Manitoba Clean Environment Commission
305-155 Carlton Street
Winnipeg, Manitoba

R3C 3H8 CANADA

Technical Review

Sio Silica Corporation's
(formerly CanWhite Sands Corp.)
Environment Act Project Proposal

dated
19. September 2022

Preamble

As requested, we have reviewed the report "Appendix A, Hydrogeological Assessment Final Report, dated July 2021 by AECOM Canada Ltd". Hereinafter, we will refer to this report as "HAFR". This material was submitted by Sio Silica Corporation (the "proponent", formerly CanWhite Sands) in support of silica-sand mining plans near Vivian, Manitoba. We have attempted to only focus on main concerns related to physical and chemical hydrogeology and the discussion herein is not meant to be all encompassing. This document may not contain sufficient information for other parties or for other purposes.

Non-technical Plain Text Summary

The following is a non-technical plain text summary. The reader is strongly encouraged to read the more complete technical-executive summary, the details within this report and our comments that are summarized at the end of each section.

1. The proposed project area in eastern Manitoba is extensive and involves many pumping wells over a long period of time. The work described in the proponent's proposal only refers to a four-year planning horizon with about 1680 wells but ultimately could result in over 10,000 wells over 24 years. The proponent needs to fully describe the entire 24-year development and its likely effects.

2. The wells described above will tap into large underground water bearing zones, called aquifers. One of the aquifers (sandstone) is to be extensively mined with a new and unproven technology. Hence, it is important to be cautious and identify areas of concern that could affect existing water well users and communities in the future that rely on these aquifers. The potential impacts are many and not all the relevant issues were identified and resolved with the work described in the proposal. For example, potential impacts include release of potentially health impacting substances from the shale formation into aquifers which is used for drinking water purposes.

3. The effects of removing sand from one of the main aquifers and its subsequent effect on the overall properties of the aquifer (locally and regionally) is not considered and this will likely be significant. Unfortunately, there are no estimates of this effect given in the report and no testing of the main sandstone aquifer after mining out a section. The effects on potential future water-well users in areas that have been disturbed by mining is not considered.

4. As an aid to judgement various hydraulic tests were conducted to fill in data gaps and provide input parameters to a computer model. One hydraulic pump-test was

completed in the sandstone aquifer, but analysis of the data suggests that the pump test need to be redone. More importantly, the project area is crudely estimated at 168,000 hectares and only one pump test was competed that tested about 460 hectares. Basically, more and better-quality testing needs to be performed.

5. A computer model was constructed over a large area in eastern Manitoba that included the project site. There are some problems noted with respect to the modeling. These issues are detailed in the main text and are related to the conditions imposed on the boundaries of the numerical model. In addition, there are numerous wells to the east of Winnipeg that are screened and connected over both main aquifers. It is not clear if these physical effects in the proponent's model were accounted for. Numerical models of geologic reality need to be compared to what data can be measured in the field. This "calibration" to an existing data set for water levels is crucial and has been attempted. However, there is insufficient detail given in the report to assess if an appropriate calibration has been achieved. There are no times or dates listed for the observation points and some suggested-statistical tests are missing. Most importantly, calibrated final hydraulic parameters from the proponent do not match with the actual well test data. The proponents also assumed that material properties were the same everywhere in each geologic unit in the model which goes against known understanding of the regional geology. Analysis suggests that the hydraulic parameters used in the modeling need to be reassessed.

6. Note that predictive computer simulations may be used to estimate the effects of mining an aquifer. However, all conclusions listed in the model simulation discussion rely on an assumption that the mining operation does not affect the hydraulic properties of the sandstone aquifer and hence cannot be viewed as being conservative or even appropriate.

7. There is a shale layer that separates the two main aquifers and helps to preserve water quality and separate hydraulic pressures and chemistry. The proponent notes that degradation of this shale layer may occur because of project operations which

would result of more direct communication between the two main aquifers: Winnipeg Sandstone and the Red River Carbonate. This is a crucial risk to the operation.

8. The analysis for chemistry changes within the aquifers was carried out at one location only and limited samples were taken. None of the analysis investigated groundwater quality changes due to the mining operations. The worst-case should be defined as the collapse of the shale barrier mentioned above. Any impacts related to groundwater quality are not investigated. The goal regarding water qualify was also somehow unclear, as the report recommends a water quality study which should have been finalized at this point.

Technical Executive Summary

The following is a technical executive summary. The reader is strongly encouraged to read all the details within this report and our comments summarized at the end of each section. PorousTec Ltd. was asked to comment on hydrogeological and geochemical aspects of the Sio Silica Corporation's (formerly CanWhite Sands Corp.) Environment Act Project Proposal. Based on a detailed review of the information provided, the following summary is made.

1. One of the stated purposes of the hydrogeological investigations is to evaluate the potential for the project to impact groundwater quantity, quality and users of the surface and groundwater in an area east of Winnipeg, Manitoba. Since the project area is extensive and involves many wells pumping over a long period of time it is important to identify areas of concern that could affect existing water well users and communities in the future. Hence, there is a need to assess the impacts of pumping and development on the aquifer structure, extent of drawdown cones, impacts on existing users, intrusion of water of questionable quality, subsidence and potential pathways connecting the limestone and sandstone aquifers. Not all of these aforementioned issues were identified and resolved with the work described below.

2. The proponent used a well-known and well-supported computer model, FEFLOW, that can account for the three-dimensional nature of the groundwater flow and many of the primary physical effects at the site. However, salinity induced density-dependent flow is something that is well understood and the majority of the flow and transport in the aquifer systems to the west of Winnipeg, and parts of the study area to the east are affected with this physical problem. Kennedy (2002) incorporated these density effects in her extensive three-dimensional model of the aquifers in southern Manitoba but the proponent did not. It is important for understanding the possibility of movement of more saline waters from the west of the Red River moving into and contaminating fresh-water portions of the sandstone aquifer.

3. The simulations presented by the proponent only refer to a 4-year planning horizon. They also refer to 1680 wells over a four 4-year horizon which could total more than 10,000 wells over 24 years. It would be very prudent for the proponent to fully describe the entire 24-year development and its likely effects.

4. Although there are schematics of the extraction wells and sub-surface geology there are no engineering drawings with the accompanying dimensions of cavities produced from the mining. There were no independent measurements of formation porosity given.

5. The effects of removing sand from the aquifer and its subsequent effect on the overall hydraulic properties of the main sandstone aquifer (locally and regionally) is not considered and this will likely be significant. Unfortunately, there are no estimates of this effect given in the report and no testing of porosity either before or after mining a section of the aquifer. It also assumes that the sandstone bridging material remains intact but does not mention if the sandstone itself may liquify and flow into the voids that are created by the mining operation. The effects of potential future water-well users in areas that have been disturbed by mining is not considered.

6. The proponent notes that degradation of the Winnipeg Shale layer may occur because of project operations which would result of more direct communication between the Winnipeg Sandstone and the Red River Carbonate. This is a crucially important risk of the operation.

7. There was no testing at a pilot-project site in which the aquifer was actually mined out and drawdowns were measured at various locations from a producing well cluster. This is another critically important point.

8. Hydraulic tests were completed in the main sandstone aquifer at the site but analysis of the data suggests that the pump tests should be re-run and the test data re-

interpreted. Drawdown data suggests a leaky connection between the two main aquifers and importantly the test methods should allow for a calculation of the leakage properties of the shale layer that separates the main aquifers.

9. The lithology at the site is described by the proponent in their conceptual model in terms of large zones and/or layers representing homogeneous aquifers and aquitards. However, there is considerable information on material heterogeneity not considered by the proponent. Certainly, if there is any information available at the site on heterogeneities, this should be considered in the numerical model.

10. There are some problems with respect to the boundary conditions in the numerical modeling. These issues are detailed in the main text. For the groundwater flow equation, these concerns are related to the conditions imposed on the boundaries of the numerical model. In addition, there are numerous wells to the east of Winnipeg that are screened over both of the main aquifers. It is not clear these if physical effects were accounted for.

11. Calibration to an existing data set for hydraulic heads has been attempted. However, there is insufficient detail given in the text to assess if an appropriate calibration has been achieved. There are no times or dates listed for the observation points and some suggested-statistical tests are missing. Most importantly, calibrated final hydraulic parameters from the proponent do not match with the actual well test data. Analysis suggests that the hydraulic parameters used in the modeling need to be reassessed.

12. Boundary condition sensitivity should be addressed in any simulations. Unfortunately, this was not done (with the exception of recharge rates).

13. Note that predictive simulations may be used to estimate the hydraulic response of an aquifer. However, all of the conclusions listed in the model simulation discussion all rely on an assumption that the mining operation does not affect the hydraulic

properties of the sandstone aquifer and hence cannot be viewed as being conservative.

14. The numerical model was used for a series of scenarios involving different pumping rates. These included the case when no water from a pumping cluster is re-injected; so, all water is lost, and the case where 50% of water pumped out is re-injected. Note that it is the proponent's intention to re-inject all pumped water from the aquifer as part of the mining operation so certainly a 100 % re-injection rate would be a theoretical ideal. A perhaps more realistic 50% re-injection rate represents cases where, it is not possible for a variety of reasons to be able to re-introduce water back into the aquifer. If this happens to be realized, it is not clear how this extra water that cannot be re-injected is disposed of or if this amount is sustainable to extract from the aquifers without replacement.

15. The numerical model predicts a maximum drawdown in the sandstone aquifer at 146 m from a producing cluster, under 0% re-injection of water and with no interconnection between aquifers, to be about 14 m. One scenario not considered is the case of a distance of 100 m from a pumping cluster (closest planned distance to nearest supply well) at 225 USGPM (50% re-injection). Based on a well-known hydraulics formula, this drawdown would be about 12 m after 72 hours. This amount, if realized, exceeds the stated the magnitude of the groundwater impacts of between 1 m and 5 m for the majority of the water supply wells.

16. The analysis for acid mine drainage, aqueous geochemistry and stable isotopes were carried out at one location only and limited samples (e.g., related to acid mine drainage) were taken. None of the analysis investigated groundwater quality changes due to the mining operations. The worst-case should be defined as at the collapse of the Winnipeg Shale. Any impacts related to groundwater quality are not investigated. The goal with regard to water qualify was also somehow unclear, as the report recommends a water quality study which should have been finalized at this point.

I Table of Content

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1 Project Scope and Objectives

One of the stated purposes of the hydrogeological investigations is to evaluate the potential for the project to impact groundwater quantity, quality and users of the surface and groundwater in an area east of Winnipeg, Manitoba. Since the project area is extensive and involves many wells pumping over a long period of time it is important to identify areas of concern that could affect existing water well users and communities in the future. Hence, there is a need to assess the impacts of pumping and development on the aquifer structure, extent of drawdown cones, impacts on existing users, intrusion of water of questionable quality, subsidence and potential pathways connecting the limestone and sandstone aquifers. Not all of these aforementioned issues were identified and resolved with the work described below.

1.1 Proposed Development

Sand extraction is to be carried out over an extensive area east of Winnipeg, Manitoba. The area is crudely estimated to be 168,000 hectares at a maximum depth of 25 m below the top of the Winnipeg Formation Sandstone (WFS). This development would impact about 4.5% of the entire areal extent of the conceptual model (about 3.8 million hectares). Sand mining is not planned within a 100 m buffer around existing homes and water supply wells. The pattern of the extraction cones across an entire extraction area, and stability, is expected in accordance with their geotechnical model (Stantec, 2022). Unfortunately, that model is not specified nor is the exact design of an individual cavity mentioned (see below). According to the proponent, the magnitude of the groundwater impacts is anticipated to be between 1 m and 5 m for the majority of the water supply wells.

Annual production rates are estimated at 1,360,000 tonnes of sand to be exacted from a series of boreholes (clusters) and then processed. Groundwater is to be recirculated by way of the same wells used for extraction. A 24-year total project time is indicated with about 392 wells per year drilled. The mining target is about 51 m to 76 m below ground surface (25 m thick). Note that the simulations presented only refer to a 4-year planning horizon. Specifically, the proponent refers to 1680 wells over a four 4-year horizon but there is no mention of the total number of wells over the entire 24-year planning horizon which could total more than 10,000 wells. It would be very prudent for the proponent to fully describe the entire 24-year development and its likely effects.

An illustration of the extraction wells and horizontal layout patterns is shown on page 21 of the HAFR. Groups of 7 wells per cluster are 60 m from the outside of cluster to the nearest group. (The report text says 22 m apart for each well in a cluster but drawing says 18 m.) As mentioned, extraction is not to occur within a 100 m buffer zone around existing homes and supply wells. Each well will be operated for 4 days at 40 USGPM to 120 USGPM with a combined rate of 540 USGPM per well cluster (see Appendix H). The majority of water is expected to be reinjected with about 10 USGPM lost to residual moisture content. It is not clear if this is from each well or per cluster. Each well cluster can produce 21,000 tonnes of sand over its lifetime. One can then make an estimate of cavity dimensions based on an assumed porosity of WFS. However, there is no available data on porosity and is only mentioned once in the report as an assumed value.

2 Method of Analysis

A standard approach of a site hydrogeological investigation was carried out as part of the overall mining plan and assessment. These steps consist of: compiling existing data, (in the forms of published papers, government reports, maps and so on), carry out necessary field investigations to support an analysis, and development of a hydrogeologic conceptual model. After these steps are completed a mathematical-groundwater model of some kind is warranted depending on the level of sophistication required.

Also, a typical approach in groundwater modeling should be followed. These steps normally consist of "*model testing, model evaluation, model calibration, and sensitivity testing, benchmarking, history matching, prediction and parameter estimation*" (Konikow and Bredehoeft, 1992). The proponent tended to adopt the specific terms "steady state calibration, transient calibration, results, predictive scenarios and sensitivity". So, therefore there are some important phases of the analysis that should be completed in the future in order to publicly defend the model.

Similarly, a standard approach of a site geochemical investigation was carried out as part of the overall mining plan and future impacts of the mining activities. Geochemical aspects have been investigated related to sampling, laboratory analysis, and geochemical modelling so that the current conditions can be characterised and that groundwater quality after the mining activities can be projected. This is critical since the groundwater is being used for drinking water purposes.

3 Hydrogeological Investigation

3.1 Compilation of Hydrogeologic Data

An important aspect of any hydrogeologic investigation is the compilation of existing data, local knowledge and experience that pertains to a particular site. This gathering of data includes obtaining information related to location of existing water wells, pumping rates, water levels, hydraulic testing, past numerical modeling, well tests, and so on. This compilation is adequately described in Section 3 of the Hydrological Assessment Final Report (HAFR) which is Appendix A of the Environmental Act Proposal. A significant amount of local and regional surficial geologic information is available.

A bibliography is listed at the back of the report in Section 9. The list of references is extensive with the exception of Kennedy and Woodbury (2002) and (Ferguson et al., 2003). The detailed geostatistical work on the major aquifers (esp. Carbonate and Sandstone) in southern Manitoba (Kennedy and Woodbury, 2002) and the work by Ferguson et al. (2003) on estimating recharge rates to sandstone aquifer using temperature logging may have been useful to the proponent in their analysis and revisions to their model.

3.2 Site Investigations

The purpose of these new investigations is indicated at the top of page in section 3.1. “to fill in data gaps “, but these gaps are not specifically identified. Under section 3.4.1 there is a description of the drilling wells and monitoring points that were installed. Each borehole was completed as a monitoring well. Well 96-2 was competed into the carbonate aquifer and 95-9 into the shale and 95-6 and 96-1 into the Winnipeg Formation Sandstone (WFS). Hole 95-7 was installed as a pumping well. This well was developed but preliminary well yields were a problem, and this indicates poor well efficiency. *As* *mentioned by Betcher et al. (1995) wells in the sandstone that are not screened are subject to collapse.*

These new boreholes were tested for hydrologic parameters. Aquifer single well response testing, (actually slug tests) were analyzed with an extension of the Bouwer-Rice method for confined aquifers. Hydraulic conductivity, K values are indicated in Table 3-A. A geometric mean K at 5.7×10^{-5} m/s is listed for the Winnipeg formation sandstone (WFS). Note from later HAFR pump tests (see below), K was determined to be 1.1×10^{-4} m/s. So, these first round tests differ by a half order of magnitude from the well tests*.* *This difference should be reconciled.* Storativity (S) values are not available from these tests above and are helpful in planning out pumping tests.

Formal pump testing at one well was carried out next and this test consisted of a brief step-test and then a constant pump test for 72 hours. The step-test was run at unusual intervals of 412 to 402 USGPM, to 421, and then finally to 372 USGPM. In general, this limited variation is not considered to be a step-test. The well was not allowed to recover to base levels before the main-constant withdrawal test and the proponent did not attempt to determine hydraulic efficiency of the well. According to (Driscoll, 1986, p.556); see also Walton (1991, p. 139) the recommended procedure is:

(1) measure water levels to determine background levels,
(2) 1-hour trial test to check equipment followed by a 1-hour recovery, then a 3-hour step-drawdown test to determine well losses, followed by a 20-hour recovery,
(3) at least 24hour constant rate test to determine aquifer coefficients and boundary conditions if present, and
(4) 24-hour recovery test to verify results from (3).

In respect of a formal-constant rate pump test and spacing, at least 3 observation wells are desirable; in confined aquifers this would be at about 31 m, 122 m and 305 m (Walton, 1991). In contrast the tests conducted were at 89 m, 333 m and 1210 m. It is recommended that observations be spaced out on one log cycle of paper on the distance axis and this would have helped the interpretation for the distance-drawdown approach. This avoids extrapolating the straight-line portion of the plot to a zero-drawdown intercept. Minor changes in the plot can result in large variations in storativity.

All results are set forth in Appendix E-2. It is obvious from a visual inspection of the plots that sub-optimal fits were achieved. The drawdown data from each well should also have been combined on one plot as t/r^2 on the X-axis and thus all of the observation well responses could have been plotted on one graph (see Kruseman and de Ridder, 1990, p. 64). Data recorded at the pumped well itself reflected a poor well efficiency. Unfortunately, the step-test performed (mentioned earlier) was not sufficient to determine well yields.

Next to the pump test, five slug and bail tests were carried out to characterize the aquifers and the Winnipeg Shale formation. These tests are inadequate for regional identification of aquifer properties. Slug and bail tests have very limited areal extent and have generally high uncertainties. This can be identified by a nearly one order of magnitude difference in hydraulic conductivity in the Red River Carbonate. Slug and bail tests can give some insights into aquitards. However, only one test was carried out in the Winnipeg Shale.

As shown in Appendix E-2 and Table 3-C, hydraulic values for the WFS by different evaluation methods for confined aquifers work out close to $K = 1 \times 10^{-4}$ m/s, with transmissivity $T = 2.2 \times 10^{-3}$ m^2/s, and storativity $S = 1.7 \times 10^{-4}$ [-]. Note Kennedy and Woodbury (2002) from their extensive analysis of all spatial values of hydraulic conductivity, K for the WFS, recorded KG (geometric mean) for the WFS at 2.0×10^{-5} m/s, differing from the aforementioned well tests but closer to the slug tests reported above. In their numerical simulations though, Kennedy and Woodbury (2005) adopted a zoned approach to the K heterogeneity in the sandstone and in the areas to the east of Winnipeg large zones were set from 4×10^{-5} to 5×10^{-6} m/s. Wang et al. (2008) reported an average of 2.4×10^{-5} m/s for the sandstone based on newer drilling and single well tests; very close to mean value identified by Kennedy and Woodbury (2002). Betcher et al. (1995) list values of K at 1.1×10^{-3} to 3.2×10^{-5} m/s for the sandstone.

Similarly, for the Carbonate aquifer, Kennedy and Woodbury (2002) on the basis of 2708 values determine a geometric mean value of K in this aquifer to be 7.3x10^{-5} m/s. Wang et al. (2008) report 8.3x10^{-4} m/s for the carbonate east of Winnipeg.

Basically, the methods of test-analysis assume that the aquifer is being pumped at a constant rate and is completely confined; i.e. there is no leakage through a confining layer. However, one can see from analysis of Figures 3-2 and 3-3 that drawdown was measured in the carbonate aquifer during the test. The amounts were measurable (note 95-8 VW2 of about 1.5 m) so the shale aquitard appears to exhibit leaky conditions. Unfortunately, the well test methods that were used do not allow for a calculation of the leakage properties of the shale layer. It is apparent that in the location of the tests, either the shale is non-existent, cracked and/or pervious or there are wells present that interconnect the aquifers. The discussion in the HAFR text is at odds with all the available data (see p. 32) where it is stated “this information suggests the Winnipeg shale is an effective barrier to interaction between the two aquifers at this location”.

It is unknown as to what effects there were from not allowing the pumped well to recover from the step test before main pumping started, or the interruption of pumping at a later time. The Theis plots (Kruseman and de Ridder, 1990) show small amounts of drawdown at times less than 10 min from well 96-1, that departs from the Theis type curve and indicates more drawdown than should be expected. A possible reason is that the proponent did not wait until the well field had recovered before starting a new test. According to radius of influence calculations (see below) 96-1 should not be reading a response at earlier times than the wells that are closer to the pumping well.

Probably what is most important is that we do not see any testing where the aquifer is actually mined out and drawdown is measured at various distances from a producing cluster. Note that the mining operation will cause permanent changes to the aquifer structure and hydraulics. One can make a crude estimate of changes in hydraulic conductivity, K over a large area as a result of mining. For illustrative purposes only, if a large area was mined (se HAFR Figure 2-B) this could result in a crudely estimated 30% increase in void space over a large area within the sandstone aquifer. Precise estimates cannot be made at this time.

If we use the Kozeny-Carmen relationship (Bear, 1972), which relates porosity to hydraulic conductivity, a 30% increase in n (porosity) results in a change of hydraulic conductivity, K from $1.1x10^{-4}$ m/s (HAFR well tests) to $1.079.6x10^{-3}$ m/s; a one order of magnitude difference. Similarly, changing porosity, n could result in an increase of the storativity from $1.7x10^{-4}$ to $2.2x10^{-4}$, all else being equal.

Note one can estimate a radius of influence from any pumping well without the pumping rate. The Jacob approximation allows us to calculate a “radius of influence” from any producing well, pumping at a constant rate in an infinite homogenous-confined aquifer, in which zero drawdown would be detected at any time. This is $R^2 = 2.25 \times T \times t / S$ where R is the radius of influence and t is the time. Rearranging we can solve for the time, t given the aquifer parameters and the radial distance R. In other words, the first possible time that any drawdown could be theoretically detected at some distance from a pumping well. This gives us a worse case for a radius of influence or effect from any well. For example, in a 24-hour period after a well had started: If the diffusion constant, $D = T / S$ goes from 12.9 to 97.9 m^2/s as a result of a large increase in void space (see estimates in paragraph above), the radius of influence goes from 1.6 km in an undisturbed aquifer to 4.3 km for a disturbed aquifer. This illustrative example just tells us that any drawdown cone in a disturbed part of the aquifer would be greatly increased over pre-developed case, and understanding how mining operates will affect any aquifer hydraulic properties is important. Recovery times from pumping would also be affected and are likely to decrease, not increase.

On a minor note on p. 32, “downward” vertical gradients are mentioned. But we believe the HAFR authors really mean is downward vertical flow. Gradients are a mathematical (vector) quantity and always point in the direction of highest potential (hydraulic head). This term is often used in error even with long-standing professionals.

PorousTec Comment #1:

There was only one pump test to characterise the aquifers. Therefore, no information on heterogeneity inside the aquifers could be obtained. The results of one non-conforming pump test cannot be used to estimate the effects of a mining operation projected to potentially include at least 1680 wells in the short-term and more than 10,000 wells over the 24-year life of the project.

The analysis of the data suggests that the pump test should be re-run and the test data re-interpreted. Drawdown data suggests a leaky connection between the two main aquifers and importantly the test methods should allow for a calculation of the leakage properties of the shale layer. For examples of multilayered aquifer systems see Kruseman and de Ridder (1990).

Slug and bail tests are inadequate for regional identification of aquifer properties.

4 Site Conceptual Model

There are always idealizations and approximations inherent in a groundwater or contaminant transport modeling exercise. Before one can solve a groundwater problem, this idealization must be made and hydrogeologists have to create a simplified geologic picture of a site so that a mathematical model can be constructed. This idealization will include dimensionality, the number of layers, location of any pumping wells, boundaries to the model, steady state vs. transient and so on. It has been realized in recent years that the most prevalent reason that groundwater models fail lies in this area, namely the wrong conceptual model. (Konikow et al., 1997) state that selection of boundary conditions is “probably the most critical step in conceptualizing and developing a model of a groundwater system”. A key to successfully develop a conceptual model is the construction of regional groundwater table maps for each aquifer. Unfortunately, the report misses this step which results in several major issues with the modelling attempt. The boundary conditions should have been derived from these maps instead of surficial drainages which have no or limited impact on confined aquifers. Boundary condition sensitivity should be addressed in any simulations. Unfortunately, this was not done (with the exception of recharge rates).

The conceptual model the proponent adopted consists of a multi-aquifer, three-dimensional, single-phase, saturated porous media. Although this is an impressive list of attributes to be solved for at the Vivian site, it is conceptually and numerically straightforward. The generic numerical tools and data structures have been in place for some time. However, there are significant challenges that remain for implementation of the conceptual model at the Vivian site. The major challenges are in the selection of material properties and appropriate boundary conditions, including the following:

- Basic water level information at some point in time where pumping was minimal is needed to establish when conditions were at equilibrium; these refer to conditions of steady-state (equilibrium) flow.

- At some point in time, we need to have a set of data points in which we can establish a time, t = 0, for the start of any time-dependent simulations These are referred to as *initial conditions.*
- We need to understand which wells in the modeling domain are screened or open over several aquifers.
- We need to know which pumping wells are in operation over the modeling area and what pumping rates are actually in effect.

It is also important to note that:

- The fluid phase is viewed as being "single", i.e. one fluid, but is actually density dependent. Is it possible to decouple the transport of denser, harder waters from the simulations and therefore solve for one set of equations involving hydraulic heads?
- The precise location of existing wells used as observation points can be difficult to ascertain from the water well database.
- The effects of mining out of the sandstone aquifer over such as large areas is likely to have a major impact on material properties of the aquifer. This effect needs to be incorporated into the modeling.
- The fluid-flow regime is coupled to the subsurface stress field because of the effects of mining. Will the remaining sand "fluidize" and flow into regions of the aquifer that have been mined out? Will the overlying shale layer crack and collapse as a result of the void spaces produced?

A conceptual hydrogeological model was developed by the proponent as a result of compilation of all the available reports, papers and so on, and the most recent testing. A three-dimensional perspective is developed and consists principally of the surficial quaternary sediments, and three hydrostatical units of the Red River Carbonates, the Winnipeg Shales and the Winnipeg Sandstone formation. The base to the model is considered impervious.

A geometric domain must be established and is a key in the appropriateness of a groundwater model. The best approach is to gradually expand the model domain, in all directions outward from an area of interest until physical features, such as impermeable boundaries, groundwater divides or lakes and so can be represented as boundaries with their attached physical-mathematical conditions. The domain must be large enough so that local effects are not propagated as far as the boundaries, or at least be considered. In this regard the writers have concerns about the overall dimensions of the model and attached boundary conditions. These conditions will be discussed further in a subsequent section. Suffice to say that the model domain may not be large enough to account for large scale physical effects such as saline water intrusion or long-term sustainability but might be adequate from the point of view of a local pumping-well field. As an alternative geometric domain east of Winnipeg see Phipps et al. (2008).

Of critical importance is the continuous, or discontinuous nature of Winnipeg shale unit and its material properties such as hydraulic conductivity K. It is noted that several wells in the regional project area report no thickness of shale. However, the proponent assumes it is continuous across their study area.

Various material properties of the hydrostratigraphic units are listed but the spatial variability of the Carbonate or the WFS aquifers are not considered. The geostatistical study by Kennedy and Woodbury (2002) is not referenced. Material heterogeneity in K is represented as an equivalent homogenous porous media in each aquifer and hydrostratigraphic unit. As noted by Rubin (2003), there are a host of applications that require simple estimates of say, average discharge over large areas, as a precursor to more detailed calculations. For example, aquifer water balances, and here the concept of effective conductivity is useful. But “any replacement in modeling of a locally heterogenous medium by an effective homogenous one will be incomplete in that the latter cannot describe the variability in hydraulic head at a local scale” (Rubin, 2003). This point is recognized by the proponent but inclusion of these effects is not adopted. The paper by Kennedy and Woodbury (2002) clearly demonstrates that the WFS is heterogenous with a geometric mean transmissivity of 4.1×10^{-4} m^2/s and log standard deviation of ±1.9. This translates into a T range of $5.0x10^{-5}$ to $2.2x10^{-3}$ m^2/s (at one standard deviation) expected in the same aquifer, which should not be considered homogeneous. The same issues apply to the carbonate aquifer. Including heterogeneity in modern aquifer simulations is relatively easy and can be accomplished in a variety of ways including simply contouring, or kriging techniques. Inclusion of heterogeneity in steady-state models (SS) models can produce much better calibrations. See Jiang et al. (2004) for an example of the Edwards aquifer or Kennedy (2002) for flow and transport in southern Manitoba.

The effects of removing sand from the aquifer and its subsequent effect on the overall K of the aquifer (locally and regionally) are not considered and these will likely be significant. This could possibly be an order of magnitude in K (or more) and a large increase in porosity. Unfortunately, there are no estimates of this effect given in the report and no testing of porosity either before or after mining a section of the aquifer. It also assumes that the limestone bridging material remains intact but does not mention if the sandstone itself may liquify and flow into the voids that are created by the mining operation. There is some indication this would occur (Betcher et al., 1995).

Recharge to the aquifer systems occurs through various units but the one that is most important for inclusion is the Sandilands area and Ferguson et al. (2003) showed thermal testing results to be about $2x10^{-8}$ m/s vertical flow. Kennedy (2002) in her thesis used $6x10^{-9}$ m/s over large area and derived this number from calibration, and this is the same value as adopted in the HAFR for the Sandilands area. Wang et al. (2008) referred to recharge from their numeral model at 6.3% of the allotted pumping rates out of the aquifer. Not 7.2% as indicated in HAFR.

The existing water well network measuring gradients in the area are presented in Table 5-B of the HAFR. This table looks at gradients across the carbonate and WFS via the shale marker. Note that as time goes on pressures and heads since 2018 have equilibrated in the two aquifers. The cause for this is unknown but the proponent speculates that new wells open across both units is responsible.

On p. 69 in the HAFR it is stated that it will be "*beyond the scope of the modeling efforts to assess water balance in the context of present and future groundwater use*". Thus, effects of saline water intrusion are not considered. Betcher et al. (1995); Ferguson et al. (2007); Kennedy and Woodbury (2005); Thorleifson et al. (1998); and Wang et al. (2008) all make the point that a major concern for the sustainability (long-term) of the WFS is that of migration of saline waters into freshwater zones east of the Red River and north and south of Winnipeg. The WFS is known to be saline 70 km west of subcrop and concentrations of TDS exceed 2 g/L immediately east of the Red River south of Winnipeg. It appears (Ferguson et al., 2007) that high TDS waters are gradually moving eastwards in response to de-glaciation and are re-salinizing portions of the aquifer that were freshwater. This eastward movement can be easily enhanced by over production in the freshwater zone. These authors note "raises the importance of insuring the segregation of the two aquifers' system during well completion". It is mentioned in the HAFR that the movement of saline waters: "even this small volume of water could dramatically affect local quality over time". This concern is also expressed by Ferguson et al. (2007). These authors used "point water" heads and plots without modeling to examine flow rates. Earlier, (Kennedy, 2002) incorporated density effects in her extensive three-dimensional model of the aquifers in southern Manitoba. She concluded that inclusion of salinity effects was not that significant for hydraulic heads as it was for concentrations in the Carbonate aquifer and not that significant for the WFS. Nevertheless, it is important for the current application to determine whether this is an important effect to consider.

PorousTec Comment #2:

The conceptual model is that of a transient, three-dimensional, layered-homogeneous, saturated, single-fluid phase, porous medium. The area of the conceptual model is not chosen using the knowledge that both aquifers are confined. Each layer is isotropic, with exceptions. However, there is considerable information on material heterogeneity not considered by the proponent. Also, it is well known that the majority of the flow and transport in the aquifer systems to the west of Winnipeg, and parts of the study area to *the east are known to be saline. (Kennedy, 2002) incorporated these salinity and density effects in her extensive three-dimensional model of the aquifers in southern Manitoba but the proponent did not. It is important that we understand the possibility of movement of more saline waters from the west of the Red River moving into fresh portions of the sandstone and carbonate aquifers. The HAFR modeling does not include* density *dependent flows and saline intrusion which may be important and is a missed opportunity.*

5 Numerical Groundwater Modeling

Objectives for the model are stated but these are given as to support decision making but are vaguely stated. Secondary objectives are listed but these are more “methodology” and not objectives. These briefly refer to calibration and predictive simulations, but the HAFR does not mention verification, full-sensitivity or uncertainty.

Three-dimensional flow and transport models should generally be used where:

- The hydrogeologic conditions are well known.
- Multiple aquifers are present.
- The vertical movement of groundwater or contaminants is important.

The rationale for selection of the appropriate model software was discussed in the HAFR. The choice of a software program for use at a site is the responsibility of the modeler. Any appropriate groundwater flow or fate and transport model software may be used provided that the model code has been tested, verified and documented.

For the analysis of the effects of the tailings, the proponent relied heavily on the use of the numerical code FEFLOW (Diersch, 2014). The code is based on the finite element method.

PorousTec Comment #3:
One of the major objectives of the hydrogeological investigations was to evaluate the potential for the project to impact groundwater quantity, quality and users of the surface and groundwater in the area. These are appropriate objectives, but they are only broadly outlined. Specifically, there is a need to assess impacts of pumping and development of the aquifer structure, extent of drawdown cones, impacts on existing users, intrusion of water of questionable quality, subsidence and potential pathways opening up through the limestone and sandstone aquifers. Not all of these aforementioned issues were

identified and resolved with the work and so not all of these anticipated project needs are addressed.

PorousTec Comment #4:
FEFLOW is a well-known and supported code. At this time, the code can fully account for all the processes contributing to groundwater movement and containment transport. It can also account for time-varying material properties; a feature that saw limited use in the various simulations. The chosen model grid appears to be adequate.

5.1 Boundary and Initial Conditions

As noted earlier in this report that appropriate boundary and initial conditions are critically important for the success of any numerical modeling. There are concerns about boundary conditions (BC's) in the HAFR simulations. In section 6.6, boundary conditions in the numerical model are discussed. The main boundary types are recharge conditions, specified heads or water levels, flow boundaries and point sources or sinks such as wells. The model domain is three dimensional and covers a variety of aquifers. A schematic of these is given on Figure 6-1. Specified heads are assigned to the model domain to represent the regional stream networks. However, since stream elevations rise and fall there was no mention of what time of year these were taken. Specified hydraulic heads are shown along long portions of streams to the north and south and it is unknown if these conditions extend in the vertical direction to the bottom of the stratigraphy. It is questionable if the water levels in these streams have any impact on any of the aquifers since both aquifers are confined which mean *per se* that the streams are hydraulically disconnected from hydraulic heads in the aquifers. The sandstone is set up as a constant head boundary but spatially varying along the Red River which is difficult to understand as there is no direct hydraulic connection with the river, and the aquifer is highly confined in these regions. The impervious boundary at the north end would force all groundwater flow to discharge into the Red River which is contrary to known understanding of the flow system (Betcher et al., 1995; Kennedy, 2002; Phipps et al., 2008). Note only the sandstone boundary condition at depth was discussed and unfortunately there are no details given for the carbonate and other aquifers. At this, time there is insufficient information with which to assess the validity of the boundaries to the flow model.

A recommended approach usually involves stetting impervious boundaries to a numerical model such that these represent actual stream lines of flow in the aquifer. Stream lines behave as impermeable boundaries and are essentially easier to incorporate in a numerical model. Using this modelling technique requires the construction of a regional groundwater table map for each aquifer which is missing in the report. In other words, the report does not discuss the proponent's understanding of regional groundwater flow. As long as these boundaries are well away from the specific area of interest, the assumption of the no flow boundaries should still hold. This particular type of approach was not adopted by the proponent.

Kennedy (2002) notes that there are a number of wells screened over both the carbonate and sandstone aquifers. This interconnection allows water to flow up from the sandstone aquifer into the carbonate aquifer and causes cross contamination between these aquifers in areas where the sandstone has inferior water quality. Kennedy (2002) identified 493 wells that were screened across both aquifers and adopted boundary conditions in the model that allowed for this interconnection. In the simulations and numerical model that was adopted a better result in calibration was achieved and deemed necessary. The model predicted flow through wells screened over both aquifers to be 0.03 m^3/s (~475 USGPM). The HAFR does not mention these interconnected wells and it is assumed they were not considered.

It is not known whether constant hydraulic head values were removed from the calibration assessment (see below). This is a common oversight in that measured values used for boundary conditions must not appear again in the calibration exercise; they are degrees of freedom that must be discounted. If these values have been "double counted" then the calibration of the model must be reassessed.

PorousTec Comment #5:

A geometric domain must be established and is a key in the appropriateness of a groundwater model. The best approach is deriving the model domain from regional groundwater table maps and potentially to expand the model domain, in all directions outward from an area of interest until physical features, such as groundwater divides or lakes and so can be represented as boundaries with attached physical-mathematical conditions. Since the model domain does not rely on these features there are concerns about the overall dimensions of the model and attached boundary conditions. Additionally, the model domain may not be large enough to account for large scale physical effects such as saline water intrusion or long-term sustainability but might be adequate from the point of view of a local pumping-well field. In addition, there are numerous wells in the area that are screened over both of the main aquifers. It is not clear these if physical effects were accounted for.

5.2 Calibration Process

5.2.1 Calibration (steady state)

Calibration is the process in which a mathematical model simulation is compared to a known data set; usually observations at a time in which an aquifer or aquifers where in a condition of equilibrium (steady flow conditions prevail). Parameter values are then adjusted within reasonable limits to achieve a match between observed and, say, calculated hydraulic heads. Calibration does not necessarily imply that a unique set of model parameters has been determined. For example, combinations of parameters such as recharge rates, well flows, storativity, and transmissivity are highly coupled in terms of their effect on hydraulic heads and it can be difficult to separate their combined effect into distinct unique-values. Unique determination can (possibly) only be done through the combination of verification, transient simulation, monitoring, and data collection, such as large well tests. There may be more than one parameter set that produces identical patterns of hydraulic head. This is why it is necessary that the final calibrated parameter set matches any available measurements within reasonable bounds.

Quantitative calibration measures include of goodness of fit between predictions and observations include (Loague and Green, 1991): maximum error (ME), root mean square error (RMSE), coefficient of determination (CD), modeling efficiency (EF), and coefficient of residual mass (CRM). Mass balance errors should also be monitored (ASTM standard D5609-94).

A manual, trial and error calibration was carried out to test if model output matches the observations. The HAFR mentions that 2,534 observation points of water levels or heads were used but several key items from the analysis are missing. First, there is no data given on the time (or date) of observations or on locations. In the HAFR it is mentioned that “an acceptable match between.” was made but the actual standards used to assess an acceptable match were not given and these should be rationalized and established before the assessments (for example see Kennedy, 2002). Some of the computed values such as mean residual of 3 m, RMS error of 5 m and correlation of 0.99 were achieved and might be acceptable but we do not know the standards that are used to determine acceptability, or whether a final error is appropriate under the circumstances. The HAFR does not list the actual calibrated values of hydraulic conductivity for the various units as a result of this first, steady-state phase of calibration.

Observed hydraulic heads versus measured hydraulic heads should be plotted and compared on a scatter plot. A fitted linear-regression line through all the data ideally should have a 1:1 slope and intercept of zero if there is a perfect fit. A correlation coefficient can also be obtained and tested for significance. With errors a perfect fit will not likely be achieved but statistical tests can be performed on the regression fits to see if the match is statistically close to that ideal. If results of a fit show a statistical bias then this is an indication of wrong boundary conditions or input parameters (see Kennedy, 2002 for examples). According to Anderson et al. (2015) definitive text on groundwater modeling, computed heads should be plotted on the X-axis and observed heads on the Y-axis. This is because in linear regression it is assumed that the variable on the X-axis is error free and all the error is on the Y-axis which represents observations. In any event it would probably be better to allow error on both axes, such as in total (orthogonal) least squares.

Figure 6-2 identifies several problem areas. First, what is on the drawing is a line showing a 1:1 slope and zero intercept but this does not appear to be obtained from a regression fit on the actual data, as intuitively by eye one can see that the best fit line would have an intercept around 160 m (simulated). Second, in the legend for the same drawing 95% confidence intervals are shown but they seem to reflect an error in the value of Y (average). The confidence area of a regression has more of a “fan like” look, with less error at the average value of X and Y, and more error at the extremes (see Anderson et al., 2015). Figure 6-3 shows the locations of observation points and within the project area and there are a number of points in which there are over 10 points with residual values of 5 to 10 m and about 5 points greater than 10 m. The majority are in the 1 to 5 m range. Note that this is the proponent’s excepted range of drawdown effects at groundwater wells from mining operations so that this is in the same range of the modelling error.

5.2.2 Calibration (transient)

The Michigan State Department of Environmental Quality (Mandle, 2002) describes history matching as the use of a steady-state (equilibrium) calibrated model to reproduce a set of historic field conditions. Further refinements to the model can then be made. Sometimes part of the original dataset used for calibration is withheld or “split-sampled” and can be used in a separate calibration phase. Either way, this process is sometimes been referred to as "model verification". A “transient calibration” is sometimes performed when there are no distinctly known periods of steady flow. It is noted above that the parameter values and boundary conditions used in this phase may not be unique, and other combinations of parameters and boundary conditions can yield similar results.

Mandle (2002) states “The most common history matching scenario consists of reproducing an observed change in the hydraulic head or solute concentrations over a different time period, typically one that follows the calibration time period. The best scenarios for model verification are ones that use the calibrated model to simulate the aquifer under transient conditions. The process of model verification may result in the need for further calibration refinement of the model. After the model has successfully reproduced measured changes in field conditions for both the calibration and history matching time periods, it is ready for predictive simulations."

A transient calibration was attempted (Figure 6-4). The steady-state model mentioned in the HAFR was simulated as a time dependent problem and further calibrated to the 72-hour pump test. Again, K, S and recharge rates were modified in the numerical simulations to match observations from the actual pump test. The statistics of actual final match that was achieved were not listed so that it is not possible to render an ultimate opinion of the acceptability of these transient runs. Graphically, we can see that (see also text on p. 73) with the exception of borehole 95-6, sub-optimal fits were achieved and these differences should be resolved. According to the HAFR, distances greater 300 m generally show higher observed drawdown than simulated, and the reverse is true for distances under 300 m. Given the available database a better fit to the data should have been possible.

PorousTec Comment #6:

Calibration to an existing data set for hydraulic heads has been attempted. However, there is insufficient detail given in the text to assess if an appropriate calibration has been achieved. There are no times or dates listed for the observation points and some suggested-statistical tests are missing. Most importantly, calibrated final hydraulic parameters from the proponent do not match with the actual well test data, or values adopted by geospatial works. History matching or a "transient calibration" to existing data for flow is incomplete and matching to an acceptable data base for concentration is non-existent.

5.2.3 Calibrated aquifer properties

The results of the two phases of trial and error adjustments are shown on Table 6-C. Values for K are all assumed to be homogenous throughout the aquifer and are listed below and compared to earlier simulations (Table 1).

Table 1: Calibrated hydraulic conductivities and literature values

Hydrostratigraphic unit	***HAFR (m/s)***	***Kennedy and Woodbury (2005) (m/s)***
Sediments, coarse grained	8.9×10^{-5} (h) 8.9×10^{-6} (v)	1×10^{-3}
Sediments, medium grained	6.8×10^{-7} (h) 6.8×10^{-8} (v)	7.8×10^{-6}
Red River Carbonate	6.9×10^{-5} (h, v)	mean*): 7.3×10^{-5}
Winnipeg Shale	2.3×10^{-8} (h) 2.3×10^{-9} (v)	1×10^{-10} (h, v)
Winnipeg Sandstone	3.2×10^{-5} (h) 3.2×10^{-6} (v)	5×10^{-6} - 4×10^{-5}
Precambrian basement	1.2×10^{-12} (h, v)	impervious

*) interpolated value
(h) horizontal
(v) vertical

The Winnipeg Sandstone K and the Winnipeg Shale aquitard are modeled as anisotropic (material properties change with direction) and yet there is no field evidence given to support this, and no reasons given as to why this was a necessary complexity to include. Also, the storage coefficient for the sandstone (not the storativity) from the calibration is set to 7.0×10^{-6} 1/m while the well test determined 8.4×10^{-6} 1/m. Kennedy and Woodbury (2005) used 2.4×10^{-6} 1/m.

The well tests determined by the proponent suggest a hydraulic conductivity K at 1.1×10^{-4} m/s for the sandstone but the calibrated model was set to 3.2×10^{-5} m/s close to 2.4×10^{-5} m/s noted by Wang et al. (2008) and also by Kennedy and Woodbury (2002).

Note that the final, <u>calibrated properties of the sandstone aquifer differ from the well tests by over an order of magnitude</u>. This difference in values needs to be reconciled.

PorousTec Comment #7:
The final material properties are chosen through the calibration process and most properties seem to be physically reasonable. The major exceptions to this are the hydraulic conductivity of the Sandstone aquifer (as in the model), which was not chosen on the basis of well test information. The heterogeneous nature of these aquifers is ignored. The shale layer that separates the two aquifers is viewed as being homogenous but anisotropic; unfortunately, there is no field data to support this conjecture.

5.3 Scenario Calculations

The numerical model was used to for a series of scenarios involving different pumping rates. While not completely clear from the HAFR text it appears that two basic schemes of re-injection were simulated. These were:

(1) the case when no water from a pumping cluster is re-injected; so, all water is lost, and
(2) the case where 50% of water pumped out is re-injected.

Note that it is the proponent’s intention to re-inject all pumped water from the aquifer as part of the mining operation so certainly a 100 % re-injection rate would be a theoretical ideal and 0% would be the worst case. A perhaps more realistic 50% re-injection rate could possibly represent cases where, technical speaking, it was not possible for a variety of reasons to be able to re-introduce water back into the aquifer. Scenarios #1 to #2 represent the case where the shale layer is degraded and can allow for flow between the aquifers. It is unclear as to what material properties for the shale were selected for these runs. Scenario #3 is similar to #1 and #2 except the shale aquitard is assumed to be intact. Scenarios #4 and #5 represent full transient versions of scenarios #1 and #2 that incorporate the full pumping schedule, but only for 4 years. See Figure 6-5. Time-variable aquifer properties were introduced that allowed for the shale layer to degrade over time to the same hydraulic properties as the WFS, but it is not clear how the material properties were chosen or how this schedule in time was determined. Nor is it clear how any extra water that cannot be re-injected is disposed of (even hypothetically) and if this amount is sustainable to extract from the aquifers without replacement.

Note also, and most importantly, the changes in hydraulic conductivity in the WFS as a result of the mining itself were not considering and represents a shortcoming of the simulations. The effects on future groundwater resource development in the affected project area has not been assessed in this report. Additionally, questions regarding the stability - and therefore, potential failure - of the Winnipeg Shale are not discussed or included in the scenario development.

A first set of results are from some of the simulations. Here cluster #213 was chosen as a typical production well and various simulations were performed, as per scenarios #1 to #3 noted above. In Table 6-1 the testing results are summarized. Various distances are indicated and the nearest observation point is located 146 m away from the pumping well. This is a curious choice in that there is a 100 m buffer suggested between pumping clusters and any domestic wells. A maximum drawdown is noted in the WFS at 146 m, under 0% re-injection of water and with no shale degradation the drawdown is 15.7 m. Interestingly there appears to be a drawdown noted in the carbonate aquifer of 4.2 m.

One scenario not simulated is the case of no shale degradation and a 50% re-injection rate. As a check on the predictive scenarios, we can use the Theis solution (recall valid for a perfectly confined aquifer and is therefore conservative). With material properties the same as in the HAFR (calibrated), the same pumping rates (550 USGPM; no reinjection) at a distance of 100 m, and after 72 hours of pumping equals 24 m of drawdown. For 225 USGPM (50% re-injection) this would be about 12 m of drawdown. Recall that the proponent stated the magnitude of the groundwater impacts is anticipated to be between 1 m and 5 m for the majority of the water supply wells. So, clearly there is a difference noted between the above results and that of the proponent and this difference should be resolved.

The fully transient simulations under scenarios #4 and #5 are presented. Figures 6-11 and 6-12 show the results after a four-year time horizon. The results are not tabulated and the only item reported is a 1 m drawdown cone and how far it extends. Again, using the Theis solution and at the outer radius of well cluster (28 m) we could expect 33.6 m drawdown (1 day, 550 USGPM, confined, HAFR calibrated properties, 0% re-injection). If we assume a 50% re-injection of water, drawdown under the above conditions would be half, at 17 m.

It is assumed by the proponent that water levels would re-equilibrate after 20 days but it is noted that removal of solids will change the aquifer properties and recovery may take 4 times as long, but no data is given to support this conclusion and is counter intuitive if K is increased as a result of mining.

5.4 Parameter Sensitivity

A sensitivity analysis involves gradually varying model parameters over reasonable ranges and observing the relative changes in model output at selected points. This variation should be done, incrementally one parameter at a time, holding the others fixed at some base level. For a groundwater flow model, the observed changes in drawdown, hydraulic head, or flow are noted. The objective of the sensitivity analysis is to aid in the development of a future data collection phase and the identification of data gaps. The sensitivity of one model parameter relative to other parameters should be clearly demonstrated.

A limited sensitivity section is presented (see HAFR Table 6-2). Here, various hydraulic parameters were altered by either increasing or decreasing values by a specified amount. On that point, scenario #1 was the only case in which these sensitivities were conducted. Recall that scenario #1 involved pumping from a production well at a constant rate and the numerical model was set for steady flow conditions. Scenario #1 also had 0% re-injection, which is conservative but allowed for degradation of the shale layer separating the two main aquifers. This was done by either decreasing or increasing the shale hydraulic conductivity by a factor of 10. As what might be of no surprise, the drawdowns in the Carbonate and WFS aquifers are “moderately sensitive” to changes in K of the WFS. This comment certainly reinforces the conclusion in this review that the hydraulic parameters used in the numerical modeling need to be re-examined.

PorousTec Comment #7:
A sensitivity testing phase has been carried out but only for a limited number of forcing functions or boundary conditions. Boundary condition sensitivity should be addressed in any simulations. Unfortunately, this was not done (with the exception of recharge rates).

5.5 Parameter Uncertainty

A sensitivity analysis differs from a full parameter uncertainty analysis mentioned above. In the former case these procedures usually illustrate graphically the consequences of imprecise knowledge of one parameter on model outputs and as mentioned above is ideally suited to identify data gaps. The latter procedure employs descriptors of parameters and models output in a probabilistic framework and is ideally suited for risk assessments (e.g., Woodbury, 1997). According to Michigan States Department of Environmental Quality “A model may be used to predict some future groundwater flow or contaminant transport condition. The model may also be used to evaluate different remediation alternatives, such as hydraulic containment, pump-and-treat or natural attenuation, and to assist with risk evaluation. In order to perform these tasks, the model, whether it is a groundwater flow or solute transport model, must be reasonably accurate, as demonstrated during the model calibration process. However, because even a well-calibrated model is based on insufficient data or oversimplifications, there are errors and uncertainties in a groundwater-flow analysis or solute transport analysis that make any model prediction no better than an approximation. For this reason, all model predictions should be expressed as a range of possible outcomes which reflect the uncertainty in model parameter values."

PorousTec Comment #8:
A general worst-case analysis on all parameters has not been performed. However, a worst-case pumping scenario of 0% return flows to the aquifer was considered. Note that all of the conclusions listed in the model simulation discussion rely on an assumption that the mining operation does not affect the hydraulic properties of the sandstone aquifer and hence cannot be viewed as being conservative.

5.6 Discussion on Model

Probably one of the best sections to read in the HAPR is section 7.2 "Residual Effects Analysis". The project impacts are discussed on p. 79-85. It is noted in the HAFR that pumping of groundwater during sand extraction may produce increased drawdown with an impact on existing users of the main aquifers.

All conclusions by the proponent rely on an assumption that the mining operation does not affect the hydraulic properties of the aquifers (see Table 7C on p. 83). Having mentioned this the proponent goes on further to say, paradoxically, that "the removal of sand will permanently increase the effective porosity and storativity of the Winnipeg Sandstone aquifer". But these effects are not considered and it is noted that the FEFLOW software used can incorporate time-dependent aquifer properties and thus, was another missed opportunity.

It is mentioned that recovery of hydraulic heads would take about 4 times longer than presently simulated because of mining effects but these results are not detailed. The porosity of sandstone estimated at 25% which is not unreasonable but is unverified, and the dimensions of the void spaces and so on are not mentioned.

The HAFR notes that degradation of the Winnipeg Shale layer may occur because of project operations which would result of more direct communication between the Winnipeg Sandstone and the Red River Carbonate. This is a crucially important facet of the operation.

6 Geochemistry

The general concerns related to geochemistry are changes in the dissolved mass in the groundwater. All changes have to be seen on the long-term. Typical questions are related to reduction of drinking water quality, release of heavy metals, replenishment of more saline water, and potential connection to existing contamination, e.g. brownfields in the impacted area.

Changes to water quality can occur from changes in pH, dissolved oxygen, inflowing water from other aquifers, and surface water introduction. Thus, the HAFR is expected to explore the changes in water quality that can occur as a result of the silica sand extraction activities. Understanding how the mining activities will contribute to these changes in water quality should be the focus of the HAFR. When looking at risk created by the project, it is important to consider exposure targets, toxicity and pathways. The most sensitive target is the drinking water quality for human health.

6.1 Review

The HAFR identified the risks of metal leaching and acid rock drainage and reviewed the geochemistry of the Winnipeg Sandstone and the Black Shale in several locations in Manitoba and neighbouring provinces and states. The presence of pyrite nodules was identified as a key driver for acid rock drainage and therefore, metal leaching. All these reviews were related to in situ geochemistry.

However, it should be considered that changes to the flow, pH, and redox conditions within the aquifer due to the mining activities could result of leaching into the aquifer itself. By this pathway, any geochemical changes become exposed via drinking water as well. In this case, concentrations should be compared to the appropriate guidelines. Leaching from surface water to groundwater should also be considered and compared to the guidelines. Potential pathways are sinkholes in the Upper Carbonate and brownfields. These features have to be mapped for such an analysis.

It is noted that although the shake flask extraction in 4.1.5.4 is meant to overpredict which is a worst-case approach to take. Especially when the action by mining could potentially create similar conditions.

6.2 Sampling

The sampling campaign related to acid mine drainage was of limited extent. A very small number (nine) of soil samples were collected and analyzed. Not a single duplicate was taken and tested so that no uncertainty ranges for each solute or mineral concentration can be presented. All samples were taken from the same borehole so that no information can be presented on regional changes.

There was also no detailed description of how the samples were retrieved and handled after the removal from the borehole. Some of the samples (Winnipeg Sandstone) were even grab samples from a stockpile (p. 34). Such sampling is inadequate to be used for the geochemical analysis described later on. The period between sampling and analysis of some samples was relatively long. E.g., water sample BRU 96-1 (Project PO 60610258) was taken on 13.11.2020 and shipped to ALS 4 days later. The analysis was carried out within a week. It is not documented how the water sample was stored between 13th and 17th November 2020. Inadequate storage conditions and the lengthy duration likely negatively impact the quality of the analysis. Adequate sampling techniques and their documentation are the key for credible analysis.

There was a lack of information regarding the stable isotope samples. HAFR states that "The primary purpose of these samples was to evaluate changes in groundwater contributions from the Winnipeg Sandstone and Winnipeg Shale during pumping." (p. 44). However, there is no information on the conditions of the pumping, the duration of the pumping, or the hydraulic conductivity, especially if there was enough time during the test to show any migration of water that may have occurred as a result. Furthermore, there is no discussion on whether this pumping is representative in volume and duration to the mining process, which is important in considering migration distances and sources.

6.3 Laboratory Analysis

All laboratory analysis was carried out by ALS Environmental Laboratories (ALS). ALS is an international recognized laboratory in environmental analysis. The chosen analytical techniques are adequate.

Analysis is meant to represent metal leaching and acid rock drainage. The investigations and report do not consider changes to the flow, pH, and redox conditions within the aquifer. These changes could be the result of leaching in the aquifer itself. A potential source of trace elements are locations such as sample Bru121-1_36.57 to 37.00 (Winnipeg Shale).

The analysis of the aqueous geochemistry included a good comparison for background water chemistry. It ensured that all species with drinking water guidelines are tested. However, this study did not include how the mining operation will impact the system. This is the critical question for future groundwater quality. The single exercise was the geochemical sampling before, during, and after the pumping test. However, this attempt cannot relate to e.g., dissolved oxygen (DO), pH concentration during the mining operations. DO and pH are key drivers for acid mine drainage. The summary of exceedances should relate back to the mining activities.

The isotope study presents background data on isotopes in the region, mainly confirming available studies. However, it does not address what these values may mean for the site once the mining process begins. For example, what is the meaning of the seawater source identified in the isotope study? Does it indicate that there is potential for upwelling of saline water from the Williston Basin?

6.4 Geochemical Modelling

Geochemical modelling was undertaken to evaluate the impact of project operations on water quality using the computer program PHREEQC and the Minteq.v4 database. However, trace metals, which are contaminants of concern for drinking water quality, are not considered. All model outputs are a direct result of model inputs, so anything that is not added to the inputs cannot be in the outputs.

The modelling selected a couple of low-risk scenarios and did not seek to address two major issues - a reduced water quality in general, or risk to human, aquatic, or agricultural life. Information on the setup of the model to examine the impact of redox conditions is missing. Standard information such as time series (and the period) or steady state, a list of minerals that was at equilibrium with the water, and which data source were used (XRD or shaker flask) needs to be added.

Similarly, the investigation on mixing of waters also included very limited information on the model. Key questions such as release of trace elements were not investigated. Risks are not identified, e.g. by worst-case scenarios (e.g. data based on sample Bru121-1_36.57 to 37.00) since the analysis was limited to the data from the water samples. Any changes to the groundwater chemistry due to the expected changes in pH and redox conditions were not investigated.

PorousTec Comment #9:
The analysis for acid mine drainage, aqueous geochemistry and stable isotopes were carried out at only one location and limited samples (e.g., related to acid mine drainage) were taken. None of the analysis discussed groundwater quality changes due to the mining operations. The worst-case should be defined as at the collapse of the Winnipeg Shale. Any impacts related to groundwater quality are not investigated. The goal of work with regard to water quality is also somewhat unclear, as the report recommends a water quality study which should have been finalized at this point.

Sincerely,

Dr. Hartmut Holländer, P.Eng.
Director
PorousTec Ltd.
Email: hartmut.hollaender@umanitoba.ca
(seal to follow)

Dr. Allan Woodbury, P.Eng.
Professor Emeritus
University of Manitoba
Email: allan.woodbury@umanitoba.ca
(seal to follow)

PROVINCE OF MANITOBA
H. M.
HOLLAENDER
Member
36164
REGISTERED PROFESSIONAL ENGINEER

19.09.2022

PROVINCE OF MANITOBA
A.D.
WOODBURY
Member
7480
REGISTERED PROFESSIONAL ENGINEER

18/09/22

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