeg Sandstone prevailed throughout the period.

Overall, groundwater elevations in the Red River Carbonate exhibited a seasonal range of between 1.74 m and 3.1 m over the 15-year record. Similarly, groundwater elevations in the Winnipeg Sandstone exhibited a seasonal range of between 1.57 m and 2.46 m over the same period of time. The lowest groundwater elevations are typically observed during late winter months prior to spring snow melt. The highest groundwater elevations are typically observed following snow melt with a lesser peak in the hydrograph often observed in early fall months, presumably in response to late summer and early fall precipitation events. Wang et al. (2008) reported that groundwater elevations have generally increased since the onset of higher precipitation between 1991 and 2005 highlighting the linkage between the aquifer water balance and longer-term climatic conditions. This period of increasing water levels follows a long period of water level decline from the 1960s to 1990. The difference between water levels in the two aquifers suggests they are not highly interconnected in the immediate vicinity of these observation wells.

Although the wells evaluated as part of this study generally show neutral to downward gradients from the Red River Carbonate to the Winnipeg Sandstone, artesian conditions have been observed in the western portion of the aquifer, with the spatial extent of the artesian zone interpreted in 1934 (by Johnston) and in 1965 (Charron 1965). Excess heads range from zero (0) at the eastern limit of the artesian zone to in excess of 10 m where the Red River enters Canada (Wang et al. 2008).

5.8.3 Groundwater Flow Directions

As shown on **Figure 5-9** (Quaternary Sediment), **Figure 5-10** (Red River Carbonate) and **Figure 5-11** (Winnipeg Sandstone), groundwater flow is primarily from southeast to northwest in all three aquifer systems. The majority of the wells are completed in the Red River Carbonate (**Figure 1-3**), and the flow system of that aquifer is well understood. Similarly, the Winnipeg Sandstone is also well characterized and understood. However, the spatial and depth variability in the Quaternary Sediments has resulted in relatively lower intensity of exploration, use and monitoring so the dataset is limited.

Based on the Red River Carbonate and Winnipeg Sandstone observation well network described in **Section 5.3**, vertical gradients are neutral to slightly downward in proximity to the Project Site, indicating groundwater flow is primarily horizontal (lateral). Historical drilling and well completion methods are thought to have resulted in some communication between the Red River Carbonate and Winnipeg Sandstone aquifers. It is also possible that natural variability in the thickness/spatial extent and hydraulic properties of the Winnipeg Shale may contribute to exchange of water between the two aquifers. Unweighting of the land mass upon glacial retreat is known to cause isostatic rebound, which often dilates partings parallel to bedding planes in sedimentary rock sequences. Differential stresses are also known to induce fracturing in brittle rock. The Winnipeg Shale encountered during the 2020 drilling campaign was friable and deeply weathered to clay minerals in some boreholes. The presence of high plasticity clay indicates the presence of a relatively low permeability aquitard that restricts exchange between the two aquifers.

Betcher and Ferguson (2003) reported that these interconnecting boreholes have resulted in localized losses in the naturally softened groundwater from the Winnipeg Formation, and local water quality changes in the carbonate aquifer. Wang et al. (2008) reported that over 1,000 wells installed as open holes to extract softer groundwater from the Winnipeg Sandstone have resulted in groundwater level decline in the Winnipeg Sandstone due to equalization of aquifer heads. Betcher and Ferguson (2003) further estimated the volumetric discharge in head between the carbonate aquifer and sandstone aquifer as shown on **Figure 5-C**. Volumetric discharge was estimated to range from zero when there was no gradient between the formations and approximately 4,400 L/day (0.8 US GPM) for a head difference of six (6) metres indicating the magnitude of exchange was relatively small in the context of the overall water balance of the aquifer. In areas of saline groundwater, even this small volume of water could dramatically affect local water quality over time.

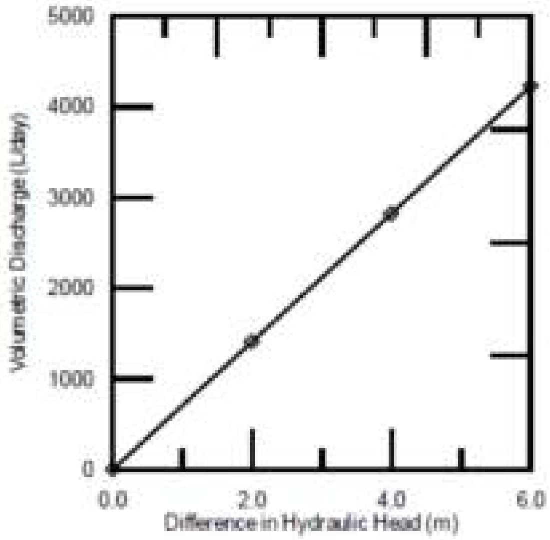

Figure 5-C. Estimated Volumetric Exchange Between the Red River Carbonate and Winnipeg Sandstone Aquifers Per Unit Difference in Hydraulic Head (Betcher and Ferguson 2003).

5.8.4 Groundwater Discharge

Groundwater discharges to the Red River Floodway, the Red River, Lake Winnipeg and several streams and rivers within the study area. The construction of the Red River Floodway illustrated the linkage between the Red River Carbonate aquifer and the Red River valley in that construction of the floodway lowered the groundwater table by up to 7.6 metres with the zone of influence extending over an area of 900 km^2 (Render 1970). Following construction, groundwater discharge to the Winnipeg Floodway was recorded at 13.6 m^3/min (Render 1970) for an extended period of time without further lowering of the water table indicating reestablishment of steady-state conditions. Additional groundwater discharge likely reports directly to the Red River and Lake Winnipeg (Betcher et al. 1995).

Groundwater wells extract groundwater from the Red River Carbonate and Winnipeg Sandstone aquifers. Wang et al. (2008) reported a combined 21,507,500 m^3/yr, with approximately 25 out of 220 licenses occupying 70% of the total licensed withdrawal rate. Based on an estimated 45,000 wells pumping at a rate of 0.5 m^3/day, they estimated the total pumping rate to be 8,211,500 m^3/year. Due to the relatively small number of wells completed in the Quaternary Sediments, groundwater extraction from the near-surface aquifer(s) is anticipated to be relatively low.

6. Numerical Groundwater Model

6.1 Objectives

The primary objective of the groundwater model is to develop a numerical tool that can be used to support the decision-making process with regards to a range of water management and planning activities in the vicinity of the Project. Secondary objectives include:

- Develop a three-dimensional numerical groundwater flow model based on the conceptual hydrogeological model;
- Calibrate the numerical model to observed groundwater level information from long-term records and recent pumping tests;
- Complete sensitivity analysis of key model parameters and boundary conditions; and
- Conduct predictive simulations to estimate the effect of climate change and groundwater and sand extraction on groundwater levels in the area throughout the mine life.

The groundwater modelling effort included simulations of both steady state and transient groundwater flow. Steady state simulations represent average moment in time conditions. Steady state simulations were completed to calibrate aquifer parameters to regional groundwater levels and in the predictive scenarios to investigate how climate change will affect the groundwater levels at the end of mine operation. Transient models, in which the magnitude and/or direction of groundwater flow may change over time, were developed to calibrate to pumping test data from the field investigation detailed in **Section 3** and to investigate the effect of sand production during the mine life.

6.2 Model Setup

6.2.1 Software

The groundwater model was developed in FEFLOW v8.1 (Diersch 2013). FEFLOW is a commonly used three-dimensional, finite-element code capable of simulating steady-state and transient groundwater conditions. FEFLOW has been applied extensively to a wide variety of hydrogeological problems for evaluation of groundwater resources and hydrogeological assessments for proposed mining projects.

6.2.2 Model Domain

The extent of the groundwater model is shown in **Figure 6-1**. The model domain encompasses an irregularly shaped 3,176 km^2 area between approximately 634,000 m and 715,000 m Easting and between approximately 5,480,000 m and 5,555,000 m Northing (UTM NAD83, Zone 14N). The groundwater model domain was selected to encompass the project and anticipated extent of impacts, the Sandilands to the east of the project, and natural hydrologic features to the west of the Project.

The groundwater model has variable spatial resolution as shown in **Figure 6-1**. The average length of the element sides near the model boundaries is approximately 400 m, refined to approximately 60 m near stream boundary conditions and approximately 5 m around production wells. The groundwater model is also refined to approximately 50 m over the footprint of the project and increases to 75 m and 100 m within a 1 km and 4 km radius respectively. The groundwater model consists of 167,760 elements (84,423 nodes) per model layer, for a total of 1,174,320 elements.

6.2.3 Hydrostratigraphy

The groundwater model consists of seven layers which encompass the following five hydrostratigraphic units:

1. Quaternary Sediments:
    a. Coarse Grained (includes proximal and distal glaciofluvial sediments, marginal glaciolacustrine sediments alluvial sediments, eolian sediments);
    b. Medium Grained (includes calcareous silt diamicton);
    c. Fine Grained (includes offshore glaciolacustrine sediments);

2. Red River Carbonate;
3. Winnipeg Shale;
4. Winnipeg Sandstone; and
5. Lower Shale / Precambrian Bedrock.

The top of the uppermost model layer represents the topographic surface (CanVec). Model layer 1 and 2 represent upper Quaternary-age sediments that were assigned to one of three classes based on interpreted texture (coarse, medium, and fine grained) of the regional surficial geology map (**Figure 5-2**). Model layer 3 represents lower Quaternary-age sediments interpreted to be dominantly medium to fine grained distal from the Sandilands Area and Birds Hill Complex. Areas in model layer 3 that underly offshore glaciolacustrine sediments in model layers 1 and 2 were assigned as Quaternary Sediments (fine grained) class while the remainder distal to the Sandilands Area and Birds Hill Complex was assigned to the Quaternary Sediments (medium grained) class. The Sandilands Area and Birds Hill Complex were assigned to the Quaternary Sediments (coarse grained) class in model layer 3.

Model layers 4 through 7 represent bedrock. Model layer 4 predominantly represents carbonate bedrock of the Red River Formation (Red River Carbonate) where mapped on the bedrock geology map (**Figure 5-3**). East of the carbonate bedrock subcrop, model layer 4 is assigned a minimal thickness (0.1 m) and assigned as the overlying material. Model layer 5 predominantly represents shale bedrock of the Winnipeg Formation (Winnipeg Shale) where mapped on the bedrock geology map (**Figure 5-3**). East of the mapped top of sandstone subcrop, model layer 5 is assigned a minimal thickness (0.1 m) and assigned as the overlying material. Model layer 6 predominantly represents sandstone bedrock of the Winnipeg Formation (Winnipeg Sandstone) where mapped on the bedrock geology map (**Figure 5-3**). East of the mapped bottom of the Winnipeg Sandstone subcrop, model layer 6 is assigned a minimal thickness (0.1 m) and assigned as the overlying material. The upper surface of model layer 7 represents the base of the Winnipeg Sandstone and, in some parts of the model domain, this contact is between the Winnipeg Sandstone and a Lower Shale (also part of the Winnipeg Formation) while in other areas it is a contact between the Winnipeg Sandstone and Precambrian Bedrock. Model layer 7 is not differentiated between these two possible lithologies and simply represents a basal aquitard. The base of the groundwater model (model layer 7) was set to mean sea level (0 m elevation).

A 3D geological model developed for the area from Groundwater Information Network (GIN) borehole data is shown in **Figure 5-4.** The spatial distribution of hydrostratigraphic units within each model layer is shown in **Figures 5-5** to **Figure 5-8**.

6.2.4 Boundary Conditions

6.2.4.1 Recharge

Recharge (R) is a key driver of the regional water balance and is defined as:

$$R = P - ET - RO$$

In this equation, P is precipitation, ET is evapotranspiration, and RO is runoff. Recharge was applied vertically downward onto the highest active layer of the groundwater model and was assigned based on a combination of calibrated recharge from peer reviewed studies focused on the Sandilands Area (e.g. Ferguson et al. 2007; Kennedy and Woodbury 2005) and the spatial distribution of surficial materials as shown in **Figure 6-1**. Recharge for the Sandilands Area was assigned as a fixed input parameter based on literature values and was not adjusted during calibration. This assumption is judged to be conservative in that recharge may increase in response to drawdown within the underlying aquifer during project operations. Recharge for areas outside of the Sandilands Area were modified as required during the calibration process (i.e., used as a fitting parameter).

6.2.4.2 Specified Head

Specified head boundary conditions were applied in the groundwater model to represent the regional stream network as shown in **Figure 6-1**. Stream elevation was assigned based on a 50 m resolution DEM that was shifted vertically downward to align the elevation of the DEM with the stream stage elevation at the north perimeter Red River stream gauge station (approximately 220 m ASL). Ponds in the vicinity of the Birds Hill Complex (e.g., Kingfisher Lake) were represented using specified head equal to ground elevation.

Specified head boundary conditions were assigned along the northwest perimeter of the groundwater model in the Winnipeg Sandstone to allow groundwater outflow from the groundwater model within this unit. Specified heads in the

Winnipeg Sandstone were assigned based on interpretation of regional groundwater level data from the Groundwater Information Network database. Similarly, specified head boundary conditions along the northwest perimeter were applied to the Red River Carbonate layer based on the regional groundwater level data. Although the regional groundwater data was not corrected for salinity, sensitivity analysis of this boundary condition on the calibration was assessed.

The Red River Floodway was represented using a specified head boundary condition based on the average measured water level data at three locations: Red River Floodway at Trans-Canada Highway (Environment Canada station number 05OC029), Red River Floodway near Saint Norbert (station number 05OC017) and Red River close to Lockport (station number 05OJ021). These locations are shown in **Figure 6-1**. In addition, during sensitivity analysis, the impact of this boundary condition was evaluated both under dry conditions and at water elevation exceeding the average water level.

6.2.4.3 No Flow

No flow boundary conditions were assigned to the inferred surface water and groundwater divides along the perimeter of the groundwater model domain where specified head boundary conditions were not present. It was assumed that vertical groundwater flow into and out of the bedrock was negligible (i.e. no flow) at the base of the groundwater model (0 m asl).

6.2.4.4 Wells

Well boundary conditions act to remove water from specified locations (nodes) at a specified extraction rate. Well boundary conditions were assigned to the groundwater model to represent regional licensed groundwater users in the study area based on available information. Locations of the well boundary conditions that represent regional groundwater users are shown in **Figure 6-1** and summarized in **Table 6-A.**

Table 6-A. Licensed Water Wells Incorporated as Well Boundary Conditions

Licensee	Location	License Number	License Type	Pumping Rate (m^3/year)
Ridgeland Holding Co. Ltd.	NE 06 010 07 E	2007-101	Agricultural-Aquaculture	52,500
Oakwood Dairy Farms Ltd. (now Springbreeze Dairy)	NE 18 011 05 E	2006-106	Agricultural	15,600
Bill Vaags Ltd.	NW 26 010 05 E	2006-118	Agricultural-Livestock	31,500
North Eastman Health Association (File 1)	NW 22 011 05 E	2000-061	Domestic	7,400
Acrylon Plastics Inc. (Spartec Profiles, Custom Extruded Profiles)	NW 16 011 04 E	2011-105	Industrial Heat/Cool	353,000
Inland Aggregates Ltd.	SE 05 012 05 E	2007-023	Industrial-Mining	4,070,000
Elmhurst Golf & Country Club	SE 01 012 04 E	2009-050	Irrigation	114,100
RM of Springfield (File 3)	NW 31 010 07 E	2012-042	Municipal	39,000
RM of Springfield (File 1)	NE 30 011 05 E	2016-102	Municipal	323,300
MB Sustainable Development (File 6-Birds Hill Park)	NW 11 012 04 E	2017-006	Municipal	30,000
MPI Corp. (File 3)	SW 17 011 04 E	2016-100	Other Firefighting	2,500
General Scrap Partnership	NW 17 011 04 E	2008-019	Other Firefighting	600
62455 MB Ltd. & 62456 MB Ltd.	NW 15 011 04 E	2015-099	Other Firefighting	320
4531672 MB Ltd.	SW 15 010 04 E	2008-075	Other Recreation	20,000
MB Conservation (File 9-Birds Hill Provincial Park)	NE 17 012 05 E	2014-008	Other Recreation	182,000
			Total	**5,241,820**

6.2.5 Key Assumptions

Key assumptions in development of the numerical groundwater model include:

- Heterogeneity within each hydrostratigraphic unit can be represented at the scale of the problem with an equivalent homogeneous porous material which is attributed a single value for its hydraulic conductivity, storativity, and other parameters which govern fluid flow through the porous material. Although heterogeneity of materials is expected due to spatial variability of materials, incorporating fine scale variability was not considered to materially affect the numerical modelling results although real-world hydrogeologic response may be locally sensitive to heterogeneity.
- Steady state groundwater model results are based on modelled recharge estimates (Kennedy 2002). Steady state is a simplification of the groundwater flow system that distills transient data (such as variability in recharge and groundwater elevations) to a single, long-term representative value.
- The steady state calibration makes use of available groundwater elevations in the Manitoba database. There are likely a considerable number of water wells not listed in the database, which introduces some uncertainty in the calibration. However, coverage of available data across the model domain was more than adequate to characterize the aquifers and provide a sufficiently dense geology and groundwater flow calibration dataset.
- Transient groundwater model results are assumed to be representative of average groundwater conditions as average annual recharge rates were assumed.
- Geotechnical or geomechanical effects of removing sand from the aquifer during production are not considered in this analysis. Groundwater modelling assumes that limestone bridging material will remain intact as depicted in Stantec (2022). In the predictive scenarios that investigate the outcome of increased vertical communication across the Winnipeg Shale confining unit, the free movement of groundwater between the Winnipeg Sandstone and Red River Carbonate is permitted.
- The numerical groundwater model assesses the short-term response of the aquifer to the stresses of groundwater and sand withdrawal. Streams, lakes, regional groundwater use and groundwater levels along the boundaries of the model domain are assumed to stay constant with time.

6.3 Model Calibration

6.3.1 Methods

6.3.1.1 Steady-State Calibration

The groundwater model was calibrated to long-term average annual conditions (i.e., steady-state) through the industry-standard practice of manually modifying hydraulic conductivity and recharge by trial-and-error to generate an acceptable match between simulated and observed groundwater levels. The percentage of mean annual precipitation assigned as recharge for each surficial material was considered during the calibration process to ensure that assigned recharge represented a reasonable percentage of mean annual precipitation (639 mm/year). Simulated groundwater levels from the groundwater model were calibrated to 2,534 observation points from the Groundwater Information Network database.

An acceptable match between simulated and observed groundwater levels was quantitatively assessed through calculation of residuals, the residual mean, root mean square error (RMSE), normalized root mean square error (NRMSE), and the correlation coefficient (r) to those considered reasonable in groundwater modelling guideline documents.

The mass balance of the groundwater model was monitored during the calibration process to ensure that boundary conditions were functioning as intended (i.e., according to the conceptual understanding of the flow system) and to ensure that the percent error between simulated model inflow and simulated model outflow was less than within the industry standard criteria of less than 1%.

6.3.1.2 Transient Calibration

The steady state groundwater model was converted to transient and subsequently calibrated to a 72-hour pumping test (see further detail in **Section 3**) conducted in November 2020 through the industry-standard practice of manually modifying hydraulic conductivity, recharge, and storativity by trial-and-error to generate an acceptable match between simulated and observed transient groundwater levels. Simulated groundwater levels from the steady state calibration were used as the initial condition for the transient calibration.

All steady state boundary conditions (listed in **Section 6.2.4**) were assigned in the transient groundwater model. A well boundary condition was incorporated into the transient groundwater model to represent the pumping well from the 72-hour pumping test according to the 5-stage pumping schedule as described below and shown in **Figure 3-2**.

- Stage 1 – 26 L/s (412 US GPM) for 0.5 hours
- Stage 2 – 25.4 L/s (402 US GPM) for 2.5 hours
- Stage 3 – 26 L/s (412 US GPM) for 1 hours
- Stage 4 – 26.6 L/S4 (21 US GPM) for 3 hours
- Stage 5 – 23.5 L/s (372 US GPM) for 65 hours

Time-variable simulated groundwater levels were compared to observed groundwater levels at several nested piezometers and vibrating wire transducers in the Red River Carbonate, Winnipeg Shale, and Winnipeg Sandstone. Simulated groundwater levels were not compared to observations within the pumping well because the pumping well was interpreted to have experienced non-linear head loss due to turbulence in the well during pumping (and other complicating factors). The discrepancy between simulated and observed groundwater elevations was quantitatively assessed using the Nash-Sutcliffe (NS) efficiency, with values near 1 indicating a good fit. Efficiency values larger than 0.5 are generally considered satisfactory.

Modifications to the hydraulic parameters during the transient calibration process were iteratively updated in the steady state calibration to re-generate an initial condition for the transient calibration until a single set of calibrated parameters yielded an acceptable match in both the steady state calibration (to regional groundwater levels) and transient calibration (to the observation wells for the pumping test).

6.3.2 Results

6.3.2.1 Steady State Calibration

Simulated versus observed groundwater levels are shown in **Figure 6-2**. Calibration was attained with a mean residual of 3 m, root mean square error of 5 m, normalized root mean squared error of 3.6%, and correlation coefficient of 0.97. While simulated groundwater levels are generally in agreement with observed groundwater levels, at lower elevations the groundwater model generally overpredicts groundwater levels and simulated groundwater levels are higher than observed groundwater levels. These data points are located primarily in the Red River Carbonate near Winnipeg. The discrepancy between simulated and observed groundwater levels in this area were interpreted to be due to increased groundwater use surrounding Winnipeg (data that was not available to incorporate into the groundwater model). Furthermore, this area is approximately 40 km from the project and is therefore considered of very low impact to the outcome of this hydrogeological assessment. Results were considered reasonable as calibration statistics are within recommended guidelines.

Simulated groundwater elevations are shown in **Figure 6-3**. The general trend of (existing condition) groundwater flow directions is from southeast to northwest towards Winnipeg and the Red River. The Sandilands Area is considered to provide the primary recharge to the Winnipeg Sandstone and Red River Carbonate aquifers. The Birds Hill Complex is also a source of local groundwater recharge and flow in that area. Shallow groundwater locally drains to the network of streams and ditches creating small surface water divides and local groundwater systems that may flow in various directions within the overall prevailing southeast to northwest direction of deeper groundwater flow.

Mass balance of the calibrated steady state groundwater model is shown in **Table 6-B.** Imbalance between model inflows and model outflows accounts for approximately 0.01% of the simulated mass balance, which illustrates reasonable conservation of mass between model inflow and model outflows.

Table 6-B. Simulated Mass Balance

Boundary Condition	Water Mass Balance (m^3/day)	
	Outflow	Inflow
Specified Head	9.0×10^5	3.2×10^5
Wells	1.4×10^4	-
Recharge	-	6×10^5
Imbalance	-	55 (0.01%)

6.3.2.2 Transient Calibration

Time series plots from the transient calibration in the Winnipeg Sandstone and Red River Carbonate are shown in **Figure 6-4**. Simulated and observed groundwater levels are in general agreement and a good fit was attained for monitoring wells within the Winnipeg Sandstone at distances of approximately 330 m away from the pumping well. Distances closer than 300 m generally show higher simulated drawdown than observed drawdown while at distances greater than 300 m from the pumping well generally show less simulated drawdown than observed drawdown (approximately 1 m less drawdown at a distance of 1,200 m). The NS efficiency of the Sandstone well Bru 95-8 VW4, with the greatest drawdown located at 89.3 m from the pumping well, was 0.5 indicating an acceptable match.

6.3.2.3 Calibrated Aquifer Properties

Calibrated aquifer properties (hydraulic conductivity, specific storage and recharge) are summarized in

Table 6-C and **Table 6-D**. Calibrated parameters are within expected ranges and/or are consistent with literature values in **Table 5-1**.

Calibrated hydraulic conductivity ranges from 1.2×10^{-12} m/s for the Lower Shale / Precambrian Bedrock to 1×10^{-4} m/s for the Red River Carbonate. All hydrostratigraphic units have an anisotropy of 10 (i.e. vertical hydraulic conductivity is 1/10th of horizontal hydraulic conductivity) except the Red River Carbonate and the Lower Shale / Precambrian Bedrock which have an anisotropy of 1.

Calibrated recharge was 250 mm/year for the Birds Hill Complex, 189 mm/year for Sandilands, 100 mm/year for inferred coarse grained surficial materials, 40 mm/year for inferred medium grained surficial materials, and 6 mm/year for inferred fine grained surficial materials. Recharge estimates represent 1% to 39% of the mean annual precipitation at Ostenfeld climate station (639 mm/year for 1981-2010 Climate Normals).

Table 6-C. Calibrated Aquifer Properties

Hydrostratigraphic Unit	Calibrated Hydraulic Conductivity (m/s)		Calibrated Specific Storage (m^{-1})
	Horizontal (K_h)	Vertical (K_v)	
Quaternary Sediments – Coarse Grained	8.9×10^{-5}	8.9×10^{-6}	1.0×10^{-3}
Quaternary Sediments – Medium Grained	6.8×10^{-7}	6.8×10^{-8}	1.0×10^{-3}
Quaternary Sediments – Fine Grained	2.4×10^{-7}	2.4×10^{-8}	1.0×10^{-3}
Red River Carbonate	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-6}
Winnipeg Shale	2.3×10^{-8}	2.3×10^{-9}	1.0×10^{-5}
Winnipeg Sandstone	3.2×10^{-5}	3.2×10^{-6}	7.0×10^{-6}

Hydrostratigraphic Unit	Calibrated Hydraulic Conductivity (m/s)		Calibrated Specific Storage (m^{-1})
	Horizontal (K_h)	Vertical (K_v)	
Lower Shale / Precambrian Bedrock	1.2×10^{-12}	1.2×10^{-12}	1.0×10^{-7}

Table 6-D. Calibrated Recharge

Recharge Area	Calibrated Recharge	
	mm/year	% Mean Annual Precipitation
Sandilands Area	189	30
Coarse Grained Sediments (sand/gravel)	100	16
Medium Grained Sediments (fine sand/silt)	40	6
Fine Grained Sediments (clay)	6	1
Birds Hill Complex	250	39

6.4 Sensitivity Analysis

6.4.1 Methods

The uncertainty associated with the model parameters was explored by conducting a manual sensitivity analysis. The sensitivity analysis assessed changes in calibration statistics in response to changes in selected calibration parameters (recharge, hydraulic conductivity and anisotropy of the bedrock units, and head boundary conditions). The final calibrated results for each model parameter were used as the reference model during the sensitivity analysis. The sensitivity of a given parameter was then determined by fixing all calibration parameters at their reference values except for the selected parameter, which was varied in sequential forward runs of the model by incrementally increasing and decreasing the value by some percent from its calibrated value. The percentage changes were determined by literature and measured values. Parameters were varied as follows:

- Recharge across the model domain was uniformly increased and decreased by 20%.
- Hydraulic conductivity of the Red River Carbonate decreased to minimum measured (1.5×10^{-5} m/s) and increased to maximum measured (8.25×10^{-4} m/s).
- Hydraulic conductivity anisotropy of the Red River Carbonate decreased by a factor of 2 to a value of 1/20 and increased by a factor of 2 to a value of 1/5.
- Hydraulic conductivity of the Winnipeg Shale decreased/increased by a factor of 10.
- Hydraulic conductivity of the Winnipeg Sandstone decreased to minimum measured (1.0×10^{-6} m/s) and increased to maximum measured (1.0×10^{-4} m/s).
- Hydraulic conductivity anisotropy of the Winnipeg Sandstone decreased by a factor of 2 to a value of 1/20 and increased by a factor of 2 to a value of 1/5.
- Red River Floodway specified head boundary increased by 2 m and assumed to be dry.
- Red River specified head boundary increased by 2 m and decreased by 2 m considering the variability of Red River surface water elevation.

6.4.2 Results

For all sensitivity analysis model runs, groundwater levels were recorded at each observation point and calibration statistics were calculated to illustrate the effects of changes to the model on goodness of fit to the observed groundwater elevations. The calibration statistics: mean residual, root mean square error (RMSE), and determination coefficient (R^2) are examined for each sensitivity case.

The NRMSE for the hydraulic head targets varied from 2.6% (scenario S8) to 7% (scenario S3), and the determination coefficient (R^2) is generally over 94% (**Table 6-E**). The mean residuals vary from -4.1 m to -0.5 m. Calibration statistics for the hydraulic heads are most sensitive to hydraulic conductivity of the Red River Carbonate (scenarios S3 and S4) and Winnipeg Shale (S8). The calibration statistics are moderately sensitive to changes in the water level elevations of the Red River and Red River Floodway (scenarios S13 to S16) which are represented by the specified hydraulic head boundary condition around the north-west boundary of the model. A change in the amount of recharge by 20% (scenarios S1 and S2) did not significantly affect the calibration statistics. Most of the sensitivity models fall within the reasonably calibrated range. When combined with predictive model runs, these models will yield either Type I or Type IV sensitivity results (ASTM 2002). Type IV sensitivity can pose challenges if any of the calibrated models produce highly sensitive predictive outcomes. In such cases, it is advisable to assess calibration statistics using observation wells near the extraction site rather than relying on the entire set of regional observation wells.

Table 6-E. Summary of Parameter Changes and Sensitivity Analysis Results

Parameter / Boundary Condition	Scenario	Description of Change	Mean Residual (m)	RMSE	NRMSE (%)	R^2
Base Case	S0	No change to calibrated model	3.3	5.3	6.3	0.97
Recharge Flux Boundary	S1	Increased by 20%	3.5	5.4	6.4	0.97
Recharge Flux Boundary	S2	Decreased by 20%	3.1	5.2	6.2	0.97
Red River Carbonate Hydraulic Conductivity	S3	Minimum measured hydraulic conductivity (K_h = 1.5x10^{-5} m/s, K_v = 1.5x10^{-6} m/s)	4.1	5.8	7.0	9.8
Red River Carbonate Hydraulic Conductivity	S4	Maximum measured hydraulic conductivity (K_h = 8.25x10^{-4} m/s, K_v = 8.25x10^{-5} m/s)	0.5	5.5	6.1	0.96
Red River Carbonate Hydraulic Conductivity Anisotropy	S5	Anisotropy of 1/20 (K_h = 1.0x10^{-4} m/s, K_v = 5x10^{-6} m/s)	3.4	5.4	6.3	0.97
Red River Carbonate Hydraulic Conductivity Anisotropy	S6	Anisotropy of 1/5 (K_h = 1.0x10^{-4} m/s, K_v = 2x10^{-5} m/s)	3.3	5.4	6.3	0.97
Winnipeg Shale Hydraulic Conductivity	S7	Decreased by one order of magnitude (K_h = 2.3x10^{-9} m/s, K_v = 2.3x10^{-10} m/s)	3.3	5.4	6.3	0.97
Winnipeg Shale Hydraulic Conductivity	S8	Increased by one order of magnitude (K_h = 2.3x10^{-7} m/s, K_v = 2.3x10^{-8} m/s)	3.4	7.4	2.6	0.94
Winnipeg Sandstone Hydraulic Conductivity	S9	Minimum measured hydraulic conductivity (K_h = 1.0x10^{-6} m/s, K_v = 1.0x10^{-7} m/s)	3.3	5.3	6.3	0.97
Winnipeg Sandstone Hydraulic Conductivity	S10	Maximum measured hydraulic conductivity (K_h = 1.0x10^{-4} m/s, K_v = 1.0x10^{-5} m/s)	3.3	5.4	6.3	0.97
Winnipeg Sandstone Hydraulic Conductivity Anisotropy	S11	Anisotropy of 1/20 (K_h = 3.2x10^{-5} m/s, K_v = 1.6x10^{-6} m/s)	3.3	5.3	6.3	0.97

Parameter / Boundary Condition	Scenario	Description of Change	Mean Residual (m)	RMSE	NRMSE (%)	R^2
Winnipeg Sandstone Hydraulic Conductivity Anisotropy	S12	Anisotropy of 1/5 ($K_h = 3.2x10^{-5}$ m/s, $K_v = 6.4x10^{-6}$ m/s)	3.3	5.3	6.3	0.97
Red River Floodway Constant Head Boundary	S13	Head equal to ground elevation (dry conditions)	3.4	5.4	6.3	0.97
Red River Floodway Constant Head Boundary	S14	Increased by 2 m	3.3	5.4	6.3	0.97
Red River Constant Head Boundary	S15	Decreased by 2 m	3.3	5.3	6.3	0.97
Red River Constant Head Boundary	S16	Increased by 2 m	3.5	5.5	6.5	0.97

6.5 Operational Predictive Scenarios

A series of predictive scenarios were developed in steady state and transient modes to make comparisons between the magnitude of drawdown in the Red River Carbonate and Winnipeg Sandstone that may result from a range of operational and parameter uncertainty.

Predictive scenarios include:

- Scenario 1: 0% re-injection (steady state, degradation of Winnipeg Shale);
- Scenario 2: 0% re-injection (steady state, no degradation of Winnipeg Shale);
- Scenario 3: 42.5% re-injection (steady state, degradation of Winnipeg Shale); and
- Scenario 4: 42.5% re-injection (transient, degradation of Winnipeg Shale).

The re-injection scenarios assume equal proportion of sand and groundwater extraction. In addition, 15% of the groundwater is assumed to remain within the sand as a residual moisture content. Hence, 85% of the groundwater will be re-injected back to the aquifer, which corresponds to 42.5% of the total volume of sand and groundwater that is extracted during production.

Scenarios 1 and 3 assess the possible range of re-injection of groundwater after solids are removed from the production fluid (0% and 42.5% of slurry volume re-injected) from the sand extraction process. The scenarios that consider zero reinjection of groundwater are presented for comparative purposes only and they are hypothetical conservative scenarios. Sio does not intend to discharge any water to ground surface. Scenarios 1 and 3 assume the Winnipeg Shale is considerably weathered and assumed to degrade (increased hydraulic conductivity) when locally disturbed/unsupported from below due to extraction of the Winnipeg Sandstone.

Scenario 2 is identical to Scenario 1 except that the Winnipeg Shale was inferred to not degrade during sand extraction (i.e. the shale remains laterally continuous with existing hydraulic properties).

Scenario 4 is a transient version of Scenario 3 that incorporates the full production schedule of the project. Shale degradation (i.e. increased hydraulic connection between the overlying Red River Carbonate and underlying Winnipeg Sandstone) was implemented in the groundwater model by converting the aquifer properties of the Winnipeg Shale to those of the Winnipeg Sandstone within 80 m of production wells as a function of time to conservatively assess the impact of operations on nearby users of the Red River Carbonate aquifer. The radius of the cavity of extraction is generally small, and the conservative 80 m radius was selected based on the results of geotechnical analysis by others (Stantec 2022). Time-variable aquifer properties were incorporated into the groundwater model by assigning a time series function to the material properties of the Winnipeg Shale within 80 m of the active wells in each production year that gradually changes to the material properties of the Winnipeg Sandstone. The aquifer properties were changed from the calibrated values for the Winnipeg Shale ($K_h = 2.3 \times 10^{-8}$ m/s; K_v = 2.3

x 10^{-9} m/s; S = 1.0 x 10^{-5}) to be equivalent to the calibrated values for the underlying Winnipeg Sandstone (K_h = 3.2 x 10^{-5} m/s; K_v = 3.2 x 10^{-6} m/s; S = 7.0 x 10^{-6}).

The majority of groundwater users obtain well from the Red River Carbonate aquifer, so this is considered a conservative approach for the protection of the majority of drinking water users. Scenario 2 provides insight into the worst case estimated impacts on groundwater users obtaining water from the Winnipeg Sandstone as there is no re-injection of water and the Winnipeg Shale is assumed to remain intact and possess the same hydraulic properties before, during and following sand extraction.

6.5.1 Methods

Model structure, boundary conditions, and aquifer properties determined during the steady state and transient calibration process (detailed in **Sections 6.2 – 6.4**) were used as a base case groundwater model. Modifications to the base case groundwater model are described below.

The five-year extraction plan indicates that most clusters have a single operational well, and frequently, two clusters operate concurrently. Hence, two clusters operating concurrently were selected to be representative of the Project to assess the impacts associated with Scenarios 1 to 3. Production number 24 consisting of two clusters with wells Bru 92-25-A and Bru 92-24-A were arbitrarily selected (**Figure 6-5**). The net extraction rate assigned to the pumping well in Scenarios 1 through 3 was adjusted according to the injection rate as follows:

- Scenario 1 (0% re-injection): Each Pumping Well with a Rate = 599.6 m^3/day (110 US GPM)
- Scenario 2 (0% re-injection): Each Pumping Well with a Rate = 599.6 m^3/day (110 US GPM)
- Scenario 3 (42.5% re-injection): Each Pumping Well with a Rate = 344.8 m^3/day (63.25 US GPM)

In the transient simulation with 42.5% re-injection (Scenario 4), pumping rates were assigned to each well cluster based on the five-year mine plan shown in **Figure 6-5** and summarized in **Appendix H**. Each well cluster is treated as a single pumping well in the groundwater model; however, production rates are the same for all pumping wells within a cluster. Well clusters were grouped to a single point to assist with model resolution and simulation times and fine-scale variability should have little to no impact on the local to regional scale impacts of the Project.

Observation wells in the Red River Carbonate and Winnipeg Sandstone were incorporated into the groundwater models to monitor groundwater elevations and drawdown. These locations are shown on **Figure 6-6** and summarized in **Table 6-F**. Two well pairs are part of the groundwater observation well network maintained by Manitoba Water Stewardship. All other well locations were located at the center of the quarter sections in the vicinity of the Project Site to provide a basis for evaluating impacts of the Project on groundwater quantity.

Table 6-F. Observation Point Details

Observation Point ID	UTM Coordinate, NAD 83 14N	
	Easting (m)	Northing (m)
G05OJ163	673,031	5,525,105
G05OJ175	673,031	5,525,105
G05SA014	681,156	5,523,658
G05SA015	681,156	5,523,658
E 0701010NE	676,012	5,521,692
E 0701011NE	677,651	5,521,735
E 0701011NW	676,847	5,521,713
E 0701012NE	679,296	5,521,780
E 0701012NW	678,488	5,521,758
E 0701013NE	679,253	5,523,417

Observation Point ID	UTM Coordinate, NAD 83 14N	
	Easting (m)	Northing (m)
E 0701013SE	679,274	5,522,613
E 0701013SW	678,466	5,522,591
E 0701013NW	678,444	5,523,394
E 0701014NE	677,607	5,523,371
E 0701014SE	677,629	5,522,568
E 0701014SW	676,825	5,522,546
E 0701014NW	676,801	5,523,348
E 0701015NE	675,965	5,523,328
E 0701015SE	675,989	5,522,526
E 0701022NE	675,920	5,524,972
E 0701022SE	675,943	5,524,164
E 0701023NE	677,562	5,525,006
E 0701023SE	677,584	5,524,204
E 0701023SW	676,778	5,524,180
E 0701023NW	676,755	5,524,988
E 0701024NE	679,210	5,525,045
E 0701024SE	679,231	5,524,247
E 0701024SW	678,423	5,524,224
E 0701024NW	678,400	5,525,027
E 0701025NE	679,164	5,526,690
E 0701025SE	679,187	5,525,881
E 0701025SW	678,378	5,525,863
E 0701025NW	678,356	5,526,671
E 0701026NE	677,517	5,526,652
E 0701026SE	677,540	5,525,844
E 0701026SW	676,732	5,525,826
E 0701027SE	675,899	5,525,807
E 0701036SE	679,141	5,527,548
E 0701036SW	678,332	5,527,529
E 0801007NE	680,872	5,521,839
E 0801007NW	680,110	5,521,807
E 0801008NE	682,495	5,521,905
E 0801008NW	681,687	5,521,872
E 0801009NW	683,327	5,521,939
E 0801016SW	683,300	5,522,772

Observation Point ID	UTM Coordinate, NAD 83 14N	
	Easting (m)	Northing (m)
E 0801016NW	683,273	5,523,573
E 0801017NE	682,440	5,523,543
E 0801017SE	682,468	5,522,740
E 0801017SW	681,656	5,522,708
E 0801017NW	681,624	5,523,512
E 0801018NE	680,812	5,523,480
E 0801018SE	680,842	5,522,675
E 0801018SW	680,086	5,522,641
E 0801018NW	680,062	5,523,445
E 0801019NE	680,752	5,525,115
E 0801019SE	680,782	5,524,313
E 0801019SW	680,038	5,524,277
E 0801019NW	680,013	5,525,076
E 0801020NE	682,358	5,525,186
E 0801020SE	682,403	5,524,379
E 0801020SW	681,590	5,524,347
E 0801020NW	681,553	5,525,152
E 0801021SW	683,238	5,524,408
E 0801021NW	683,195	5,525,217
E 0801028SW	683,161	5,526,055
E 0801029NE	682,301	5,526,827
E 0801029SE	682,324	5,526,022
E 0801029SW	681,522	5,525,987
E 0801029NW	681,497	5,526,793
E 0801030NE	680,699	5,526,757
E 0801030SE	680,724	5,525,950
E 0801030SW	679,989	5,525,910
E 0801030NW	679,966	5,526,718
E 0801031SE	680,673	5,527,610
E 0801031SW	679,942	5,527,575
E 0801032SE	682,276	5,527,674
E 0801032SW	681,472	5,527,643

6.5.2 Results

Simulated groundwater elevation and drawdown contours for Scenarios 1 to 3 is presented in **Table 6-1**. From the table the following statements can be made:

- The largest simulated drawdown in the Red River Carbonate was in Scenario 1 (0% re-injection). Simulated drawdown was 2.3 m at the nearest observation point 200 m from the production well.
- The largest simulated drawdown in the Winnipeg Sandstone was in Scenario 2 (0% re-injection with no shale degradation). Simulated drawdown in Scenario 2 is more pervasive in the Winnipeg Sandstone and does not impact the Red River Carbonate to a large degree.
- Scenarios 1, 2 and 3 did not cause drawdown exceeding 2 m in the Red River Carbonate and Winnipeg Sandstone at a distance greater than approximately 500 m from the production wells.
- The drawdown with the 42.5% re-injection (Scenario 3) did not exceed 1.5 m in both the Red River Carbonate and Winnipeg Sandstone at distances beyond 200 m from the production well. Generally, lower net withdrawal rates will reduce the magnitude and spatial extent of drawdown impacts.
- At a distance of 910 m from the extraction wells, the drawdown in the Red River Carbonate was approximately 1.2 m for the 0% re-injection case and around 0.7 m with re-injection. Similarly, for the Winnipeg Sandstone, the drawdown did not exceed 1.0 m and 0.5 m for the 0% re-injection and the 42.5% re-injection scenarios, respectively. From this, it can be inferred that the drawdown at a 1 km distance for both the Red River Carbonate and Winnipeg Sandstone from the extraction wells will be approximately 1 m or lower for the 0% re-injection case and about 0.5 m for the 42.5% re-injection case. The 0.5 m simulated drawdown contour extends up to 2.3 km for Scenarios 1 and 2.
- If re-injection does not happen concurrently with groundwater withdrawal, the observed drawdown would resemble the simulated drawdown in Scenario 1, where water is not re-injected during the time interval but only withdrawn.

Figure 6-7 shows the simulated groundwater level fluctuations at selected observation points near the production wells during the extraction period from Year 0 to 4. These fluctuations align with the characteristics of a highly transmissive aquifer with moderate storativity. Notably, the maximum simulated drawdown in one of the Winnipeg Sandstone observation points (E0801019SW) is approximately 2.5 m, while in the Red River Carbonate observation points, the maximum simulated drawdown remains below 2.0 m. Project operations will result in a very small decline in water levels over the five-year operational period. Groundwater levels were shown to recover to near pre-development groundwater elevations or within one metre baseline conditions following the end of project operations when recharge is held fixed and is not allowed to increase in response to increased drawdown. This conservative assumption warrants further exploration to determine if recharge rates are reasonable, or if they increase in response to drawdown in the underlying aquifer.

The simulated horizontal extent of drawdown for Scenario 4 in the Red River Carbonate and Winnipeg Sandstone during each of the five periods of production and recovery are shown on **Figure 6-8 to Figure 6-10** for production Years 0 through 4. The largest 1.0 m drawdown contour simulated in Winnipeg Sandstone occurred in production Year 0 (**Figure 6-8**) and was simulated to extend approximately to a maximum of 270 m from the center of the active sand extraction wells. In the Red River Carbonate, the largest 1.0 m drawdown contour simulated extends to a maximum distance of approximately 320 m as shown for production Year 4 on **Figure 6-10**. During this period, there were four operating clusters, and the simulated drawdowns did not exhibit circular contours.

As shown in **Figure 6-7** simulated groundwater levels at observation points return to near static water level conditions within 60 days after production ceases each year. Removal of solids will change the aquifer properties within the void created by sand removal and complete recovery may take longer in proximity to sand extraction wells.

6.6 Future Climate Scenario

Canada's climate will continue to warm due to global emissions of greenhouse gases (Bush and Lemmen 2019). The warming is expected to lead to increases in extreme heat and extreme precipitation events, raise sea-levels, and cause further declines in snow and ice cover. This will affect all areas of the environment, society, and the economy. Consequently, regulators request assessment of climate impacts on major projects, and many codes of practice have been developed across the country to guide professional geoscientists and engineers in the evaluation of climate change impacts on projects, with particular focus on projects having interactions with groundwater and surface water. Climate change predictions are available through the ClimateData.ca website. The website provides access to visualize and analyze climate data (Cannon et al. 2015; Tam et al. 2018).

6.6.1 Methods

6.6.1.1 Predictive Climate Modelling

Projected climate data for the project area was derived from ClimateData.ca. The projected climate variables including precipitation, and maximum and minimum temperature were generated based on multi-model ensemble approach from 27 Global Climate Models (GCMs). This data set is obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and referred as Canadian Downscaled Climate Scenarios – Univariate (CMIP5), or CanDCS-U5. Data from each GCM was downscaled using the BCCAQv2 downscaling approach. The CMIP5 projections make use of Representative Concentration Pathways (RCPs) that are designed to provide plausible future scenarios of anthropogenic forcing, spanning a range from a low emission scenario to a high emission scenario. The selected climate projection was for climate normal period from year 2051 to 2080 under a high emission scenario (RCP8.5), and the median response (50th percentile) of the multi-model ensemble. This scenario provides a more conservative assessment of the impacts of climate change on groundwater conditions.

6.6.1.2 Climate Change Impacts to Groundwater

Climate change significantly influences hydrological processes. Hydrological models quantify variables like evapotranspiration, runoff, snowmelt, infiltration, and recharge based on projected climate variables. These models provide estimates of groundwater recharge, which inform groundwater flow models used to assess groundwater elevations and water balances. In the absence of rigorous hydrological models, groundwater recharge can be approximated as a percentage of precipitation minus evapotranspiration (derived based on water balances) or just precipitation. To assess the impact of climate change on groundwater conditions at the project site, the following models were used:

- Existing Condition Model: This model serves as the baseline representation of project operations under the current climatic conditions. The Scenario 3 model, presented in **Section 6.5**, is assumed to be representative of existing conditions and was utilized as the baseline model.
- Projected Climate Model: This model represents the future project operation under projected climatic conditions. This model was modified from the Existing Condition Model based on the projected mid-century climate. The model modifications and assumptions are as follows:
  - Recharge values at the end of operation around year 2050 were projected based on the projected precipitation and assuming the current percentages of mean annual precipitation as recharge remains constant.
  - The same pumping wells as in Scenario 3 were assumed to be used for extraction in year 2050. This approach allows us to isolate the impact of climate change from other changes that will occur by the end of the project operation.
  - Both the Existing Condition Model and Projected Climate Model were constructed as steady-state models, capturing long-term average conditions rather than the short-term operation of the extraction wells.
  - The projected climate analysis incorporated a single conservative climate scenario.

Although this approach makes some simplifying assumptions, they are reasonable and allow for a practical assessment of groundwater conditions under future climate scenarios.

6.6.2 Results

The projected climate variables including precipitation and maximum and minimum temperature are presented in **Table 6-G**. The projected precipitation is lower than the precipitation of the current climatic normals by about 14%. The projected minimum and maximum temperatures are predicted to increase by 25% and 23% compared to the climatic normal, respectively. These climate variables are one possibility of several projected climate conditions for year 2050 and there is considerable uncertainty associated with their application. The existing and projected climate is presented graphically in **Figure 6-11**. In most months, the projected temperatures are higher, and there is less precipitation.

Table 6-G. Projected 2051 – 2080 Monthly Average Climate Variables

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature													
Daily Average (°C)	-12.0	-9.2	-0.2	7.1	15.0	20.5	24.1	23.3	16.9	9.8	0.4	-7.5	7.3
Daily Maximum (°C)	-7.4	-4.1	3.6	13.4	21.9	27.1	31.0	30.0	23.2	15.1	4.2	-3.4	12.9
Daily Minimum (°C)	-16.6	-14.3	-7.3	0.9	8.0	13.8	17.2	16.3	10.6	4.4	-3.7	-11.2	1.5
Precipitation													
Precipitation (mm)	31.2	21.5	28.5	34.7	78.2	94.2	68.1	23.3	64.6	41.5	29.0	31.9	546.6

Monthly projected recharge values for year 2050 were determined using the current percentage of mean annual precipitation and the projected precipitation. The projected annual recharge varies from 5.5 mm for fine grained sediments to 213.2 mm for Birds Hill complex as shown in **Table 6-H.** The projected total recharge for the entire model domain (area weighted) was about 59 mm/y. The projected total recharge is lower by about 14% compared to the current recharge. This is attributed to the overall projected lower precipitation.

Table 6-H. Projected Recharge

Recharge Area	Calibrated Recharge		Projected Recharge
	mm/year	% Mean Annual Precipitation	mm/year
Sandilands Area	189	30	164.0
Coarse Grained Sediments (sand/gravel)	100	16	87.5
Medium Grained Sediments (fine sand/silt)	40	6	32.8
Fine Grained Sediments (clay)	6	1	5.5
Birds Hill Complex	250	39	213.2

The impact of climate change on the mid-century groundwater condition was assessed using the water balance within the model domain and the drawdowns around the vicinity of the extraction wells. The water balance (**Table 6-I**) indicates that due to projected lower recharge, there will be reduced groundwater outflow to rivers and streams (specified head boundary conditions). **Figure 6-12** shows the simulated drawdowns during the existing and projected groundwater conditions. Under existing conditions, the 1 m drawdowns of the Winnipeg Sandstone reach a distance of 290 m away from the extraction wells. However, in the projected scenario, these drawdowns extend up to 1,300 m from the extraction wells. It is important to note that these extended drawdowns are based on the assumption of long-term steady-state extraction wells, and the drawdowns may not expand to the same extent during shorter pumping durations as proposed during project operations. In reality, the magnitude of drawdown impacts will be less as different wells will be pumping for relatively short duration of time and then allowed to recover. Conversely, the spatial extent of drawdown impacts would be larger, and correlated with the wells in operation at the time. Overall, this simulation highlights that climate change will reduce the volume of groundwater recharge to the aquifer and slightly reduce groundwater elevations even in the absence of project operations. Climate change will result in a slight increase in the magnitude and spatial extent of drawdown impacts during project operations relative to existing climate conditions. Further, climate change will slightly reduce the magnitude of groundwater recharge to the aquifers over time, highlighting the importance of long term monitoring and adaptive management of the groundwater resource.

Table 6-I. Simulated Mass Balance Existing and Projected Conditions

Boundary Condition	Existing Condition Model – Scenario 3 (m^3/day)		Projected Climate Model – Modified after Scenario 3 (m^3/day)	
	Outflow	Inflow	Outflow	Inflow
Specified Head	2.4×10^6	1.8×10^6	2.3×10^6	1.8×10^6
Wells	1.5×10^4	-	1.5×10^4	-
Recharge	-	6×10^5	-	5.2×10^5
Imbalance	-	8 (<0.001%)	-	168 (<0.001%)

7. Vulnerability Analysis

Intrinsic aquifer vulnerability, herein referred to simply as vulnerability, is a description of the degree to which the natural environment provides protection to groundwater resources from contamination originating on the ground surface. Properties of the land and subsurface which can influence the potential for contamination to enter a groundwater system includes, but is not limited to, soil and unsaturated zone material, depth to the water table/aquifer, recharge amount and location, slope of the land surface, hydraulic conductivity of the aquifer, and the presence of preferential flow pathways.

Because vulnerability is an intrinsic property of the subsurface (i.e. aquifers/aquitards), this metric does not account for the presence of a hazard threat (i.e. a contaminant), transport properties of the contaminant, the likelihood of a contaminant release, or the consequences associated with groundwater contamination. For example, although an area may highly be vulnerable to contamination, the risk to groundwater contamination is unlikely to occurs if there is no contamination present at the ground surface.

7.1 Objectives

This vulnerability analysis aimed to assess how the localized collapse of the Winnipeg Shale aquitard near proposed extraction wells will impact groundwater vulnerability in the Sandstone Aquifer to contamination originating on the ground surface. A spatial map of relative vulnerability was produced for current conditions (pre-collapse of the Winnipeg Shale) as well as future conditions (post-collapse of the Winnipeg Shale) conditions. Differences between these maps were used to quantify the relative impact of the Winnipeg Shale collapse on aquifer vulnerability.

7.2 Methods

Characterization of intrinsic vulnerability was completed using a modified-DRASTIC method (Aller et al., 1987). The DRASTIC method is a qualitative indexing method commonly used in groundwater resource assessments to show the relative differences in vulnerability across regional scales. This approach has been used around the world, both with and without modification to the method. It typically considers:

- D: Depth to Groundwater
- R: Net Recharge
- A: Aquifer Media
- S: Soil Media
- T: Topography or Slope
- I: Vadose Zone
- C: Hydraulic Conductivity of the Aquifer.

However, the vulnerability analysis completed herein expands on the DRASTIC method by considering project specific conditions (i.e. confinement of the aquifer, time-variable hydraulic properties due to changes in the Winnipeg Shale) and incorporating numerical modelling results for current and future conditions.

Assumptions underlying the DRASTIC method include:

- The contaminant is introduced at ground surface,
- The contaminant transports vertically at the same rate as water (i.e. not considering specifics of a particular contaminant's transport or preferential pathways);
- More rapid pathways such as open wells are not considered, and
- The size of the mapped area is greater than 0.5 km2.

Intrinsic aquifer vulnerability (V) was defined as the sum of the representative overlying vertical hydraulic conductivity (K), the vertical hydraulic gradient (H), and the depth to the top of the aquifer (D):

$$V = K + H + D$$

The vulnerability equation is computed across the regional groundwater modelling domain, where the Winnipeg Sandstone is present, at a 50 m x 50 m spatial resolution. Each of the input parameters in this equation were derived from the inputs and results of the numerical groundwater model and are also spatially varying at a 50 m x 50 m spatial resolution. Vulnerability was calculated spatially for current conditions (pre-collapse of the Winnipeg Shale) as well as future conditions (post-collapse of the Winnipeg Shale) conditions, yielding a current and future map of relative intrinsic vulnerability. Differences between these maps were used to quantify the relative impact of the Winnipeg Shale collapse on aquifer vulnerability.

7.2.1 Overlying Vertical Hydraulic Conductivity

The representative vertical hydraulic conductivity for current and future conditions were calculated using a weighted geometric mean of the subsurface material overlying the Winnipeg Sandstone aquifer. Weights used in the geometric mean were calculated for every 50 m x 50 m grid cell according to the percent of overlying material accounted for by each of the five hydrostratigraphic units overlying the Winnipeg Sandstone aquifer:

- Coarse Grained Quaternary Sediments;
- Medium Grained Quaternary Sediments;
- Fine Grained Quaternary Sediments;
- Red River Carbonate; and
- Winnipeg Shale.

The calibrated vertical hydraulic conductivity values from the steady state numerical groundwater model (**Table 6-C**) were used in the geometric mean calculation. Overlying vertical hydraulic conductivity values were normalized on a scale from zero (0) to one (1), with zero (0) relating to comparatively low hydraulic conductivity and one (1) relating to comparatively high hydraulic conductivity. Areas with lower vertical hydraulic conductivity are expected to reduce vulnerability.

7.2.2 Vertical Hydraulic Gradient

The vertical hydraulic gradient for current and future conditions were calculated between the top of the Quaternary Sediments and the top of the Winnipeg Sandstone Aquifer. Hydraulic gradients were normalized on a scale from zero (0) to one (1), with zero (0) relating to upward vertical flow (from the Winnipeg Sandstone aquifer to the Quaternary Sediments) and one (1) relating to downward (from the Quaternary Sediments to the Winnipeg Sandstone aquifer) vertical flow. Upward hydraulic gradients are expected to decrease vulnerability because water is moving from the Winnipeg Sandstone toward the ground surface, preventing contaminant transport from ground surface to the underlying Winnipeg Sandstone aquifer.

7.2.3 Depth to the Aquifer

Depth to the top of the Winnipeg Sandstone aquifer was calculated between the ground surface and the bottom of the Winnipeg Shale. Where the Winnipeg Shale does not exist (i.e. post-collapse), the depth was calculated from ground surface to the bottom of the Red River Carbonate aquifer. Depths were normalized on a scale from zero (0) to one (1), with zero (0) relating increased depth (near the Red River) and one (1) relating to decreased depth (near the eastern boundary where the Winnipeg Sandstone pinches out). Increased depths reduce the vulnerability to the aquifer because a contaminant originating at the ground surface would need to travel further to reach the Winnipeg Sandstone aquifer.

7.3 Results

7.3.1 Overlying Vertical Hydraulic Conductivity

The geometric mean of the overlying vertical hydraulic conductivity is highest along the western half of the model. Although there are fine-grained Quaternary Sediments in this area, this low hydraulic conductivity unit occupies a relatively smaller portion of the overlying material when compared with the high hydraulic conductivity Red River Carbonate aquifer. The lowest average overlying vertical hydraulic conductivity occurs along the eastern boundary of the Winnipeg Sandstone. This area of relatively low hydraulic conductivity is attributed to a higher proportion of the overlying material being comprised of the low hydraulic conductivity of the Winnipeg Shale aquitard.

7.3.2 Vertical Hydraulic Gradient

Regionally, the vertical hydraulic gradient between the Winnipeg Sandstone and the ground surface is primarily downward, with a maximum downward hydraulic gradient 0.2 m/m occurring within the Bird's Hill Complex. Upward vertical hydraulic gradients exist where there are surface water features, primarily along the Red River, the Red River Floodway, Cooks Creek, and the Brokenhead River.

Within the project area, the vertical hydraulic gradient ranges from 0.02 m/m downward to 0.01 m/m upward prior to the collapse of the Winnipeg Shale. The localized collapse of the Winnipeg Shale is projected to increase the existing vertical hydraulic gradient by up to 0.01 m/m. This results in a maximum vertical hydraulic gradient of 0.03 m/m downward and 0.01 m/m upward after the localized collapse of the Winnipeg Shale. The changes in vertical hydraulic gradient are primarily the result of the slight lowering of the groundwater elevation in the Winnipeg Sandstone during and immediately following project operations, but the groundwater levels and hydraulic gradients are expected to recover to pre-development conditions following operations.

7.3.3 Depth to the Aquifer

Depth to the top of the Winnipeg Sandstone aquifer is greatest along the western boundary of the regional modelling domain, near the Red River. In this area, the top of the Winnipeg Sandstone aquifer is up to 140 m bgs. Depth to the top of the aquifer decreases to the east and is shallowest near the confluence of Brokenhead River and Hazel Creek, at 24 m bgs.

Within the project area, the depth to the top of the Winnipeg Sandstone aquifer is between 45 m bgs to 60 m bgs. After the localized collapse of the Winnipeg Shale, the depth to the top of the aquifer will be between 43 m bgs and 57 m bgs. The maximum difference between the pre- and post-collapse depth to the aquifer is 9 m.

7.3.4 Vulnerability

Regionally, vulnerability is greatest near the Bird's Hill complex and smallest along the eastern boundary of the Winnipeg Sandstone, shown in **Figure 7-1**. Because vulnerability is normalized across the regional area, vulnerability ranges from zero to one, with zero representing relatively low vulnerability and one representing relatively high vulnerability. The collapse of the Winnipeg Shale does not affect the overall regional vulnerability and only impacts vulnerability within the project site, as shown in **Figure 7-2**.

Within the project site, vulnerability before the Winnipeg Shale collapse ranges from 0.2 to 0.5. Vulnerability within this area increases due to the Winnipeg Shale collapse by up to 0.15 (equivalent to 15%). Post-collapse vulnerability values across the site range from 0.3 to 0.7, indicating a relatively minor and localized change in vulnerability. Although vulnerability does increase within the project area, the project area remains at 0.3 (30%) lower than the highest vulnerability regionally.

It is important to note that all vulnerability measures are relative throughout the region. In general, the thick (approximately 30 m) fine-grained Quaternary sediments overlying all bedrock aquifers in the area provide substantial protection to all underlying aquifers. Geotechnical modelling and subsidence monitoring indicates sand extraction will not cause failure of the limestone caprock or Quaternary sediments. Therefore, even areas indicating a relatively higher vulnerability remain at low risk to groundwater contamination originating from the ground surface.

The collapse of the Winnipeg shale has no impact on the vulnerability of the Red River Carbonate aquifer because there is no change in the hydraulic conductivity, hydraulic gradient, and depth to the top of the aquifer. The slight increase in vulnerability to the Winnipeg Sandstone only has the potential to impact groundwater quality in the presence of a hazard. Mitigating hazards, such as surface spills or agricultural runoff, remains the most effective way to prevent groundwater contamination. Additionally, aquifer quality is most vulnerable where there is a direct, uninhibited connection between the aquifer and ground surface (e,g, through an open well for instance). The Progressive Well Abandonment Plan ensures that all wells will be properly closed to ensure protection of groundwater resources. Similar approaches should be implemented for any disused water supply wells in the study area.

8. Impact Assessment

8.1 Project Interactions and Mitigation

8.1.1 Community Consultation

Information obtained from a literature review and community and First Nations engagement has indicated that in the area of the Project Site, groundwater in the Red River Carbonate and Winnipeg Sandstone is used extensively to meet demands for a variety of water uses. Groundwater use in the Local Project Area is primarily domestic, with the remaining wells classified as air conditioning, industrial, irrigation, livestock, municipal or other. The majority of the wells are completed in the Red River Carbonate aquifer, although several wells are completed in the Winnipeg Sandstone aquifer. Therefore, it is critical to ensure the groundwater supply is not negatively impacted by project operations, and the aquifer system continues to meet the needs of the community. Furthermore, it is important that groundwater quality is not degraded as a result of project activities.

Key issues raised by regulatory agencies and the public relate to the need to preserve groundwater quantity (avoid well interference) and ensure cuttings derived from the lithified bedrock units (Red River Carbonate, Winnipeg Shale, Winnipeg Sandstone, etc.) are properly characterized and managed to avoid impacts to groundwater quality.

8.1.2 Pathways Analysis

Project components and activities interact with groundwater quantity and quality and may result in changes. The primary pathways for impacts to groundwater quantity and groundwater quality that were evaluated within this assessment are presented below:

<u>Groundwater Quantity</u>:

- Pumping of groundwater during sand extraction may produce increased drawdown with resultant impacts on well yield for nearby groundwater users with wells completed in Winnipeg Sandstone and the Red River Carbonate aquifers.
- Degradation of the Winnipeg Shale as a result of project operations resulting in increased hydraulic connection between the Winnipeg Sandstone and Red River Carbonate with possible well yield reduction impacts on groundwater users in the Red River Carbonate. This may also result in reduced impacts on groundwater users in the Winnipeg Sandstone because extracted water would be derived from both aquifers rather than being derived almost entirely from the Winnipeg Sandstone if the Winnipeg Shale remained intact.

<u>Groundwater Quality</u>:

- Installation of numerous wells may create preferential flow pathways from surface to either the Red River Carbonate aquifer and/or the Winnipeg Sandstone aquifer, with resultant impacts on groundwater quality due to mixing of waters of different water quality and geochemical equilibration with prevailing oxidation-reduction conditions in each aquifer.
- Degradation of the Winnipeg Shale as a result of project operations resulting in mixing of groundwaters in the Winnipeg Sandstone and Red River Carbonate with possible impacts on groundwater quality in one or more of the aquifers.

8.2 Residual Effects Analysis

Residual effects are the effects of the project remaining after the application of mitigation measures to avoid or minimize potential adverse effects. This section assesses the predicted changes to groundwater quantity and quality resulting from the project activities described in **Section 2**. This analysis was completed to compare conditions during Project Operations and Post-Closure phases of the project to Existing Conditions. Project induced changes to measurement indicators are provided for the Red River Carbonate aquifer and Winnipeg Sandstone aquifer that could experience changes in groundwater quantity and groundwater quality. The impacts of any ML/ARD were assessed to evaluate the possibility of impacts to the drinking water aquifers.

Project effects on groundwater quantity and groundwater quality are discussed in terms of changes to measurement indicators within the Local Project Area for each phase of the project. The effects on groundwater quantity were calculated by numerically integrating the project components into a three-dimensional numerical groundwater model for each year of project operations as described in **Section 6** of this report. The groundwater model grid and boundary conditions including extraction wells were modified to reflect project operations and post-closure. Drawdown in each aquifer was numerically calculated within the framework of the groundwater model to predict the influence of sand extraction wells daily. The simulated 1 m drawdown contour was used to provide context to the modelling results. As noted in **Section 5.8.2**, the Red River Carbonate and Winnipeg Sandstone aquifers exhibit seasonal water level fluctuations on the order of 1.5 m to 3 m. **Table 8-A** presents the definitions applied to the effects criteria to evaluate impacts related to the project.

Table 8-A. Definitions Applied to Effects Criteria for Residual Effect Analysis

Criterion	Rating	Definition
Direction	Positive	Change in measurement indicator results in net improvement or benefit to groundwater quantity or groundwater quality
	Neutral	Change in measurement indicator results in net balance to groundwater quantity or groundwater quality
	Negative	Change in measurement indicator results in net degradation or loss to groundwater quantity or groundwater quality
Magnitude	Narrative or Numeric Quantification	Change in measurement indicator is described by effect size (e.g., quantity of groundwater quantity (e.g., levels, flow) or concentration of constituent of potential concern in groundwater relative to existing conditions)
Geographic Extent	Maximum Disturbance Footprint	Change in groundwater quantity or groundwater quality is confined to the Project Site Footprint
	Local	Change in groundwater quantity or groundwater quality extends outside the maximum disturbance footprint but within the Local Project Area
	Regional	Change in groundwater quantity or groundwater quality extends beyond the Local Project Area but is confined to the Regional Project Area
	Beyond Regional	Change in groundwater quantity or groundwater quality extends beyond the Regional Project Area
Duration	Narrative or Numeric Quantification	Change in groundwater quantity or groundwater quality is described by effect duration (e.g., months, years, decades, permanent)
Reversibility	Reversible	Change in groundwater quantity or groundwater quality is reversible within a clearly defined time period
	Irreversible	Change in groundwater quantity or groundwater quality is predicted to influence the component indefinitely
Frequency	Occasional	Change in groundwater quantity or groundwater quality is expected to occur rarely (e.g., once or a few times)
	Periodic	Change in groundwater quantity or groundwater quality is expected to occur consistently at regular intervals or associated with temporal events (e.g., during spring freshet, low flows, drought, etc.)
	Continuous	Change in groundwater quantity or groundwater quality is expected to occur all the time
Probability of Occurrence	Unlikely	Change in groundwater quantity or groundwater quality is not expected to occur, but not impossible
	Possible	Change in groundwater quantity or groundwater quality may occur, but is not likely
	Probable	Change in groundwater quantity or groundwater quality is likely to occur, but is uncertain
	Certain	Change in groundwater quantity or groundwater quality will occur

8.2.1 Groundwater Quantity

Groundwater model simulations indicate that groundwater users of the Red River Carbonate aquifer and the Winnipeg Sandstone aquifer beyond a radial distance of approximately 2.3 km from the active extraction wells are unlikely to experience effects due to extraction at the active extraction wells within the Project Site area (even without any re-injection of groundwater). Assuming the re-injection system operates simultaneously with production, the extent of the simulated 0.5 m drawdown contour reduces to a radial distance of approximately 1.0 km from the production well. The projected climate impact indicates that the 0.5 m drawdown contour could expand up to 1.3 km from the production well. If there is any time between sand extraction and re-injection of water during operations, drawdown may be between the 0% and 42.5% re-injection scenario (Scenario 1 and Scenario 3). Based on this assessment, most of the wells within the Project Area are not likely to be affected by operations because they fall outside the 0.5 m drawdown cone. However, several licensed wells fall between the estimated 0.5 m and 5 m drawdown cones and pumps installed a short distance below the water table may experience diminished well yield during operations. Appropriate mitigations may include conducting a survey in advance of operations to determine the location, depth, use and configuration of each well, lowering of pumps in advance of sand extraction or providing treated makeup water during periods of time when drawdown impacts may occur.

During each year of sand extraction, drawdown migrates across the footprint of the project as various planned production wells become operational. Drawdown during active production remains approximately the same size and magnitude as illustrated in **Figure 6-8**, **Figure 6-9** and **Figure 6-10** because the shape and extent of the drawdown cone is determined primarily by aquifer properties (hydraulic conductivity and storativity), which was assumed to remain constant over the footprint of the project, and recharge, which was assumed to not increase in response to drawdown in the underlying aquifers and remain constant over time. The spatial extent of the drawdown will also vary based on the extraction rate, the number of concurrent operations, the distance between these operations, and the time since wells were last operated.

The Regional Project Area (**Figure 1-3**) contains approximately 1,505 domestic water wells (from the Groundwater Information Network database). Assuming a water use of 200 L/day per person (Friesen, 2019) and an average of four (4) people per domestic well, consumptive water use in the Regional Project Area is approximately 439,000 m^3/year. In the 0% re-injection scenario (unlikely worst case), the annual average water use for Years 0 through 4 would be approximately 520,200 m^3/year which would amount to 119% of the volume used for domestic purposes in a single year. Comparatively, in the 42.5% re-injection scenario (the targeted scenario), the annual average water use for Years 0 through 4 would be approximately 299,100 m^3/year which is 68% of the volume used for domestic purposes in a single year. Known large volume licensed groundwater users in the model domain have a combined allotment of 4,070,000 m^3/year. Groundwater use for the project under the 42.5% Re-Injection scenario equates to approximately 7.3% of the existing allotment to other large industrial users within the model domain over the 5-year operational period.

Simulated groundwater elevations return to near static groundwater elevations approximately two (2) months after production stops (in 42.5% re-injection scenario) as shown in **Figure 6-7**. Recovery was simulated to occur following the end of production each fall over a period of approximately one (1) to two (2) months. Recovery during the winter months when recharge is reduced may be slower although substantive recharge is derived from lateral recharge in the Sandilands Area which may reduce the impacts of seasonality. Nearly full recovery of groundwater elevations was simulated to occur during the Post-Closure period (i.e. after operations cease) in the same manner as after each year of production in the absence of other external factors. Overall, the removal of sand will permanently increase the effective porosity and storativity of the Winnipeg Sandstone aquifer within the Project Site through the annual extraction of material and resulting creation of void space. The quantity of groundwater will be preserved and potentially increase as a result of the increased porosity and storativity of the aquifer following sand extraction and recovery. Additional characterization and monitoring of groundwater levels in the Sandilands Area may improve the understanding of recharge to the aquifers and help determine if recharge is likely to increase in response to drawdown in the underlying aquifers.

8.2.2 Groundwater Quality

The Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone units exhibit water quality that is relatively fresh. Project operations may induce short-term and very localized changes in oxidation-reduction conditions as a result of reinjecting water with residual dissolved oxygen concentrations and increase communication between the Winnipeg Sandstone and the Red River Carbonate aquifers following any degradation of the Winnipeg Shale. Geochemical modelling results indicate that degradation of the Winnipeg Shale will have a low to negligible impact on groundwater quality in either aquifer.

Geochemical modelling also indicated that if groundwater with a residual dissolved oxygen concentrations is reinjected into the Winnipeg Sandstone, carbonate minerals such as siderite, rhodochrosite, strontianite and gypsum remained undersaturated and would therefore not form precipitates. The increasingly oxidizing conditions were simulated to further reduce iron, manganese and aluminum concentrations, but have a minor impact on sulphate concentrations in groundwater. Besides iron and manganese, calcium concentrations in Bru 95-5 decreased by over 90% from 50.7 mg/L to 5.19 mg/L following re-equilibration of calcite in groundwater. Degassing of carbon dioxide was simulated to result in super saturation of groundwater with respect to calcium and would promote precipitation of calcite. The reinjection of partially oxygenated water will likely result in the oxidation and hydrolysis of iron and manganese leading to co-precipitation of metals.

Iron and manganese naturally exceed the CDWQ and MWQSOG. These are aesthetic objectives associated with staining of plumbing fixtures and clothing. If the Winnipeg Shale degrades as a result of project operations and prevailing groundwater gradients result in upward groundwater flow from the Winnipeg Sandstone to the overlying Red River Carbonate aquifer, metal concentrations in groundwater within the Red River Carbonate aquifer were simulated to be low and meet applicable guidelines with the exception of manganese and iron. Iron concentrations were simulated to marginally exceed the CDWQ AO of 0.3 mg/L in all simulated water, except for water containing less than 20% of groundwater derived from the Red River Carbonate end member. This indicates that although iron concentrations were simulated to improve as a result of inter-aquifer mixing, concentrations are likely to remain naturally elevated above aesthetic guidelines. Dissolved manganese concentrations in the Winnipeg Sandstone were approximately 20 times higher those in the Red River Carbonate. As a result, the simulated manganese concentrations increase with an increasing proportion of groundwater derived from the Winnipeg Sandstone, and simulated water quality exceeded CDWQ AO of 0.02 mg/L when the mixing fraction of groundwater derived from the Winnipeg Sandstone was greater than 70%. Concentrations of alkalinity, chloride, calcium, magnesium, arsenic, iron, uranium and strontium concentrations progressively decreased with an increasing proportion of groundwater derived from the Winnipeg Sandstone because concentrations of these parameters are generally lower in the Winnipeg Sandstone unit. Simulated dissolved zinc concentrations gradually increased from <0.001 mg/L to 0.01 mg/L, but remained well below the CDWO AO of 5 mg/L.

If prevailing groundwater gradients result in downward groundwater flow from the Red River Carbonate to the underlying Winnipeg Sandstone, metal concentrations in groundwater within the Winnipeg Sandstone were simulated to be low and meet the applicable guidelines, except for manganese and iron. Iron concentrations in the Winnipeg Sandstone were low, but water quality was simulated to marginally exceed CDWQ AO of 0.3 mg/L when the mixture contained over 30% of Red River Carbonate end member. The simulated dissolved manganese concentrations decreased with increasing proportions of groundwater derived from the Red River Carbonate and only exceeded CDWQ AO of 0.02 mg/L when the proportion of water derived from the carbonate aquifer was below 30%. As noted above, iron and manganese naturally exceed CDWQ and MWQSOG aesthetic objectives in the Red River Carbonate. Concentrations of sulphate, sodium and zinc concentrations were simulated to progressively decrease with increasing proportions of groundwater from the Red River Carbonate where concentrations of these parameters are generally lower. Simulated calcium concentrations ranged from 36.4 mg/L to 49.3 mg/L and were generally lower than those for the scenario involving upward groundwater flow. This is because calcite is controlling the mineral equilibrium in the Red River Carbonate aquifer, and it is allowed to precipitate out of solution when it is saturated with respect to calcite.

The impact of the collapse of the Winnipeg Shale on water quality of the Winnipeg Sandstone Aquifer will be negligible, temporary and very localized. Simulated mixing of the Winnipeg Sandstone, Red River Carbonate, and Winnipeg Shale porewater indicated a mixing ratio in the collapsed cavity of 97%, 2% and 1%, respectively, which was developed as described in **Section 4.3.3.1**. The results of the conservative reactive transport model suggest that only selenium may marginally exceed the MWQSOG in the cavity for a short period of time after the collapse. The impact of the collapse on water quality in the Winnipeg Sandstone will be limited to the area around extraction wells because groundwater flow is very slow. Water quality in the cavity will have a negligible impact downstream as its concentration will be gradually diluted and dispersed by groundwater flowing from the recharge area east of the site. The trace concentrations of pyrite in the Winnipeg Shale may oxidize following the reinjection of water with residual concentrations of dissolved oxygen, however reaction rates will be limited due to the low pyrite content and low (finite) dissolved oxygen concentrations in the subsurface. Any acidity released by the reaction will be immediately neutralized by the abundant calcite in the Red River Carbonate fragments that will likely be present in the void.

All samples of Red River Carbonate and Winnipeg Sandstone have NPR values significantly greater than 2, and those samples were classified as non-PAG. Two samples collected from the Winnipeg Shale had NPR values below 2 (1.25 to 1.39) and they were classified as uncertain acid generation potential. The third sample of Winnipeg Shale was classified as non-PAG. Although mineralogy results indicated trace concentrations of pyrite are present in the samples of Winnipeg Shale, ABA test results suggested that the ARD potential was uncertain. The accuracy of the mineralogy or AP measurements should be confirmed by additional sampling to help confirm the quantity and type of sulphide minerals in the Winnipeg Shale.

Shake flask extraction results indicated that the rock types display varied metal leaching potential. Selenium was identified as the main COPI in samples of Red River Carbonate, Winnipeg Shale and one sample of Winnipeg Sandstone. Arsenic and uranium were identified as marginal COPI in one sample of Winnipeg Shale. However, arsenic, selenium and uranium concentrations in groundwater were below or close to detection limits indicating that these metals(loid)s are not elevated in natural groundwater despite laboratory results. Their elevated concentrations in the shake flask extraction leachate are interpreted to be the result of sample preparation for testing that involves crushing of the material followed by continuous swirling of the fluids that often results in excessive leaching.

All waste derived from the Winnipeg Shale and Red River Carbonate should be managed conservatively in accordance with the Waste Characterization and Management Plan. The overall impacts of the Project on water quality have been conservatively assessed, and additional characterization, monitoring and management initiatives are recommended for integration into project operations and post-closure phases in accordance with the Groundwater Monitoring and Impact Mitigation Plan.

8.3 Residual Effects Classification

Residual effects were described after the implementation of effective mitigation, and summarized according to direction, magnitude, geographic extent, duration/reversibility, frequency, and probability of occurrence of the effect occurring. Effective implementation of mitigation measures (Waste Characterization and Management Plan, Groundwater Monitoring and Impact Mitigation Plan, Water Management Plan and Progressive Well Abandonment Plan) is expected to reduce the magnitude and duration of residual effects on groundwater quantity and groundwater quality.

The effect of the project on groundwater quantity within the Local Project Area is predicted to be negative during operations and neutral during post-closure as shown in **Table 8-B**.

Table 8-B. Classification of Residual Effects on Groundwater Quantity

Measurement Indicator	Criterion	Rating / Effect Size (Operations)	Rating / Effect Size (Post-Closure)
Groundwater Quantity	Direction	Negative	Neutral (Positive and Negative)
	Magnitude (Drawdown)	2 m in Red River Carbonate 2.5 m in Winnipeg Sandstone	Negligible
	Geographic Extent	Local	Local
	Duration	Temporary	Permanent
	Reversibility	Reversible	Permanent
	Frequency	Periodic	Continuous
	Probability of Occurrence	Certain	Certain

The overall quantity of groundwater within the maximum disturbance footprint is preserved. Although the project will utilize groundwater, there are plans to reinject the majority of the surplus water into the aquifer after appropriate treatment. Even without any reinjection of water, the impacts are limited in extent, and local impacts on groundwater users can likely be avoided or resolved through lowering of pumps or provision of alternate supply during operations. Measurable impacts to groundwater quantity are simulated to end within 60 days after project operations cease each year. Sand extraction will impact aquifer storage properties and recovery times will be up to four (4) times longer than presently simulated based on the difference between the porosity of the sandstone (est. 25%) and the combined volume of water and solids removed during pumping. Water levels were simulated to decline a negligible amount (<0.5m) due to the locally elevated porosity of the system if recharge does not increase in response to drawdown within the underlying aquifers. Because the groundwater recharge rates were assumed to be fixed (constant) for the purposes of this assessment, observed drawdown may be less that simulated. A robust and proactive Groundwater Monitoring and Impact Mitigation Plan will be implemented to monitor and address any impacts in advance of issues.

The effect of the project on groundwater quality within the Local Project Area is predicted to range from positive to negative during operations and positive to negative during post-closure as shown in **Table 8-C**. The residual effects on groundwater quality were primarily evaluated based on measured and simulated concentrations of selenium, uranium and arsenic, which are the primary COPI. Additional consideration was given to iron and manganese.

The overall quality of groundwater within the maximum disturbance footprint is largely preserved. Residual concentrations of dissolved oxygen in the aquifer may improve water quality by reducing concentrations of iron and manganese through precipitation. Interconnection of the aquifers is not anticipated to result in material changes to groundwater quality due to the presence of neutral to downward groundwater gradients and freshwater quality in the Red River Carbonate and Winnipeg Sandstone aquifers. Interconnection of the Red River Carbonate and Winnipeg Sandstone aquifers is not anticipated to result in material changes in water quality within the Local Project Area because both aquifers contain fresh water within the Local Project Area and Regional Project Area, and the collapse of the shale will have a very localized and minor effect on selenium concentrations. Hydraulic gradients are likely to equilibrate following recovery and any exchange of water and COPI between the aquifers will be very small. Even though changes in water quality may range from negative to positive, the magnitude of change is anticipated to be small. Some concentrations were simulated to decrease, while others may increase without impacting the potability of water in both aquifers. Naturally elevated concentrations of dissolved iron and manganese that exceed aesthetic water quality objectives were simulated to persist during and following operations as they would in the absence of this Project.

Table 8-C. Classification of Residual Effects on Groundwater Quality

Measurement Indicator	Criterion	Rating / Effect Size (Operations)	Rating / Effect Size (Post-Closure)
Groundwater Quality	Direction	Positive to Negative	Neutral
	Magnitude	Small changes in concentrations	Neutral
	Geographic Extent	Maximum Disturbance Footprint	Maximum Disturbance Footprint
	Duration	Temporary	Permanent
	Reversibility	Reversible	Irreversible
	Frequency	Periodic	Continuous
	Probability of Occurrence	Certain	Certain

8.4 Prediction Confidence and Uncertainty

The groundwater flow system within the Project Site is well understood and AECOM has applied industry standard methods to interpret geology and evaluate the impacts of project operations on groundwater quantity and quality. Site-specific field investigations have been undertaken to characterize conditions in the vicinity of the project and inform the numerical modelling evaluations. However, subsurface conditions and groundwater flow are variable in space and time, so a robust uncertainty analysis and sensitivity analysis was undertaken to evaluate the impact of alternative operating scenarios and variability in input parameters on the conclusions presented herein. The results are consistent with the results of the 2020 field investigation and are anticipated to bracket the range of possible outcomes. Sources of uncertainty and efforts to minimize uncertainty are as follows:

- Hydrostratigraphic Interpretations: A continuous hydrostratigraphic surface was developed for the groundwater model based on kriging geological contacts at borehole and monitoring well locations. Lithology at borehole and monitoring well locations is specific to that location and some uncertainty is introduced when a continuous hydrostratigraphic surface is generated from data at discrete locations. Hydrostratigraphic uncertainty was managed by conducting a thorough review of available hydrogeological information and literature, following standard groundwater modelling practices, and making hydrostratigraphic inferences based on available geological data collected from hundreds of boreholes and water supply wells. Boreholes contained in the GIN database are mapped to the centre of each section or quarter section and the true coordinates of each well may be up to 600 m away. Furthermore, public well databases are known to be incomplete and field surveys should be completed to confirm the location and completion details of all groundwater wells.
- Availability of Hydrogeological Data: Borehole data, groundwater elevation data, hydraulic testing data, and surface water quantity data may be concentrated or absent from many areas of the Project Site and subsurface layers. For example, there is a limited data set for select areas of the groundwater model domain where historical subsurface investigations have not been conducted (e.g. Sandilands Area). Interpretation, inference, and historical data and literature were used to fill data gaps. Furthermore, the accuracy of hydrogeological data that were collected may be influenced by data collection methods and performance of equipment. Quality assurance and quality control was completed for measured hydrogeological data so that values seem reasonable.
- Groundwater Model Calibration: While the groundwater model reasonably simulates groundwater elevations (with acceptable statistical measures), equifinality, or non-uniqueness, may be introduced by groundwater modelling. Equifinality, or non-uniqueness, is the ability to achieve a similar simulated result with a different combination of input parameters. This uncertainty was managed by following industry standard practices for geological modelling and numerical groundwater modelling, including incorporation of information derived from a large body of academic research, long-term monitoring and conducting a robust scenario analysis, uncertainty analysis and sensitivity analysis. Conservative assumptions were adopted, and the range of possible outcomes was bracketed. The location of groundwater supply wells has not been accurately mapped using GPS survey equipment, so the exact magnitude and timing of any impacts may vary based on proximity to extraction wells. Boundary conditions that specify recharge and discharge were based on a combination of academic research and professional judgment, resulting in a very conservative model that likely overpredicts drawdown, and underpredicts recovery of water levels. Although groundwater use has not been directly measured and a water balance has not been established for the aquifers, a robust Groundwater Monitoring and Impact Mitigation Plan will be developed to confirm the results of this assessment, ensure project operations do not unduly impact surrounding groundwater users and address any impacts on well yield and the availability of water near operating extraction wells.
- Heterogeneity and Scale: Many hydrogeological processes occur at scales of centimetres to metres, but hydrogeological characterization and regional groundwater flow modelling reflect a larger scale of hydrogeological behavior. Groundwater modelling focused on refining the regional groundwater model as much as practical while incorporating local scale information.
- Performance of Mitigation Measures: The assessment generally assumes that mitigation measures operate efficiently. However, for our base case assessment we have assumed that groundwater reinjection does not occur and that groundwater is discharged elsewhere. While this will not be the case, it provides a conservative basis for assessment of groundwater impacts to nearby well users. For example, the ability to reinject the majority of groundwater into extraction wells has not been tested for full scale operations, and pumping rates and reinjection efficiency may vary over time. Uncertainty in performance of mitigation measures was managed by conservatively assuming a reduced reinjection efficiency in the groundwater quantity assessment. The planned scenario involving reinjection of all groundwater is presented for comparative purposes, but the hydrogeological impact assessment for groundwater quantity is based on a hypothetical conservative (i.e. 'worst-case') scenario involving zero reinjection of water. The performance of the systems will be closely monitored as described in the Groundwater Monitoring and Impact Mitigation Plan and Water Management Plan, which will be developed during licencing. Monitoring data will be routinely evaluated to determine if there are performance issues associated with mitigation measures.

- Geochemical Interpretations: Geochemical conditions for solid phase and aqueous phase data were interpreted based on limited number of samples (3) for each formation and aquifer. However, the laboratory tests indicate that the geological and geochemical conditions may be variable spatially across the site, and the concentrations of pyrite minerals in shale unit require additional investigation. The geochemical source terms usually represent the greatest source of uncertainty in geochemical modelling, as many of the source terms are based on small volumes of sediments and laboratory experiment conditions are not representative of field conditions. Geochemical uncertainty can be minimized by conducting a thorough review of available geochemical information and literature, following standard characterization and modelling practices, and making inferences based on available geological data. This uncertainty will be addressed through additional characterization during early project operations including additional solid phase testing and measuring water quality in the cavity after the collapse of the Winnipeg Shale unit. There are a range of mitigation measures that can be applied to effectively mitigate any potential ML/ARD at the site as described in the Waste Characterization and Management Plan. Groundwater monitoring will be implemented to monitor the effectiveness of ML/ARD mitigation measures and identify any further actions that required to address unexpected conditions.

8.5 Follow Up Mitigation and Monitoring

The project is located in an area where groundwater is used for drinking water purposes and the impacts of the project on groundwater quantity and quality should be monitored and evaluated in advance of, during and following project operations.

To confirm the results of this hydrogeological and geochemical assessment, guide the appropriate management of materials (waste and water), and protect groundwater users, the following mitigation and monitoring measures should be implemented:

1. Waste Characterization and Management Plan: This document focuses on expanding the dataset for geochemical interpretations and validating the conclusions of the geochemical assessment and the mitigation and management of ML/ARD. It was developed by a senior geochemist with specialization in ML/ARD to guide necessary supplemental characterization, management and monitoring of geologic waste materials generated during project operations. It is consistent with industry guidance pertaining to the characterization and management of waste materials to prevent, manage and mitigate ML/ARD risks. It relies on the collection and characterization of drill cuttings during early operations to better evaluate the geochemical behaviour of each rock type. The plan provides an adequate assessment and management framework to ensure each material type is managed in a way that is protective of groundwater quality and consistent with industry standard methods (MEND 2009)

2. Water Management Plan: This document will present a refined water balance for the extraction and reinjection/treatment of groundwater following additional testing to refine the solid/liquid ratio and the volume of water required to commission and decommission the conveyance system each year. The overall purpose will be to confirm the operational efficiency for groundwater reinjection and identify groundwater disposal or source areas to balance water supply and demands. It will specify elements that require ongoing monitoring to confirm pumping rates, groundwater use, reinjection rates, etc.

3. Progressive Well Abandonment Plan: This document presents an operational plan for progressive closure of each extraction well to ensure groundwater resource remains protected. It was developed in a manner that is consistent with industry standard practice and meets or exceeds the requirements of the Manitoba Groundwater and *Water Well Act* and its supporting regulations, including the Groundwater and Water Well Regulation and the Well Standards Regulation. It also meets borehole abandonment requirements of *The Mines and Minerals Act* and borehole licences issued under Part 3 of the Drilling Regulation. The Manitoba *Water Rights Act* prohibits connecting two aquifers within a single well completion to minimize hydraulic communication between saline and freshwater portions of drinking water aquifers and the well abandonment plan will be developed to meet that requirement even though inter-aquifer mixing within the Project Area would involve mixing of two fresh water sources until water levels in each aquifer equilibrate.

4. Groundwater Monitoring and Impact Mitigation Plan: This document establishes a framework for survey of existing domestic wells in advance of operations, monitoring of groundwater quantity and quality during and following project operations and responding to well owner complaints. It establishes the parameters that will be monitored, the frequency of monitoring, monitoring locations and reporting requirements. Mitigation

measures will be developed to avoid and/or mitigate any well interference issues as required by the Manitoba *Water Rights Act*. Mitigation measures would be specific to each complaint, and may include lowering of pumps, provision of alternate water supply or adjustment of operations. Findings will be reported to the community on a regular basis. This may also involve specific studies to confirm boundary conditions (e.g. recharge) for the groundwater model.

Implementation of the above-recommended plans are expected to mitigate potential adverse effects on groundwater quantity and quality. The plans outline follow-up adaptive management measures that will be implemented in consultation with Manitoba Conservation and Climate, Environmental Assessment Branch should any unforeseen adverse effects on groundwater occur beyond an acceptable threshold or regulatory guidelines.

9. Conclusions

9.1 Groundwater Quantity

Overall, groundwater quantity will be largely preserved within the Project Area due to the seasonal operation of sand extraction wells and reinjection of surplus groundwater following separation of solids. Although the spatial extent of the drawdown is anticipated to be laterally extensive, the magnitude of drawdown impacts is anticipated to be generally under 5 m for the majority of the licensed water supply wells. Impacts of this magnitude will not require any mitigation if well pumps are installed at depths of greater than 5 m below the piezometric surface. Consistent with the results of field testing, water levels were simulated to recover relatively rapidly, with relatively rapid recovery of groundwater levels following the end of production at each well cluster. Groundwater levels are anticipated to return to near static water groundwater levels within approximately 60 days of the end of production at each well cluster.

A three-dimensional geological model was translated into a three-dimensional regional scale groundwater model using FEFLOW software following industry-standard practice. The model was calibrated to measured steady-state and transient groundwater elevations using aquifer properties within the range of historical measurements reported in the literature. Calibration statistics were consistent with industry standard practice for groundwater modelling.

With re-injection of 42.5% of groundwater during the five-year operational period, the largest 1.0 m drawdown contour in the Winnipeg Sandstone aquifer was simulated to extend to a maximum of 270 m from the active sand extraction wells. In the Red River Carbonate aquifer, the largest 1.0 m drawdown contour was simulated to extend a maximum distance of 320 m from the active extraction well clusters, which coincided with simultaneous operation of four well clusters. The maximum simulated drawdown at the selected observation points was 2.5 m in the Winnipeg Sandstone and less than 2.0 m in the Red River Carbonate.

Observation wells located in the center of the extraction wells (e.g., G05SA014/015) consistently experience a decline in water levels throughout the operational period. The maximum drawdown observed for these wells is generally less than 2 m. Groundwater levels were shown to recover to within 0.5 m of pre-development groundwater elevations following the end of project operations.

Generally, the drawdowns are not continuous across the entire mine plan area as the drawdowns associated with each pumping well tend to recover while the extraction moves to a different location. Rather, they are concentrated around the active extraction wells for a short period of time during and immediately following extraction. This suggests that drawdowns from the preceding extraction period sufficiently recover and limit the expansion of the drawdown cone following short-lived extraction activities. Simulated groundwater levels at observation points return to near static water level conditions within 60 days after production ceases each year. Removal of solids will change the aquifer properties within the void created by sand removal and complete recovery may take longer in proximity to sand extraction wells. Although minor changes in groundwater levels may occur, the overall quantity of groundwater is anticipated to be similar to, or greater than present. The volume of groundwater recharge and discharge are assumed to be relatively unaffected by project operations. Only the local aquifer properties will change, but the increase in porosity will allow for more groundwater to occupy the pore space within the voids created by sand removal.

These simulation results are consistent with the results of the 2020 field investigation that observed relatively minor drawdown in residential water supply wells, but well yield was not impacted, and impact mitigation was not required. The majority of domestic water supply wells are completed in the Red River Carbonate and will be impacted to a much lesser degree by sand extraction from the underlying Winnipeg Sandstone.

Pumps installed near the piezometric surface may need to be lowered if the well is within the drawdown cone (i.e. within 1,000 m) associated with operating sand extraction wells or an alternative supply will need to be provided. Potential impacts, which would be temporary and reversible, would be limited to the period during and immediately following project operations at each extraction well cluster.

A Water Management Plan will be developed and the Groundwater Monitoring and Impact Mitigation Plan will be implemented to monitor groundwater extraction/injection and water levels within the aquifer surrounding the Project Area and mitigate any impacts to surrounding wells.

9.2 Bedrock Geochemistry and Waste Management

Based on the results of the hydrogeological and geochemical assessment, with the application of industry standard mitigation measures as per a Waste Characterization and Management Plan, material impacts to groundwater quality are unlikely. Over 81% of the waste material extracted during drilling during the five year operational period will consist of glacial sediments similar to those exposed at ground surface within the Project Area today. A much smaller fraction of the waste material will be comprised of bedrock cuttings from the Red River Carbonate (15%) and Winnipeg Shale (4%). The Winnipeg Sandstone will be processed and sold as a commercial product and is therefore not considered to be waste.

Although evidence of pyrite has been noted in mineralogy testing results for the Winnipeg Shale, visual core inspection did not find evidence of sulphide mineralization. Laboratory testing of Red River Carbonate, Winnipeg Shale and Winnipeg Sandstone indicates the Red River Carbonate and Winnipeg Sandstone are classified as non-potentially acid generating. However, some of the Winnipeg Shale samples were classified as 'uncertain'. Therefore, all waste material will be conservatively managed in a manner that is protective of groundwater quality. All drill cuttings and overs resulting from the extraction and processing activities will be hauled from the Site and disposed of in a licensed facility.

Although some trace metals reported elevated concentrations in shake flask test results, the parameters are present at low to non-detectable concentrations in groundwater suggesting they are not likely to appreciably affect water quality.

Overall, waste materials including bedrock can be safely managed by conducting additional testing of bedrock core and/or cuttings to confirm ML/ARD potential and guide management of waste cuttings prior to or during the early operations phase. This approach is routinely applied in the mining industry, whereby samples are collected from production boreholes for laboratory testing.

The Waste Characterization and Management Plan will be implemented to further characterize waste materials and direct their management and use to protect groundwater quality.

9.3 Groundwater Quality

Groundwater quality is very good in both the Red River Carbonate and Winnipeg Sandstone aquifers as well as within the Winnipeg Shale aquitard. However, naturally elevated concentrations of iron and manganese exceeded drinking water aesthetic criteria as is commonly found in natural systems and within these aquifers.

Overall, material impacts to groundwater quality within the Project Area are unlikely because both the Red River Carbonate and Winnipeg Sandstone host fresh and relatively dilute groundwater. Based on the results of geochemical assessment and modelling, the activities associated with project operations and post-closure phases of the project were determined to have no material impact on groundwater quality. In many cases, the impact was simulated to be positive due to reduction of concentrations of iron and manganese when oxygen is introduced into the aquifer which in turn favor the co-precipitation of metals(loids). Should project operations result in a more interconnected aquifer system comprising the Red River Carbonate aquifer and the underlying Winnipeg Sandstone aquifer in extraction areas, groundwater quality would tend to reflect conservative mixing of the two water types with a trend generally towards the water quality of the Winnipeg Sandstone aquifer.

In addition, the collapse of a section of the Winnipeg Shale and Red River Carbonate in the cavity formed in the Winnipeg Sandstone following the sand extraction is likely to occur. Water quality within the void may temporarily exhibit slightly elevated concentrations of selenium and manganese caused by dissolution of minerals and following the physical collapse of the overlying Winnipeg Shale and a small portion of the Red River Carbonate. The assessment and modelling of the impact of the collapse of the overlying materials on the water quality of the Winnipeg Sandstone aquifer show that the concentrations of arsenic, selenium, and uranium will decrease and remain below the Manitoba and Canadian Drinking Water Quality Guidelines. While arsenic and uranium concentrations will remain below these guidelines in the void as well, selenium concentrations will remain slightly above Manitoba water quality in the void for approximately seven years after the collapse, until they decline below the Manitoba water quality standard. The lateral migration of the water quality temporarily impacted by the collapse in the void is very slow and will have a significant amount of time to stabilize (re-equilibrate) which will minimize the effect on the water quality in adjacent and downstream portions of the aquifer.

Although the injection of water containing residual dissolved oxygen will reduce concentrations of iron and manganese in the vicinity of extraction wells, it is not anticipated to induce ML/ARD reactions due to the very low to absent concentrations of minerals prone to oxidation (i.e. pyrite and pyrrhotite) coupled with low and finite concentrations of dissolved oxygen in subsurface groundwater and re-injected water. This is supported by the presence of very good water quality in both aquifers today. The vertical gradients between the two aquifers are downward and near neutral such that the magnitude of any inter-aquifer exchange during and following project operations is likely to be small.

A Waste Characterization and Management Plan and Groundwater Monitoring and Impact Mitigation Plan were developed and will be implemented to protect groundwater quality and guide responses to any potential impacts. A comprehensive vulnerability analysis demonstrated that small declines in simulated groundwater levels within the Winnipeg Sandstone as observed at the end of project operations (maximum vulnerability) result in relatively minor and local scale increases in aquifer vulnerability following the modified DRASTIC method. Even for this time period of maximum downward gradients (and hence vulnerability), there are other areas of the aquifer that have been and will continue to be more vulnerable to surface contamination as they are not protected by overlying fine-grained (low permeability) units and are associated with areas of groundwater recharge. It is noteworthy that the deep Winnipeg Sandstone aquifer will remain protected by thick and low permeability glacial sediments and separated from ground surface by the Red River Carbonate aquifer and residual intact portions of the Winnipeg Shale. As such, a Progressive Well Abandonment Plan will limit hydraulic communication between the Red River Carbonate and the Winnipeg Sandstone by plugging boreholes upon completion of sand extraction from each well.

Implementation of the monitoring and management plans discussed herein are expected to mitigate potential adverse effects on groundwater. The plans will outline follow-up adaptive management measures that will be implemented in consultation with Manitoba Conservation and Climate, Environmental Assessment Branch should there be any unforeseen adverse impacts on groundwater (i.e. beyond an acceptable threshold or regulatory guidelines).

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