Manitoba Clean Environment Commission

Expert Report on the Sio Silica Proposed Vivian Silica Sand Project

Prepared for:

The Rural Municipality of Springfield, Manitoba

Prepared by:

Christopher J. Neville, M.Sc., P.Eng.

S.S. PAPADOPULOS & ASSOCIATES, INC.
Waterloo, Ontario

January 12, 2023

90 Frobisher Drive, Unit 2B, Waterloo, Ontario N2V 2A1 • (519) 579-2100

Executive Summary

The Rural Municipality of Springfield (RM of Springfield) has retained Christopher J. Neville, M.Sc., P.Eng., to advise the municipality on the proposed groundwater aspects of the Vivian Silica Sand Project to be developed by Sio Silica (previously CanWhite Sands Corp.). Mr. Neville has reviewed the technical submissions presented in the report *Vivian Sand Extraction Project – Environmental Act Proposal* (AECOM, 2021a) and Appendix A of that report, *Hydrogeology and Geochemistry Assessment Report* (AECOM, 2021b). This expert report has been prepared to identify issues of potential concern for the groundwater resources of the RM of Springfield. These issues may be conveyed to the Manitoba Clean Environment Commission (CEC), which will advise the Province of Manitoba. The ultimate decision to approve the proposal, and the conditions that may be attached to that approval, rest with the Province.

There is much uncertainty regarding this proposal. Some of this uncertainty is related to the testing that has been conducted during the site investigations, some is related to the interpretations made of the data, and some is related to the approach that has been adopted to assess the potential impacts of mining. The material presented in the *Vivian Sand Extraction Project – Environmental Act Proposal* and the *Hydrogeology and Geochemistry Assessment Report* raises concerns that the site investigations have not adequately characterized the essential elements of the site and the potential impacts to groundwater resources in the RM of Springfield.

Creating a slurry of the Winnipeg Sandstone and extracting silica sand is expected to result in the development of horizontal arrays of “rooms and pillars” in the Winnipeg Sandstone. The proponent has referred to the loss of strength of the sandstone and has also referred to pilot testing that has been conducted. However, there is no indication of whether the loss of strength was assessed during the pilot testing. The proponent has indicated that “Some collapse of the overlying strata may occur but collapse is expected to be limited and not to spread to the surface.” It is not clear from the project documentation whether this is an assumption, or data have been collected and analyzed to support this expectation. In the absence of data, it may be safer to assume that the operations will result in a mass of loose sand with the potential for progressive, large-scale collapse of the overlying strata.

By any standard, the proposal project will require a large number of wells to be subsequently abandoned. The wells will extend across and may connect the otherwise isolated Red River Carbonate and Winnipeg Sandstone. Improperly abandoned wells may act as preferential pathways for the migration of surface contamination into deeper aquifers. The practices adopted for well abandonment will be of particular concern for this project. It is suggested on Page iv of the Executive Summary of the *Vivian Sand Extraction Project – Environmental Act Proposal* that well drill cuttings may be included in the materials used to seal wells. It is also suggested on Page vii that calcified sand (“overs”) may be used in well sealing activities. I caution against using drill cuttings and “overs” for this purpose. Wells should be sealed with bentonite and/or grout to surface to ensure that over the long term they can never act to connect the two aquifers. Furthermore, wells that are no longer in operation should be sealed in a continuous abandonment program rather than being left as open holes until groups of wells are abandoned.

Table of Contents

Page

Section 1
Introduction

I am a professional engineer registered in the Province of Manitoba, #48048. I am the Chief Hydrogeologist of S.S. Papadopulos & Associates, Inc. (SSP&A), environmental and water-resource consultants. SSP&A operates under Engineers Geoscientists Manitoba Certificate of Authorization No. 7922. I was educated as a civil engineer and I have advanced training in the discipline of hydrogeology. I have over 30 years of professional experience. I am recognized internationally as an expert in the quantitative analysis of groundwater flow and solute transport. In my role of Chief Hydrogeologist and director of SSP&A's Canadian operations I synthesize hydrogeologic data, evaluate groundwater resources, and develop regional and site-scale analyses of groundwater flow and solute transport. My resumé is included as appendix to this report.

The Rural Municipality of Springfield (RM of Springfield) has retained me to advise the municipality on the proposed groundwater aspects of the Vivian Sand Project to be developed by Sio Silica (previously CanWhite Sands Corp.). My role consists of reviewing the technical submissions presented in the report *Vivian Sand Extraction Project – Environmental Act Proposal* (AECOM, 2021a) and Appendix A of that report, *Hydrogeology and Geochemistry Assessment Report* (AECOM, 2021b). My role as a hydrogeology peer reviewer involves identifying issues of potential concern for the RM of Springfield. These issues may be conveyed to the Manitoba Clean Environment Commission (CEC), which will advise the Province of Manitoba. The ultimate decision to approve the proposal, and the conditions that may be attached to that approval, rest with the Province.

My role as hydrogeology peer reviewer for the RM of Springfield has involved the following activities.

1. Supporting the RM of Springfield in its application for Participant Standing for the Clean Environment Commission Panel. The RM of Springfield was granted standing on October 12, 2022.

2. With the assistance of Mr. Mark Prydon, conversion of the requests for clarifications in my May 13, 2022 letter into Information Requests (IRs) in the format required by the Clean Environment Commission. A total of 18 IRs were submitted on November 16, 2022.

3. Preparation of a note summarizing my major concerns regarding the development on December 14, 2022. On December 21, 2022 I attended a virtual meeting with Council to discuss these concerns and respond to questions.

4. Preparation of this expert report.

Section 2
Overview of the major concerns related to the hydrogeologic aspects of the proposed Vivian Sand Extraction Project

The following elements are essential to the assessment of the potential impacts of any major proposal:

- Identification of the natural resources that are potentially affected;
- Prediction of the potential impacts to those resources;
- Evaluation of potential mitigation measures; and
- Evaluation of contingency measures in case the potential mitigation measures are either not feasible or not effective.

The proposed Vivian Sand Extraction Project is a major undertaking involving the fluidization and removal of a portion of the Winnipeg Sandstone aquifer with potential impacts to the overlying Red River Carbonate aquifer. It is indicated in the *Environmental Act Proposal* report that in the area of the Project Site, groundwater in the Red River Carbonate and Winnipeg Sandstone aquifers is used extensively to meet demands for a variety of water uses.[1] It is critical to ensure the groundwater supply is not negatively affected by project operations, and that the Red River Carbonate and Winnipeg Sandstone continue to meet the needs of the community.

It is clear from the reporting that a substantial effort has been involved in conducting the field investigations and developing and documenting the analyses of potential impacts. In my opinion the work has been conducted to a high technical standard. However, at the end of my review I was left two major concerns:

- That the impact assessment may not adequately address the impacts to the Winnipeg Sandstone and the Red River Carbonate aquifers; and
- The drilling and relatively rapid abandonment of a large number of wells may compromise the integrity of the Winnipeg Sandstone and Red River Carbonate aquifers and introduce preferential pathways for the vertical migration of contaminants into the aquifers

By design, the mining will locally alter the properties of the Winnipeg Sandstone. In particular, the Winnipeg Sandstone will made into a slurry that will be extracted. It is indicated that "the removal of sand will permanently increase the effective porosity and storativity of the Winnipeg Sandstone aquifer within the Project Site through the extraction of material and resulting creation of void space."[2] I anticipate that the hydraulic conductivity of the Winnipeg Sandstone will also change substantially, both due to an increase in its porosity and to the collapse of its structure. The analyses conducted for the assessment do not consider the potential effects of the changes in the properties of the Winnipeg Sandstone, either during mining or following the progression of mining around the site.

[1] AECOM, 2021a: *Environmental Act Proposal*, p. 36
[2] AECOM, 2021b: *Hydrogeology and Geochemistry Assessment Report*, Page 81

It is indicated on Page 75 of the *Hydrogeology and Geochemistry Assessment Report* that for the predictive scenarios one production well is specified at any one time, since production is occurring at one well cluster. However, by the time the wells in cluster 213 have been activated, the Winnipeg Sandstone will have been extensively disturbed by the fluidization and extraction of sand at the other clusters that have been operated in 2025. In my opinion, the assessment of potential impacts of the proposal does not address the cumulative impact of the removal of the sandstone.

It is not clear whether there are data that can support an assessment of the effects of changes in the sandstone properties. I am left with the concern that changes in the properties of the sandstone may invalidate the predictions of local and temporary changes in water levels. It is assumed that the drawdown effects associated with sand extraction are expected to be localized [3]. In my opinion, it is important to recognize that this assumes that the fluidized sandstone will eventually returns to its pre-mining condition and that mining does not lead to progressive, widespread collapse of the formation.

The Winnipeg Sandstone regional aquifer is protected by the overlying Winnipeg Shale. It is acknowledged in the assessment that mining may result in degradation of the shale and enhanced hydraulic connection between the Red River Carbonate and the Winnipeg Sandstone within the Project Area. It is indicated that degradation of the shale may occur due to fractures and borehole annuli extending across the Winnipeg Shale aquitard. After completing my review, I was left questioning whether any geotechnical analyses have been undertaken to rule out the possibility of widespread collapse of the shale due to its being undermined.

It is indicated that if the impacts of mining exceed expectations, pumps installed near the current elevation of the piezometric surface can be lowered, or alternative water supplies could be provided. There is no analysis to suggest that these mitigation measures might be feasible and whether the provision of alternative water supplies is an acceptable mitigation measure.

I have never encountered a project with as many production wells proposed to be drilled, operated and abandoned. I estimate from the information on the preliminary design that has been provided that almost 400 wells are planned to be abandoned during each year of operation:

$$56 \frac{clusters}{year} \times 7 \frac{wells}{cluster} = 392 \frac{wells}{year}$$

By any standard this is a large number of wells that will have to be abandoned. The wells will extend across and may connect the otherwise isolated Red River Carbonate and Winnipeg Sandstone. Improperly abandoned wells may act as preferential pathways for the migration of surface contamination into deeper aquifers. The practices adopted for well abandonment will be of particular concern for this project. Furthermore, the proponent must commit to initiate abandonment procedures immediately following the end of operations at each well, rather than waiting until operations have ceased at a large number of wells.

[3] AECOM, 2021b: *Hydrogeology and Geochemistry Assessment Report*, p. 67

Section 3
Major comments regarding the hydrogeologic aspects of the proposed Vivian Sand Extraction Project

1. It is indicated at the beginning of Section 4.1.4 of the *Environmental Act Proposal* report that groundwater in the vicinity of the Project is obtained from Red River Carbonate Formation and the Winnipeg Sandstone Formation. Referring to Page 16 Figure 1-3 of the *Hydrogeology and Geochemistry Assessment Report*, there are relatively large numbers of existing groundwater users in the Quaternary Sediments, the Red River Carbonate and the Winnipeg Sandstone in the Regional Project Area:

   - Number of registered wells within the limits of the groundwater flow model: 10,879;
   - Number of registered wells within the Regional Project Area: 1,612; and
   - Number of registered wells within the Local Project Area: 406.

   In response to RM of Springfield Information Request RMSF-IR-001(a), the proponent has indicated that within the Project Site Area there are an estimated 19 wells completed in the Winnipeg Sandstone aquifer, 62 wells completed in the Red River Carbonate aquifer and 5 wells completed in the overburden aquifer.

   Referring to Figure 1-3 of the of the *Hydrogeology and Geochemistry Assessment Report*, there also appear to be 17 existing users in the Winnipeg Shale within the Regional Project Area. In response to RM of Springfield Information Request RMSF-IR-001(b), the proponent confirmed that it is unlikely that groundwater users rely on the Winnipeg Shale for supply. The proponent's reply highlighted the uncertainties associated with the well database.

   > *Screen intervals were not available for all wells. Further, well databases are known to contain information that may not be accurate or is out of date. It is possible that some wells were incorrectly assigned to the Winnipeg Shale, but that cannot be verified without detailed information on screen intervals, well yield and geology in some cases. This is a known uncertainty associated with work completed to date and is best addressed by completing site-specific well surveys in advance of any groundwater or sand extraction activities.*

   At a minimum, the proponent will need to conduct a detailed survey of neighboring wells to confirm the locations and details of the open intervals and the non-pumping levels in the wells within the Project Site Area.

2. It is indicated on Page 7 of the of the *Hydrogeology and Geochemistry Assessment Report* that the waste materials (calcified sand, bedrock cuttings and shale) "have 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 linked to ML/ARD [metal leaching/acid rock drainage]". While this may be true, it is important to note that the number of wells that are proposed to be drilled over a relatively small area is unprecedented.

3. It is indicated on Page 22 of the of the *Hydrogeology and Geochemistry Assessment Report* that water extracted from the slurry will be passed through an ultraviolet treatment system prior to being re-injected into the Winnipeg Sandstone. In my experience, ultraviolet treatment is effective only if the water is filtered prior to passing through the UV lamps. In response to RM of Springfield Information Request RMSF-IR-002(a), the proponent has confirmed that filtration will be included in the treatment system. In response to RM of Springfield Information Request RMSF-IR-002(b), the proponent has committed to appropriate handling of the materials collected from the filtration system.

4. It is indicated on Page 67 of the *Environmental Act Proposal* report that the effects of mining are reversible (i.e., the aquifer will recharge over time). In my opinion, the indication that the that the effects of mining will be reversible is only an *assumption*. There are no data to assess whether the assumption of reversibility depends on the properties of the Winnipeg Sandstone and the overlying shale. The changes to these wells will <u>not</u> be reversible. In response to RM of Springfield Information Request RMSF-IR-003(a), the proponent has indicated that:

   The sensitivity of modelling results and recovery to the properties of the fine-grained materials that overlie the Red River Carbonate was not directly evaluated.

   In response to RM of Springfield Information Request RMSF-IR-003(a), the proponents indicate, "The influence of variable hydraulic conductivity of the shale on recovery rates could be further evaluated as part of future modelling updates." It is important to note that the assessment of the properties of the shale must go well beyond the sensitivity of modelling results. The proponent would have to commit to detailed monitoring of each hydrostratigraphic unit and evaluation of the data during operations.

   The proponent indicates that groundwater flow conditions in the Red River Carbonate aquifer and the Winnipeg Formation are likely to recover relatively quickly following mining: *Both aquifers are relatively permeable and connected to a known significant source of recharge below the Sandilands Glaciofluvial Complex* (response to RM of Springfield Information Request RMSF-IR-003(b)). However, the proponent has noted that, "*The sensitivity of the predicted recoveries in the Red River Carbonate Formation and the Winnipeg Formation to recharge in areas where the aquifers are in direct contact with coarse-grained sediments at surface was not directly evaluated.*" In my opinion, the recovery of the aquifer system to mining is an important uncertainty of the proposal.

5. It is indicated on Page 24 of the *Hydrogeology and Geochemistry Assessment Report* that the field investigation was focused on characterizing the hydrogeology of the Local Project Area. Referring to Figure 1-4 and Figure 3-1 of the report, it is important to note that the characterization is actually limited to a small portion of the Local Project Area. Only two wells, Bru 121 and Bru-146 were installed beyond the limits of the yellow rectangle shown in Figure 3-1.

6. It is difficult to draw any general conclusions regarding the potential long-term effects of mining from the available data. The site characterization included a constant-rate test with pumping from a single well at a rate of 372 USgpm for 3 days. In contrast, referring to Figures 6-7 and 6-8 of the *Hydrogeology and Geochemistry Assessment Report*, during each year of operation there will be continuous pumping from an array of 7 wells at a combined rate of 550 USgpm for about 210 days (the arrays will move around during this time). Applying the results of the pumping test to the overall impact assessment therefore necessarily involves a large degree of extrapolation. Referring to the pumping test analysis files included in Appendix E.2 of the *Hydrogeology and Geochemistry Assessment Report*, while water levels in the test pumping well (Bru 95-7) appeared to stabilize, water levels in the observation wells in the Winnipeg Sandstone were continuing to decline at the end of the pumping test. From the available data it is not possible to infer the likely magnitudes of the long-term changes in groundwater levels that would be observed during operations.

Section 4
Detailed comments regarding the assessment of potential groundwater impacts of the proposed Vivian Sand Extraction Project

4.1 References for the *Hydrogeology and Geochemistry Assessment Report*

1. The references in the *Hydrogeology and Geochemistry Assessment Report* are incomplete. Some, but not all, of the missing references are included in Section 10 of the *Environmental Act Proposal* (AECOM, 2021a). No references are provided for the following documents cited in the *Hydrogeology and Geochemistry Assessment Report* (AECOM, 2021b).

   - Matile and Keller (2004)
   - Teller and Fenton (1980)
   - Peltier (1994)
   - Betcher (1986)
   - Ferguson (2004)
   - Matile and Keller (2011)
   - Simpson et al. (1987)
   - Cherry (2000)
   - Friesen (2015)
   - Johnston (1934)
   - Charron (1965)

4.2 Details on proposed project operations

2. A mining plan for the first five years of operations is presented in Figure 6-5 of the *Hydrogeology and Geochemistry Assessment Report*. Referring to the excerpt from this figure shown here in Figure 1, each blue dot represents a cluster of 7 wells that will be drilled, operated and abandoned during 2025. The corresponding schedule of pumping is shown in Figure 6-7 of the report. During each year, pumping will shift from one cluster to the next (for example, from Cluster 213 to Cluster 214).

   In response to RMSF-IR-004, the proponent clarified the pumping rates assumed in the impact assessment. Each well in the cluster is planned to be operated for approximately 4 days at a variable rate ranging from 262 m^3/day to 654 m^3/day (48 to 120 USgpm). If all 7 wells in a cluster were operating continuously this would correspond to 1,834 m^3/day to 4,578 m^3/day (336 to 840 USgpm). It is indicated in the response that the overall average combined production rate is expected to be 2,943 m^3/day. For the predictive simulations, during each year's simulated operating period the cumulative pumping is assumed to be 2,998 m^3/day (540 USgpm), slightly higher than the expected average. The cumulative pumping of 2,998 m^3/day corresponds to 550 USgpm, which is the rate assumed in the impact assessment, as indicated in Figure 6-7 of the *Hydrogeology and Geochemistry Assessment Report*.

3. The responses to RMSF-IR-005 clarify that there may be extraction pumping at the same time as treated pumped water is re-injected at wells in the same cluster. The *net* groundwater withdrawals may therefore vary from 100% to some smaller fraction of the 550 USgpm, depending on the rate at which water is re-injected.

4. It is indicated on Page 22 of the *Hydrogeology and Geochemistry Assessment Report* that extraction wells within each cluster will be located "approximately 22 m apart". This is not consistent with the conceptual layout shown in Figure 2-B (see Figure 1 below), which suggests that the wells will be spaced 18 m apart. In response to RMSF-IR-006, the proponent has indicated that the text in Section 2.3 and Figure 2-B of the *Hydrogeology and Geochemistry Assessment Report* should have reflected a well spacing of 18 m.

   The proponent has also indicated in the response to RMSF-IR-006 that "new efficiencies have been realized" that may allow for an increase in the distance between wells to produce the same amount of sand. It is my understanding that these efficiencies are inferred from updated geotechnical analyses, but they may also have been inferred from pilot testing referred to the response to RMSF-IR-005. The critical factor controlling the spacing between wells will be the stability of the rock that overlies the Winnipeg Sandstone. This implies that the geotechnical investigations and analyses will have a critical bearing on the final design of the project.

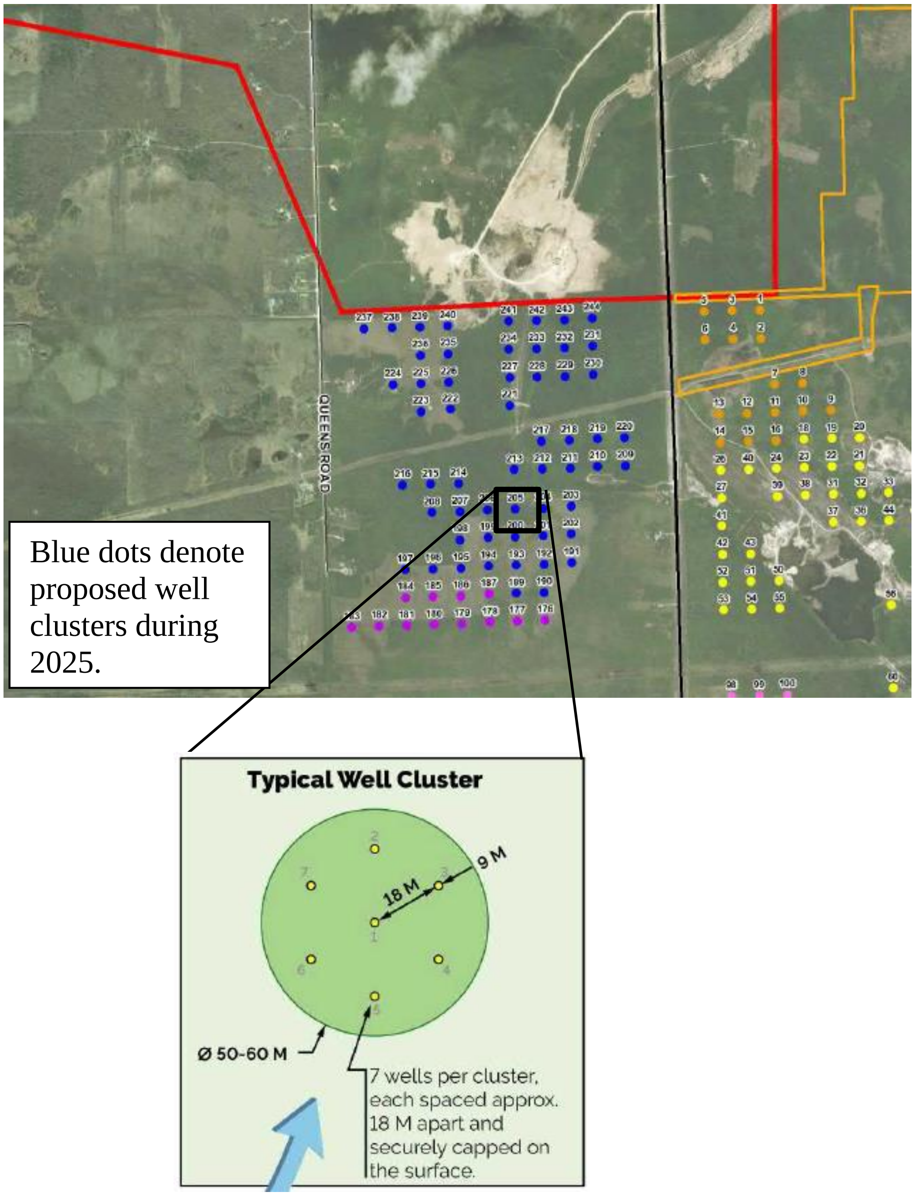


Figure 1. Concept for the proposed well layout during operations

5. It is indicated on Page 19 of the *Hydrogeology and Geochemistry Assessment Report* that the proponent proposes to extract Winnipeg Sandstone from an approximate depth of 51 m to 76 m. However, the conceptual illustration in Figure A-2 suggests that the Winnipeg Shale lies at a depth of 51 m to 54 m. In RMSF-IR-007 it was asked whether the extraction depth of the sandstone should be at least 54 m. The proponent has provided a detailed response to RMSF-IR-007, explaining that the elevations shown in Figure 2-A referred to only one well at a specific location and were included only for illustration purposes.

   The sedimentary rocks dip to the west. Based on the available logs for water wells, the interpreted elevations of the top of the Winnipeg Sandstone range from 240 masl to 180 masl across the Project Site Area and the elevations of the base of the Winnipeg Sandstone range from 200 masl to 160 masl. The response to RMSF-IR-007 (b) refers to the estimated depth to the top of the Winnipeg Sandstone indicated in the response to RMSF-IR-007 (a). However, only the elevations of the top and bottom of the Winnipeg Sandstone are indicated in the response, not the depth to the top of the unit. Estimating a ground surface elevation of about 290 masl from Figure 5-1, the estimated depths to the top of the Winnipeg Sandstone range from 50 m to 110 m.

6. It is indicated on Page vi of the *Environmental Act Proposal* that through 2025, "approximately" 0.18% of the silica sand resource will removed and that over the full 24-year lifespan of the project "approximately" 1.06% of the silica sand will be removed. In the response to RMSF IR-008, the proponent has provided the basis for the values. Since these calculations are not developed elsewhere in the documentation, the values are checked here.

   - Sio Silica has been granted mineral claims over an area that was estimated in 2019 to contain 3,202 Mt of sand-in-place. The proponent has proposed extracting 5,628,000 tonnes of sand over the initial 4 years of operation.

$$\frac{5{,}628{,}000\ \text{tonnes}}{3{,}202\ \text{Mt}\left|\frac{1{,}000{,}000\ \text{tonnes}}{\text{Mt}}\right|} \times 100 = 0.18\%\ \surd$$

   - Sio Silica has proposed extracting 1,360,000 tonnes of sand per year for 24 years. This corresponds to a total extraction of 32,640,000 tonnes.

$$\frac{32{,}640{,}000\ \text{tonnes}}{3{,}202\ \text{Mt}\left|\frac{1{,}000{,}000\ \text{tonnes}}{\text{Mt}}\right|} \times 100 = 1.02\%\ \surd$$

4.3 Site characterization

7. As part of the site investigation, a constant-rate pumping test was conducted at well Bru 95-7, which is open across the Winnipeg Sandstone. As shown in Figure 1-4 and Figure 3-1 of the *Hydrogeology and Geochemistry Assessment Report* and here in Figure 2, a relatively large number of domestic wells in the vicinity of Bru 95-7 were identified from the Manitoba provincial database. In the response to RMSF-IR-011 it is confirmed that only three of these wells were monitored during the pumping test, Obs 23901, Obs 66124 and Obs S1. Obs 23901 and Obs 66124 are open across the Red River Carbonate Formation and are located 660 m and 491 m from the pumping well, respectively.

   Only Obs S1 is open across the same formation as the pumping well and it is located 960 m from the pumping well. It is indicated in the response to RMSF-IR-011 that well Obs S1 is a geoexchange well. The yellow dots in Figure 2 denote the locations of wells indicated the water well database as being open across the Winnipeg Sandstone. It is not indicated in the report whether Obs S1 was the nearest accessible domestic well in the Winnipeg Sandstone.

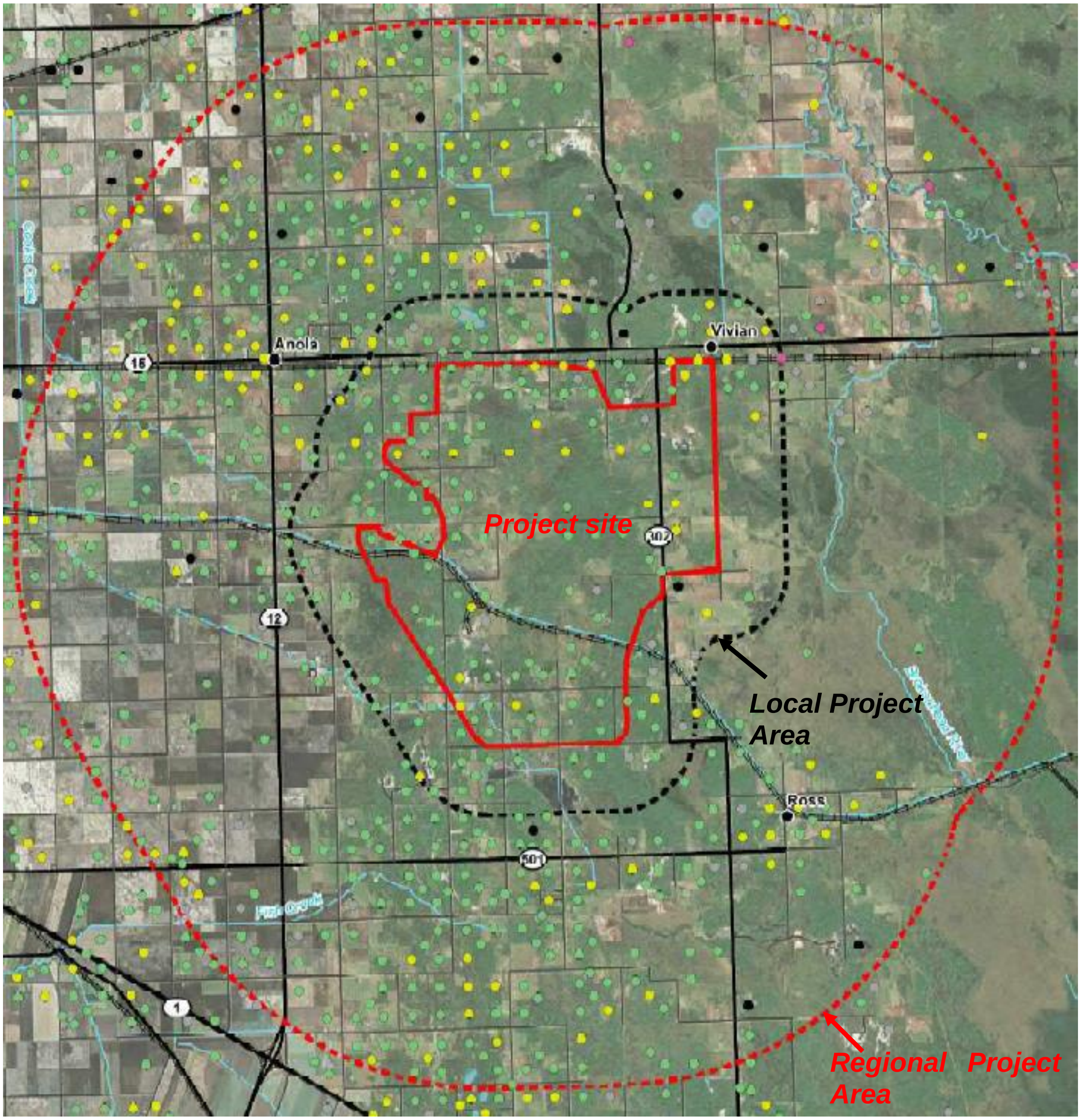


Figure 2. Map of existing groundwater users, colour-coded by aquifer
(Excerpt from AECOM, 2021b, Figure 1-3)

8. Although it is indicated on Page 29 of the *Hydrogeology and Geochemistry Assessment Report* that a step test was conducted at the pumping well Bru 95-7 prior to the constant-rate pumping test, no data or analyses are reported. It is indicated that “Evaluating the hydraulic efficiency of the pumping well was not part of the scope of work.” It is unfortunate that the data from the step test were not analyzed. In my experience, distance-drawdown analyses provide the most reliable estimates of the bulk-average transmissivity. As shown in the distance-drawdown plot reproduced from Appendix E shown here in Figure 3, the data from only three observation wells were considered in the proponent’s estimation of the representative bulk-average transmissivity of the Winnipeg Sandstone. This is important here because the transmissivity of the Winnipeg Sandstone is the key parameter for the prediction of the propagation of the effects of pumping.

9. The data from step drawdown tests can frequently be used to identify additional well losses so that the drawdowns from the pumping well can be treated as if the well was another observation well. The data from the step test may have provided valuable insights explaining the relatively low efficiency of the pumping well (the observed drawdown at the end of pumping of about 32.5 m is about double that inferred from the distance-drawdown analysis).

   It is suggested on Page 31 of the *Hydrogeology and Geochemistry Assessment Report* that the “excess drawdown” in the pumping well was due primarily to residual drilling mud in the sand pack and surrounding formation. This does not appear to be consistent with the text on Page 26 of the report, which indicates that an extensive development effort was undertaken prior to conducting the constant-rate pumping test.

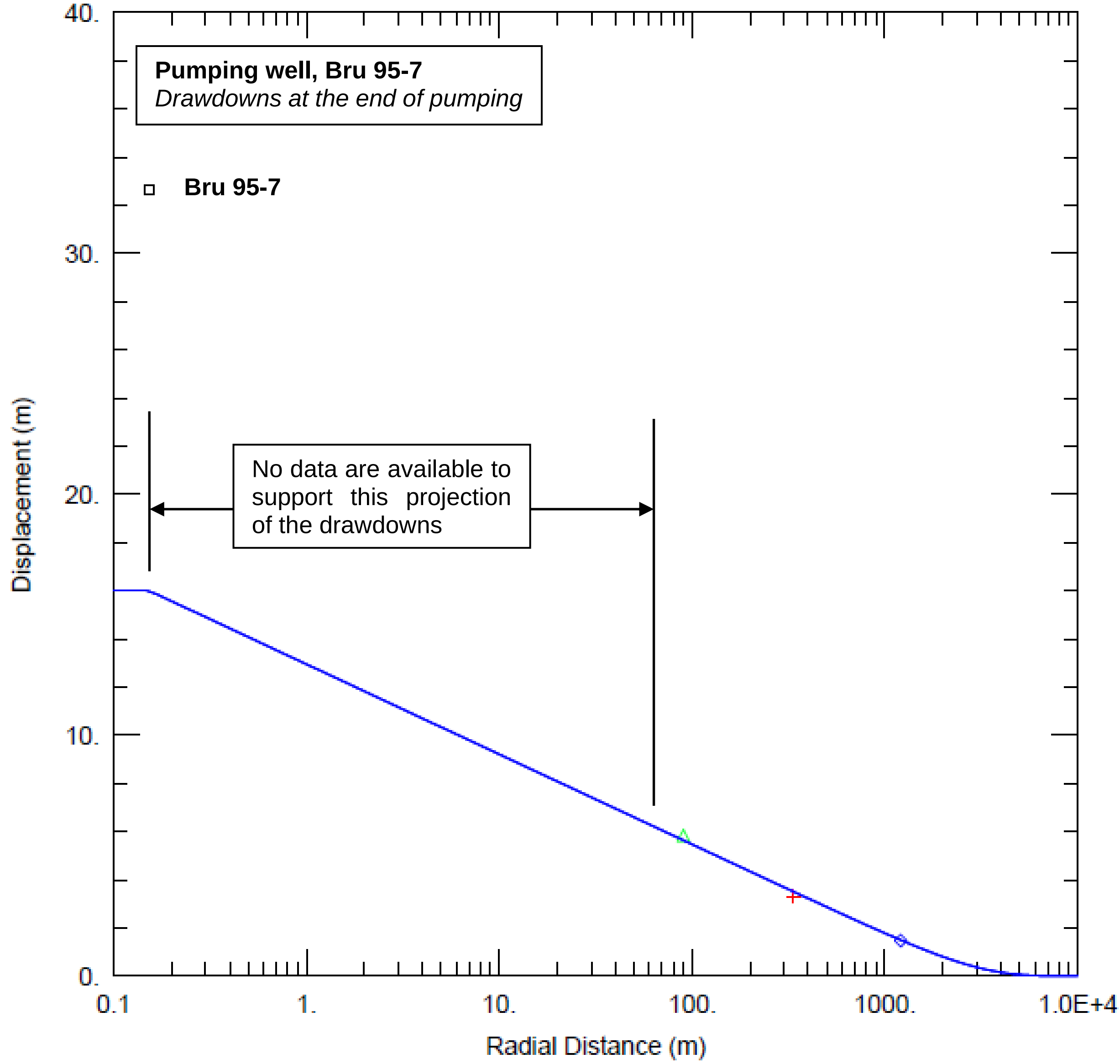


Figure 3. Distance-drawdown analysis for Bru 95-7 pumping test
Adapted from AECOM (2021; Appendix E.2)

10. The analytical models used to match the observations from the Bru 95-7 pumping test are the based on the Theis (1935) model of an ideal confined aquifer. Among the most important assumptions of the Theis solution is that the aquifer is homogeneous. Some of the results of the analyses listed on Table 3-C of the *Hydrogeology and Geochemistry Assessment Report* are consistent with this assumption, while others are not. The transmissivities estimated from matching the observation well drawdowns with the Theis solution and the Cooper and Jacob (1946) straight-line analysis are consistent, as they should be when applied in a consistent manner. In contrast, the matching of the pumping well drawdowns with the Theis solution yields a transmissivity that is about half of the value estimated for the observation wells. The transmissivity estimated by matching the observed pumping well drawdowns with the Theis (1935) solution is not reliable here, as the analysis is affected by additional well losses. As shown in Figure 4 here, the Cooper-Jacob analysis effectively filters the additional well losses and the transmissivity estimated for the pumping well is consistent with the observation wells.

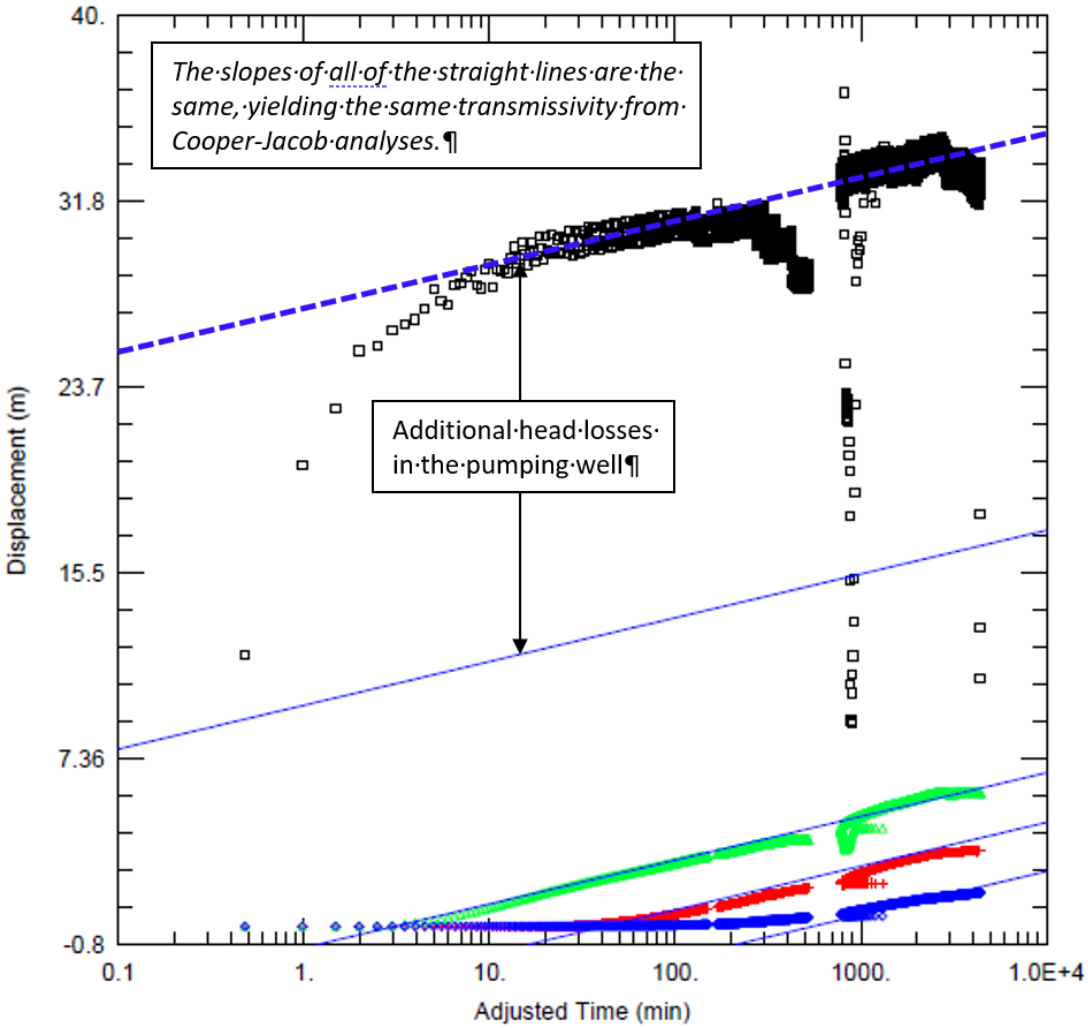


Figure 4 Inference of additional well losses in Bru 95-7
Adapted from AECOM (2021; Appendix E.2)

11. The responses observed following the end of pumping are complex. In an ideal confined aquifer, the recovery data for the pumping well and observation wells should eventually approximate a single straight line that approaches the asymptotic value of zero residual drawdown as *t/t'* approaches a value of 1.0 (indicated by the red circle in Figure 5). The data satisfy neither of these conditions. The fact that the recovery records approach values of zero drawdown for values of *t/t'* of about 9, 20 and 25 rather than 1.0 suggests that the drawdown cone at the end of pumping is replenished by a source of water in addition to confined storage.

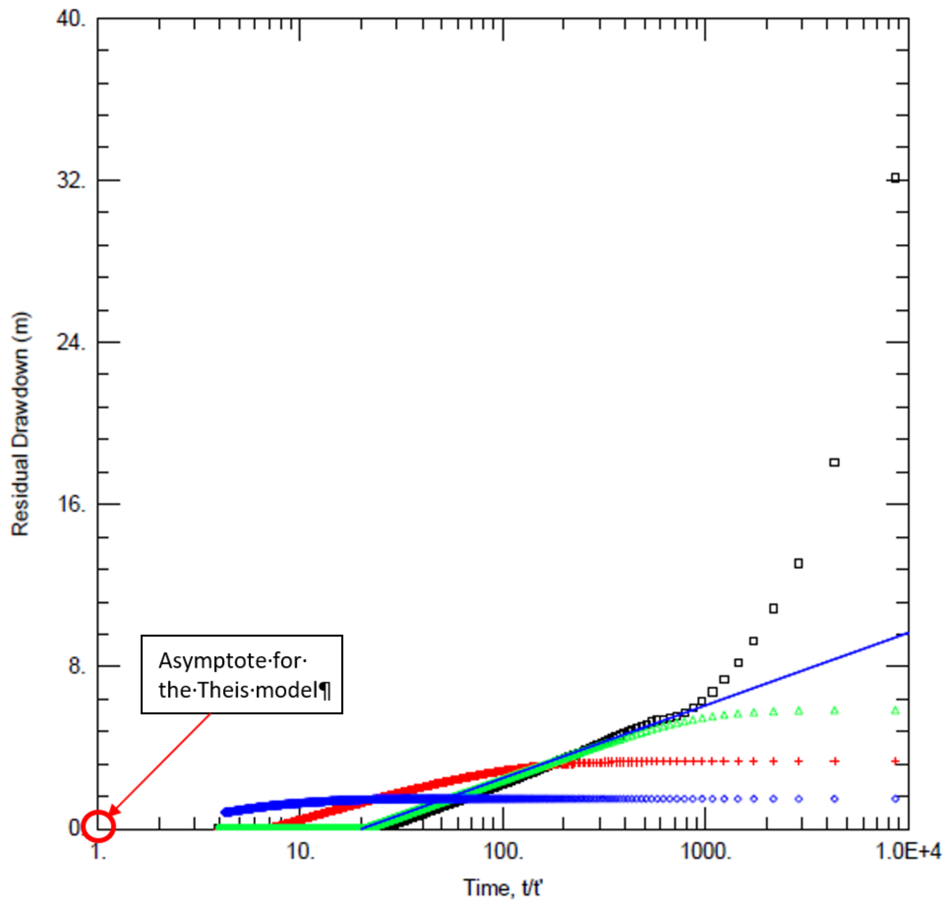


Figure 5. Recovery analysis for the Bru 95-7 pumping test
Adapted from AECOM (2021; Appendix E.2)

12. The additional source of water that is inferred from the recovery portion of the pumping test may be leakage across the Winnipeg Shale. A drawdown of 2.8 m was observed at the vibrating wire piezometer in the shale (Bru 95-8 VW3). Drawdowns in the Red River Carbonate Formation were observed during the pumping test. Variable, but detectible, drawdowns (*s*) at the end of the pumping test are estimated from the hydrographs.

    - Bru 96-2: *s* = 0.18 m
    - Bru 95-5: *s* = 0.4 m
    - Bru 95-8 (VW2): *s* = 1.2 m
    - Bru 95-8 (VW1): *s* = 0.3 m

    The properties of the Winnipeg Shale are important with respect to the assessment, as this unit controls the hydraulic connection between the Winnipeg Sandstone and the Red River Carbonate. The report provides conflicting assessments of the Winnipeg Shale. It is indicated on page 32 of the report that in the area of proposed operations the Winnipeg Shale is "an effective hydraulic barrier to interaction" between the Winnipeg Sandstone and the Red River Carbonate. However, it is indicated on Page 60 of the *Hydrogeology and Geochemistry Assessment Report* that the shale "is not well understood" and that its thickness is variable, ranging in thickness from 1 m to 24 m (citing Stantec, 2019). Only one slug test was conducted in the Winnipeg shale (Bru 95-9) and the vertical hydraulic gradients reported on Page 32 of the *Hydrogeology and Geochemistry Assessment Report* are based on only one monitoring located in the shale (Bru 95-8 VW3). In my opinion, there is limited evidence to support the conclusion that the shale is an effective hydraulic barrier between the sandstone and the shale.

13. The interpretations of the vertical hydraulic gradients and directions of vertical groundwater flow on Pages 64-65 of the *Hydrogeology and Geochemistry Assessment Report* are consistent with the values reported on Table 5-B. However, they are not consistent with the sign convention for the gradient adopted in Figures 5-12 to 5-14.

    <u>G05SA003 – G050SA013 [G05SA013] (Figure 5-12)</u>

    - G05SA003 is the upper well, open in the Red River Carbonate.
    - G050SA013 is the lower well, open in the Winnipeg Sandstone.
    - The water levels in G05SA003 are almost always lower than in G050SA013. Therefore, the hydraulic gradient is *negative*, not positive as indicated in Figure 5-12. Vertical groundwater flow should almost always be upwards.

    <u>G05SA014 – G050SA015 [G05SA015] (Figure 5-13)</u>

    - G05SA014 is the upper well, open in the Red River Carbonate.
    - G05SA015 is the lower well, open in the Winnipeg Sandstone.
    - The water levels in G05SA014 are always higher than in G05SA015. Therefore, the hydraulic gradient is *positive*, not negative as indicated in Figure 5-13. Vertical groundwater flow should always be downwards.

<u>G050J163 – G050J175 (Figure 5-14)</u>

- G05OJ163 is the upper well, open in the Red River Carbonate.
- G05OJ175 is the lower well, open in the Winnipeg Sandstone.
- The water levels in G05OJ163 are always higher than in G05OJ175. Therefore, the hydraulic gradient is *positive*, not negative as indicated in Figure 5-14. Vertical groundwater flow should always be downwards.

<u>G050J176 – G050J177</u>

Hydrographs for the fourth pair of wells listed on Table 5-B, G050J176 and G050J177, were not included in the *Hydrogeology and Geochemistry Assessment Report*. The hydrographs have been included in the response to RMSF-OR-013. Contrary to what is suggested on Table 5-B, the vertical hydraulic gradient at this location is generally <u>not</u> neutral. The data shown in the hydrograph suggest that during the spring the water level in G050J177 was higher than in G050J176, while through the summer and fall of 2020 the water level in G050J176 was higher. These data suggest that the vertical hydraulic gradient changes direction during the year.

14. It is indicated on Page 66 of the *Hydrogeology and Geochemistry Assessment Report* that the difference between water levels in the Red River Carbonate Formation and the Winnipeg Sandstone Formation suggest that the two aquifers are "not highly interconnected in the immediate vicinity of the observation wells listed on Table 5-B". The data that are presented do not support this suggestion. Inspection of Figures 5-12 through 5-14 suggests there is a direct connection between the two aquifers. In the case of wells G05SA003 and G050SA013 (Figure 5-12), the water levels in the two wells are nearly identical. In the cases of wells G05SA014/G050SA015 and G050J175/G050J163 (Figure 5-13 and Figure 5-14), the trends in the water levels are similar and the daily fluctuations in the records in the two wells at each location track each other closely.

    The data suggest it is likely that the natural variability in the thickness/spatial extent and hydraulic properties of the Winnipeg Shale are the most important contributors to the exchange of water between the two aquifers.

4.4 Groundwater modelling

15. The groundwater model includes single layers representing the Red River Carbonate (model layer 4) and the Winnipeg Shale (model layer 5). In my experience, where carbonate rocks are the uppermost rocks, it is typical to encounter an interval of weathered rock that has properties quite distinct from the underlying rock. It is generally appropriate modelling practice to incorporate a separate layer representing the top-of-rock zone.

16. I concur that recharge is a key driver of the regional flow balance. Referring to Table 6-B of the *Hydrogeology and Geochemistry Assessment Report*, I note that recharge accounts for 98% of the simulated inflows to the groundwater model. Calibrated hydraulic conductivity values are reported on Table 6-C and calibrated recharge rates are reported on Table 6-D. The recharge rates and vertical hydraulic conductivities of the surficial sediments are directly correlated and cannot be estimated independently. The reporting does not include any indication of how the correlation between hydraulic conductivity and recharge has been addressed in the analyses.

17. In my opinion, it is possible that the recharge over the model area is overestimated. It is indicated on Page 73 of the *Hydrogeology and Geochemistry Assessment Report* that the recharge is related to the mean annual precipitation at the Ostenfeld climate station for 1981-2020, 639 mm. Depending on the source, it appears that the average annual precipitation near Winnipeg is substantially less, between about 450 mm and 520 mm (see for example, (https://weather-and-climate.com/average-monthly-precipitation-Rainfall-inches,winnipeg,Canada and https://www.weather-atlas.com/en/canada/winnipeg-climate#snowfall). Referring to the excerpt from the Atlas of Canada reproduced here in Figure 6, the average annual precipitation over the study area is about 21 inches (530 mm).

    A simplified analysis of the precipitation surplus (Precipitation – Evapotranspiration), which represents the maximum amount of water that is available to recharge the water table, has been developed with the Thornthwaite-Mather analysis. According to the results of my calculations shown in Figure 7, the average annual surplus is about 130 mm. The implied annual evapotranspiration from the Thornthwaite-Mather analysis is 400 mm, which is roughly consistent with the average annual value of 450 mm mapped in Morton (1975) [see Figure 8].

    The recharge rates applied for the Birds Hill and Sandilands areas of the groundwater model are substantially larger than 130 mm (250 mm/yr and 189 mm/yr, respectively). Specification of too high recharge rates will have the effect of attenuating the simulated effects of the proposed development. In my opinion, it is appropriate practice to obtain water budgets from the Engineering Climate Services of Environment Canada for several climate stations around the study area (ec.scg-ecs.ec@canada.ca).

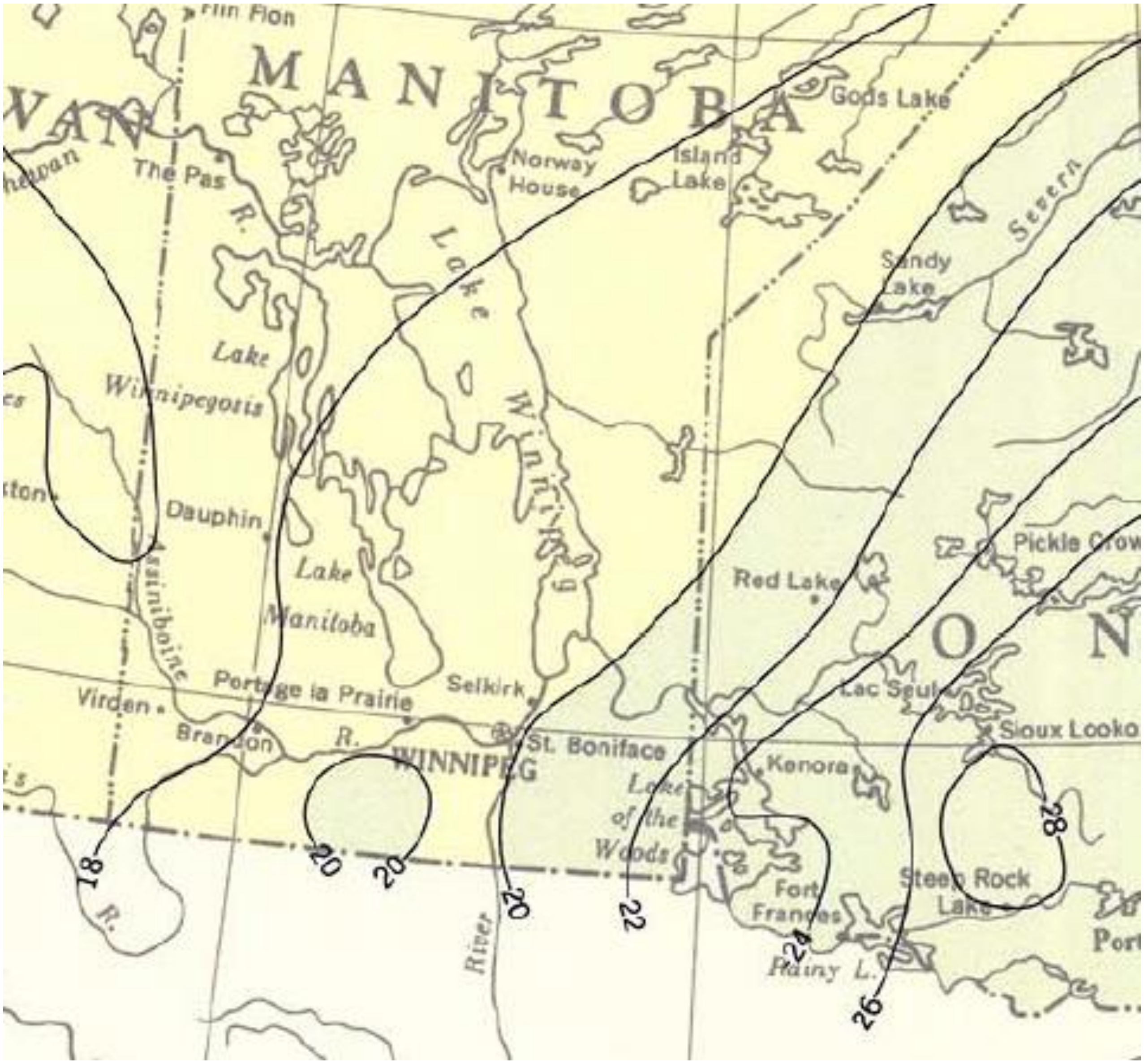


Figure 6. Average annual precipitation (inches)
Reproduced from Atlas of Canada (Meteorological Division, Department of Transport, 1957)

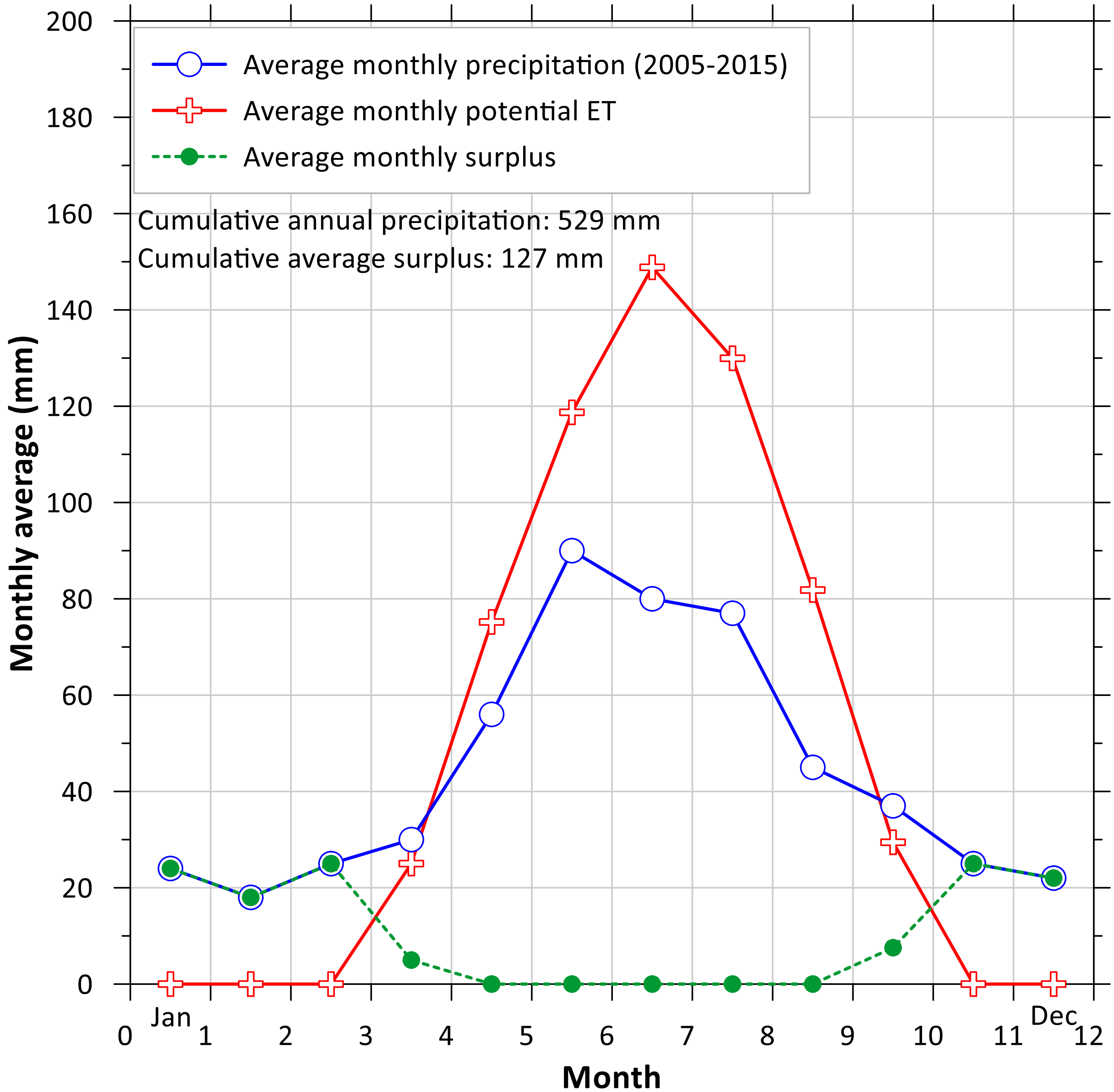


Figure 7. Simplified Thornthwaite-Mather analysis to estimate the average annual surplus

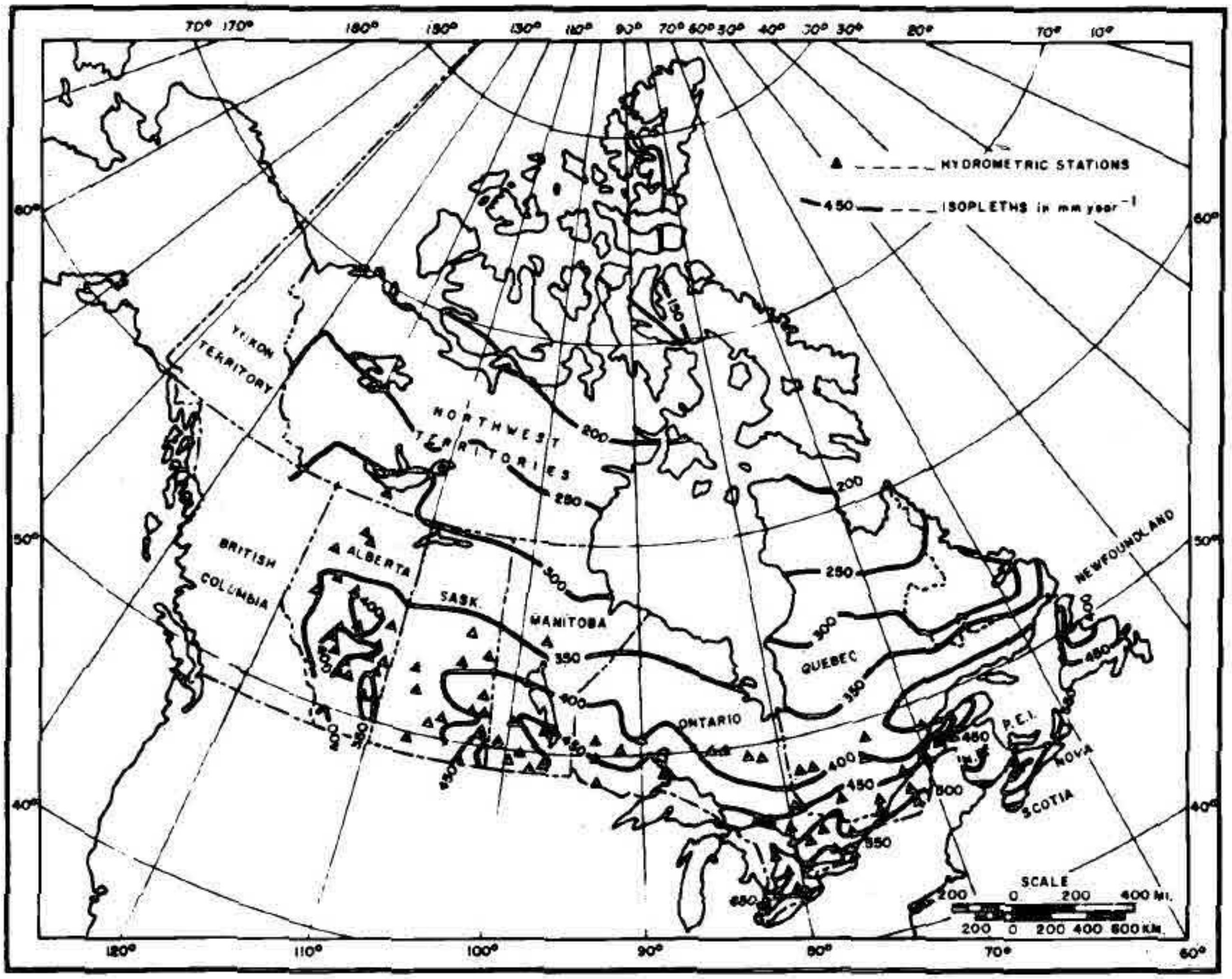


Figure 8. Average annual evapotranspiration (mm)
(Reproduced from Morton, 1975)

18. A scatterplot comparing the model results against the targets for the steady-state calibration is presented in Figure 6-2 of the *Hydrogeology and Geochemistry Assessment Report* and reproduced here in Figure 9. In my opinion, the scatterplot does not provide a convincing demonstration that the model has been adequately calibrated. I base my opinion on the following observations.

    - No distinction is made between the reliability of the water levels that are used as targets. Average water levels estimated for dedicated observation wells installed for the project and the wells from the Manitoba Provincial Monitoring Program should be assigned higher weights in the calibration. In terms of the graphical presentation, the symbols for these wells should be prominent.

    - As shown in Figure 9, the model exhibits a clear bias to overpredict water levels. The mean residual is 3.27 m.

    - As indicated by the red dashed lines added in Figure 9, at the location of any particular target it appears that the mismatch of the model is likely on the order of ±15 m. It may be debated that the Root Mean Square Error (RMSE) is a better measure of the local mismatch than the range of the errors estimated here by eye. Acknowledging this, it is still important to note that for this model the RMSE of 5.46 m is relatively large compared to the anticipated effects of the proposed operations.

    - Although the Normalized Root Mean Square Error (NRMSE) is frequently adopted as a measure of the model goodness-of-fit, it is important to note that it is open to mis-application. In particular, the value of the NRMSE depends on the interpreted range of the observed water level targets. The NRMSE is defined as:

    $$NRMSE\ (\%) = \frac{RMSE}{Range\ of\ Observations} \times 100$$

    Noting that the reported RMSE is 5.46 m and the reported NRMSE is 1.70%, the back-calculated Range of Observations is 321.2 m. As shown in Figure 9, the range of the observations is more likely 125 m. With this range the NRMSE is re-calculated as 4.3%.

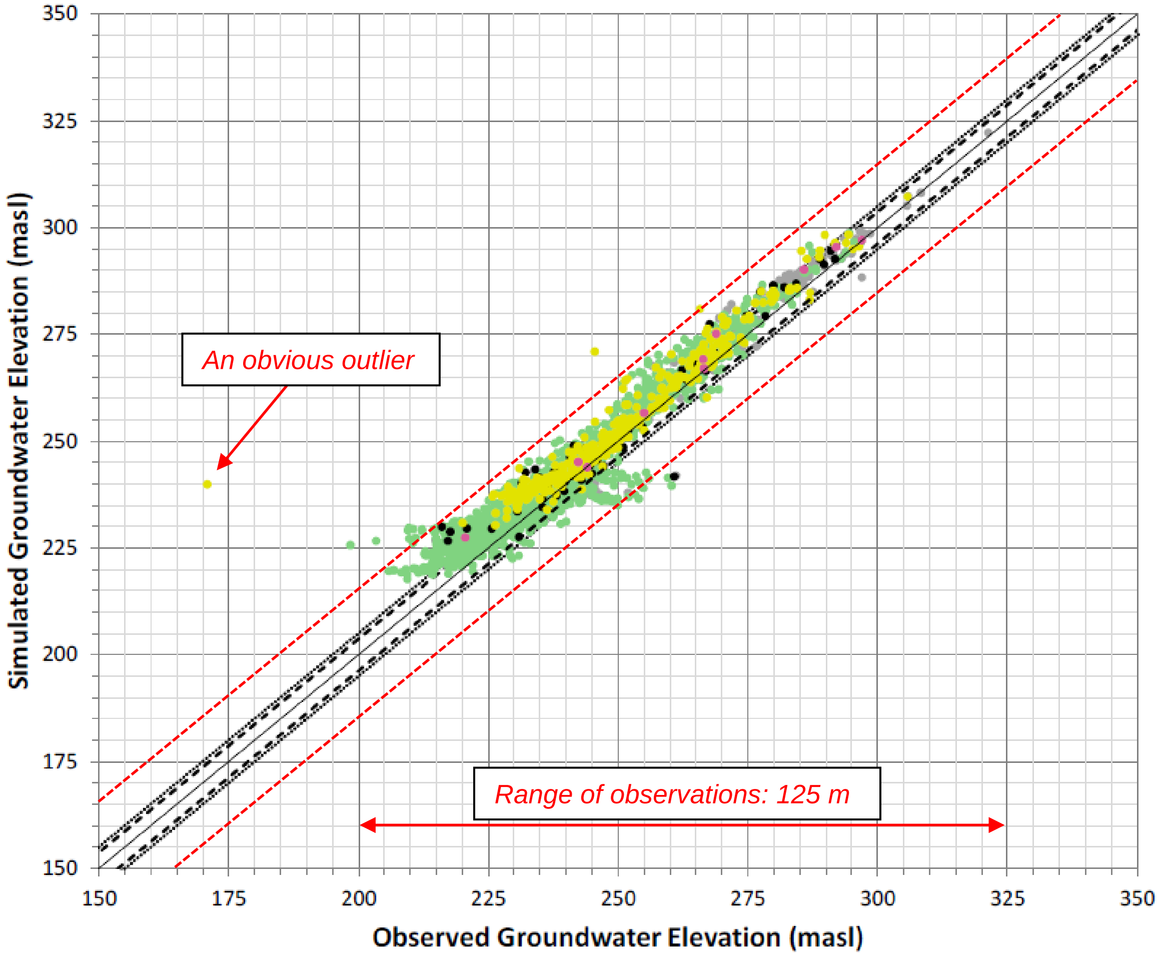


Figure 9. Scatterplot for the steady-state model calibration
Adapted from AECOM (2021b; Figure 6-2)

19. It is indicated on Page 72 the *Hydrogeology and Geochemistry Assessment Report* that at lower elevations, the calibrated steady-state groundwater model simulates groundwater levels that are higher than observed. The mismatch near Winnipeg is attributed to increased groundwater use in the area east of Winnipeg that is not accounted for in the modelling analysis. Based on my examination of Figure 6-3, the mismatch along the Red River is more suggestive of a problem with the model structure. As shown in the excerpt from Figure 6-3 shown here in Figure 10, there is an area close to Winnipeg where the simulated water levels are more than 10 m *lower* than observed (red circles; observed – simulated > 10 m). North of this area there is an area close to Red River Floodway where the simulated water levels are more than 10 m *higher* than observed (pink circles; observed – simulated < - 0 m). The large positive and negative residuals suggests that the boundary conditions may not be assigned appropriately.

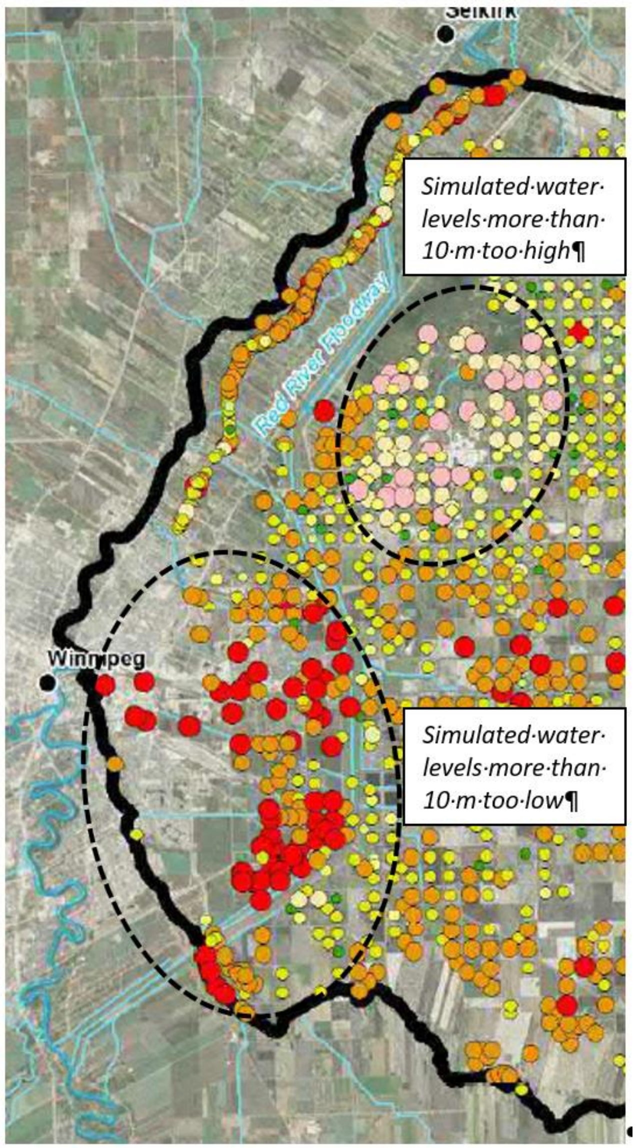


Figure 10. Detail of calibration residuals near Winnipeg
Excerpt from AECOM (2021b; Figure 6-3)

20. It is indicated on page 73 of the *Hydrogeology and Geochemistry Assessment Report* that at distances greater than 300 m the groundwater model simulates smaller drawdowns than were observed during the pumping test. This is highlighted in the comparison between observed and simulated drawdowns at the end of the pumping test. The drawdowns have been estimated from Figure 6-4. The results shown here in Figure 11 suggest that there is a systematic underestimation of the drawdowns at more distant locations in the Winnipeg Sandstone. This has important implications with respect to the impact assessment, as it is an indication that potential impacts on neighboring private wells may be underestimated.

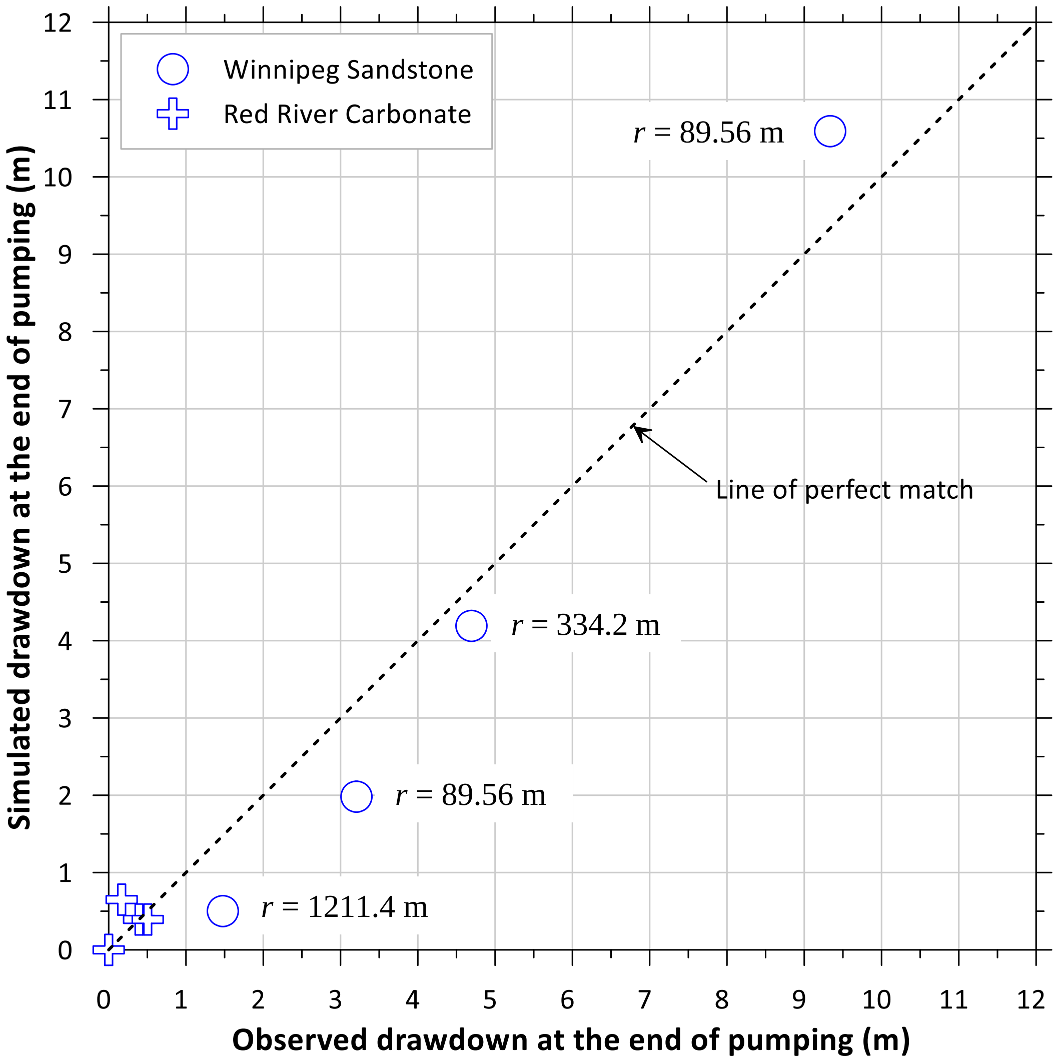


Figure 11. Comparison of observed and simulated drawdowns for the Bru 95-7 pumping test

21. Limited data are available to assess whether representative values of the hydraulic conductivities of the Winnipeg Sandstone and the Red River Carbonate have been inferred through model calibration. As shown here in Figure 12, although the value of the hydraulic conductivity of the Winnipeg Sandstone specified in the groundwater model is consistent with the estimates obtained from the two slug tests, it is substantially lower than the value inferred from the pumping test. The hydraulic conductivity of the Red River Carbonate specified in the groundwater model is within the range of the two estimates obtained from slug tests, but the most important conclusion that might be drawn from the comparison is that the two slug test estimates vary by a factor of about 25.

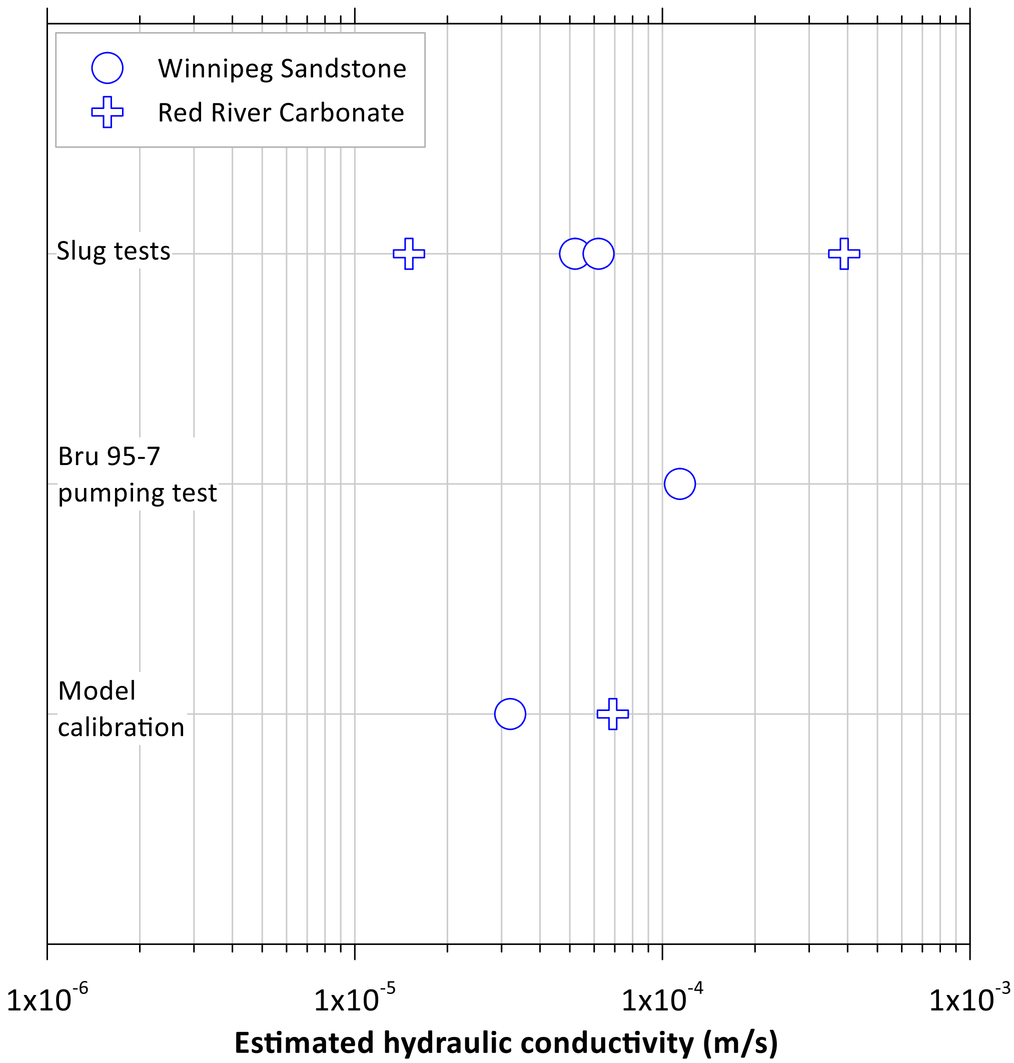


Figure 12. Summary of hydraulic conductivity estimates

22. Certain other aspects of the presentation of the calibrated aquifer properties in Section 6.9.3 are not clear in the documentation.

- Referring to Figure 5-4 of the *Hydrogeology and Geochemistry Assessment Report*, the Lower Shale/Precambrian Bedrock is represented with a model layer that extends to an elevation of 0.0 m (i.e., mean sea level). The model layer is assigned a hydraulic conductivity that is 7 orders of magnitude less than the overlying Winnipeg Sandstone. It was not clear from documentation what data were available to constrain the assignment of the hydraulic conductivity of the Lower Shale/Precambrian bedrock. Details for supporting the specification of the of the hydraulic conductivity of the Lower Shale/Precambrian bedrock are provided in response to RMSF-IR-014.

  "*It is acknowledged that the hydraulic properties of these very deep units are poorly constrained, but they are not likely important to the conclusions and recommendations of the Hydrogeology and Geochemistry Assessment given their depth and likely low permeability in comparison to the overlying units*."

- The basis for assigning the vertical hydraulic conductivities of the stratigraphic units was not indicated in the documentation. In the response to RMSF-IR-014 it is indicated that with the exception of the Red River Carbonate, a vertical anisotropy ratio of 1:10 was simply assumed. It is also indicated in the response that sensitivity analyses were not conducted to assess the significance of the vertical hydraulic conductivity with respect to the model calibration and predictions. It is not clear whether the vertical hydraulic conductivities specified in the groundwater model have an important influence on the prediction of potential impacts of the development. Of greater significance is the potential large-scale change in the properties of the Red River Carbonate and the Winnipeg Sandstone arising from collapse of the intervening shale.

- In response to RMSF-IR-014 it is indicated that although a sensitivity analysis with respect to values of the specific storage was not conducted, the results "are relatively well constrained by literature values".

4.5 Impact assessment

23. For the case of 0% re-injection, the pumped water is simply removed from the model. From the perspective of the impact assessment, this simulation will yield worst-case results, that is, it will have the effect of exaggerating the potential impacts.

24. Referring to the response to RMSF-IR-015, it is my understanding that the re-injection of groundwater is not explicitly simulated. Instead, for the case of 50% re-injection an "effective" pumping rate equal to about half the extraction rate from the equivalent well at the center of a cluster is specified. The relatively small difference between 550 USgpm/2 and the rates of 265 USgpm and 275 USgpm cited in the response to RMSF-IR-015 reflects the residual moisture on the extracted sandstone.

25. Referring to Pages 5-6 and Figures 6-9 to 6-13 of the *Hydrogeology and Geochemistry Assessment Report*, the limits of groundwater impacts are defined as the 1.0 m drawdown contour. It is indicated that changes in groundwater levels of this magnitude are similar to those experienced due to natural seasonal variability. This interpretation should be confirmed with a review of the magnitudes of the natural fluctuations in the water levels in the wells in the Manitoba groundwater monitoring program within the model area (Figure 6-1).

26. The predictions shown in Figure 6-7 of the *Hydrogeology and Geochemistry Assessment Report* should correspond to Scenario 4 (p. 74) and the predictions shown in Figure 6-8 should correspond to Scenario 5. However, the same pumping histories are shown in Figures 6-7 and 6-8. The following correction is issued in the response to RMSF-IR-016.

    The pumping history shown on Figure 6-8 does not reflect the pumping history simulated by Scenario 5. This graph should reflect pumping rates that follow a similar temporal pattern to those shown, but vary in magnitude from approximately 280 US gpm to 0 US gpm seasonally as illustrated in Appendix H of the Hydrogeology and Geochemistry Assessment Report.

27. Mining is assumed to have no effect on the properties of the Winnipeg Sandstone, either during or after pumping. The basis for the assumption is presented in the response to RMSF-IR-017.

    The project proposes to remove a very small proportion of the overall volume of sand in the Winnipeg Sandstone aquifer and will leave residual water-filled voids where the sand has been extracted. It is understood that this will increase the overall storativity of the aquifer as the effective porosity of the water-filled void will be 100%. Between the voids, the sandstone aquifer will not be disturbed by mining and will remain intact. Local hydrogeological properties (e.g., hydraulic conductivity and storativity) will be quite variable depending on whether measurements are collected within a water-filled void or within the intact aquifer between the voids. However, the scale of the project is regional, and the response of the aquifer to sand removal will be governed by regional aquifer properties as measured at the scale of the Representative Elementary Volume (REV), as the source of recharge is from both surface and distal inputs near the Sandilands Complex east of the project.

Reasonable efforts were undertaken to simulate the effects of sand extraction and groundwater reinjection on the aquifer and adjacent well users. Similar to other conventional underground mining projects, it is not possible to directly measure the magnitude of any change in aquifer properties prior to completion of mining. The numerical groundwater model developed for this assessment implemented time-variant changes in hydraulic properties around the production wells, in an effort to simulate the response of the aquifer to sand extraction.

The assumption that between the voids created by mining the Winnipeg Sandstone aquifer will not be disturbed by mining and will remain intact is a very strong assumption. While there is no evidence that sand extraction will lead to widespread collapse of the Winnipeg Sandstone and the rock units that overlie it, there is no evidence that this possibility can be discounted outright. In the response to RMSF-IR-017 it is indicated that the scale of the project is regional. It is possible that the scale of the *impacts* of sandstone mining will also be regional in scale. In the response to RMSF-IR-005 reference is made to pilot testing. However, no descriptions of the pilot testing are presented and there are no indications as to whether displacements of rock unit were measured during the testing. Although it may not be possible to directly measure the magnitude of any change in aquifer properties prior to completion of mining, it is certainly possible to measure ground movements and changes in groundwater conditions around the site during operations.

In the response to RMSF-IR-018 it is indicated that the areas with the potential for degradation of the Winnipeg Shale are estimated to be 188 ha (Year 0) to 691 ha (Years 1 through 4), "based on the simplified assumptions taken during groundwater modelling". These areas are sufficiently large to support detailed monitoring, which is the only real way to test the assumptions incorporated in the analyses. As the center of production shifts through time, the extent of zone of degraded shale is assumed to expand. Referring to the excerpt from Figure 6-5 of *Hydrogeology and Geochemistry Assessment Report*, shown here in Figure 13, the extent of the degraded shale is assumed to extend 200 m beyond the limits of the 2025 wells. It is indicated in the response to RMSF-IR-018 that the extent of the degraded zone will be "validated during operations". This validation will be essential to demonstrate that the effects of mining are understood, controllable and limited to the Project Site Area.

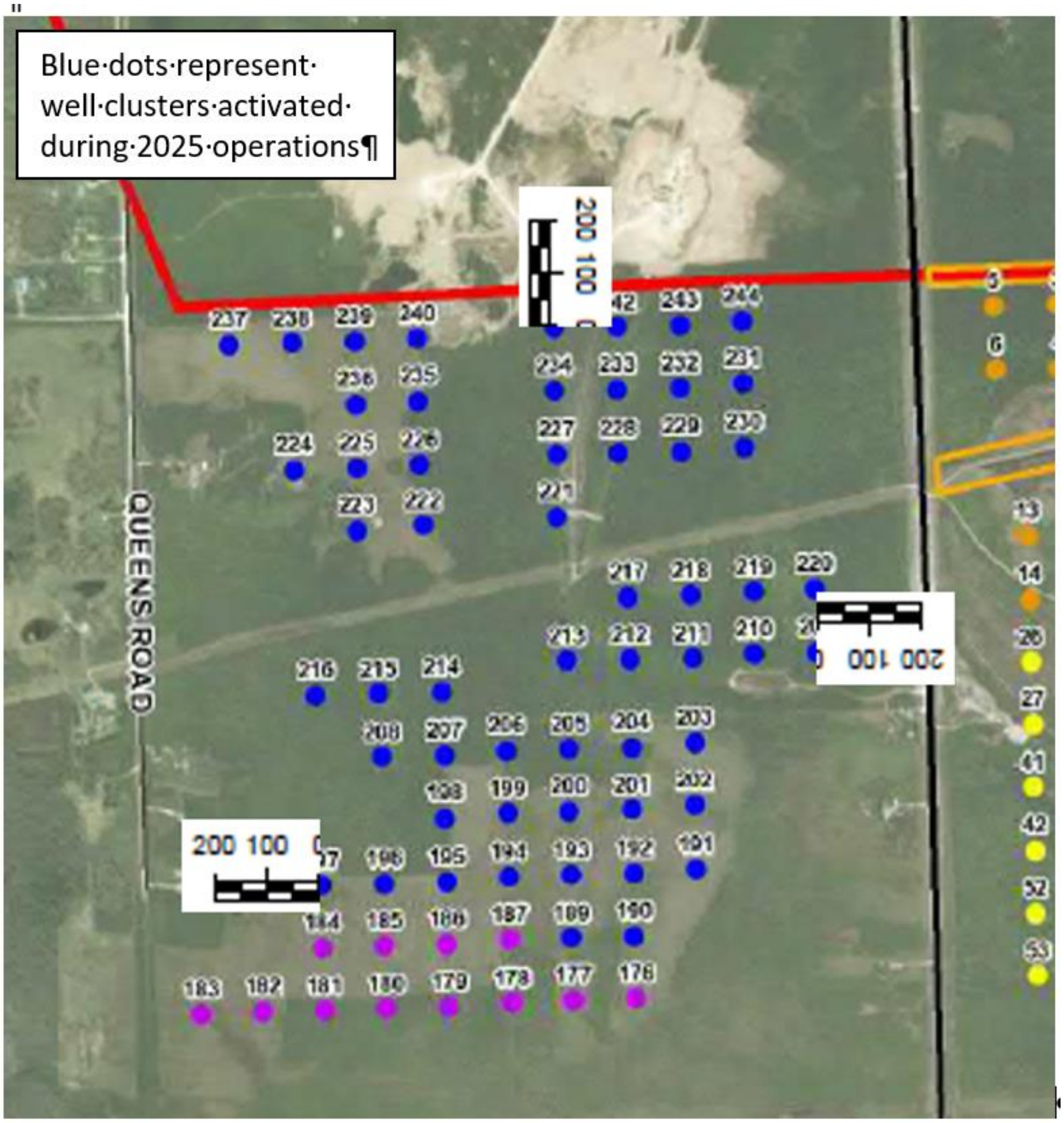


Figure 13. Well clusters activated during 2025
Adapted from AECOM (2021b; Figure 6-5)

28. In theory, it should be feasible to conduct a back-of-the-envelope check on the results for the steady-state analysis of Scenario 3 (0% re-injection, no degradation of Winnipeg Shale). Referring to Table 6-1, steady-state drawdowns of 0.9 m and 0.0 are reported for G05SA014 and G05OJ163, respectively. The Theis (1935) solution is applied here with the parameter values listed on Table 6-C, assuming an aquifer thickness of 21.1 m and specifying the approximate radial distances between 30-10-8E1 and G05SA014 and G05OJ163. It is not clear why the results of the groundwater model are so much smaller than those estimated with the Theis solution. My expectation is that the steady-state analysis would provide conservative upper-bound estimates on the drawdown.

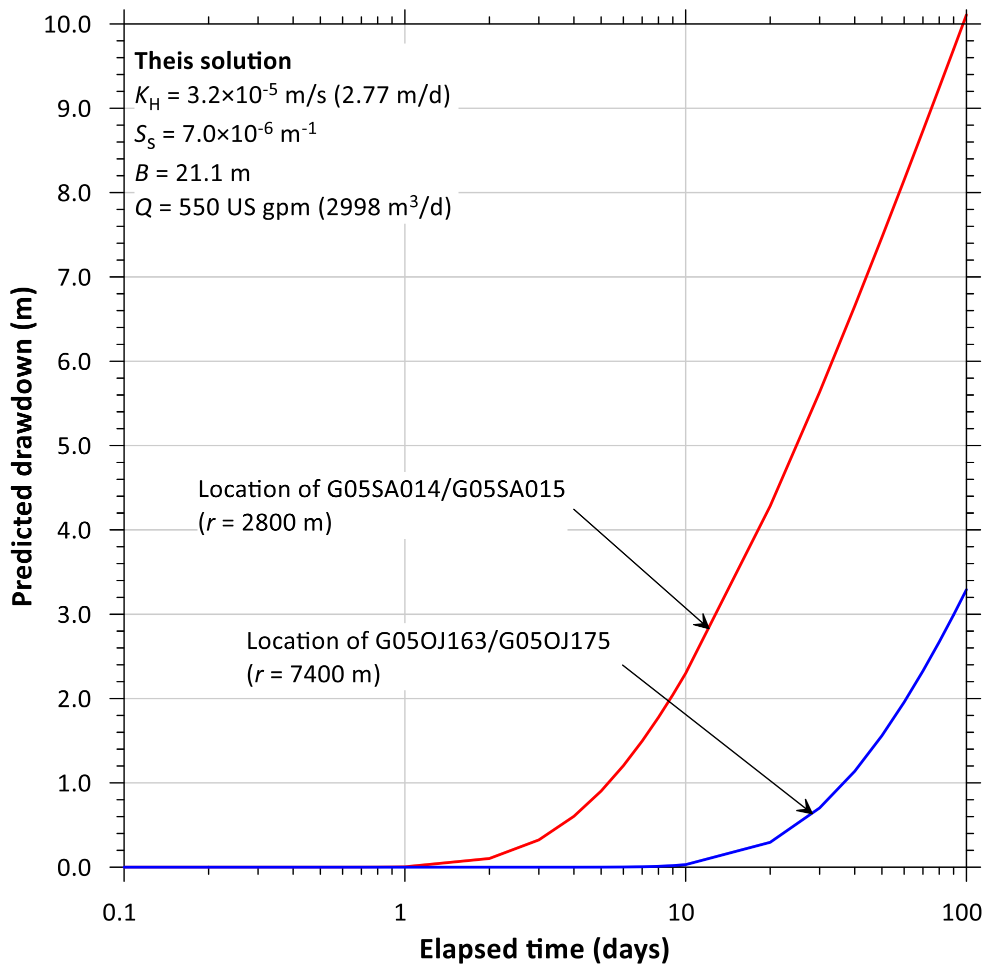


Figure 14. Results of simplified analysis of the transient response to pumping near well 30-10-8E1

29. It is not clear that the predictions of transient drawdowns are consistent with the results of the steady-state analyses presented in the *Hydrogeology and Geochemistry Assessment Report*. To compare the results between the scenarios, I have identified the time when pumping is closest to observation well 20-10-8E1 and extracted the results for well 20-10-8E1 from Table 6-1, Figure 6-7 and Figure 6-8. For the transient scenarios, the drawdowns listed below are estimated as the maximum drawdowns from the figures. Comparing the results of Scenarios 1 and 2, and Scenarios 4 and 5, it appears that the drawdowns scale with respect to the amount of re-injection. However, I cannot reconcile the differences in the magnitudes of the drawdowns for steady-state and transient conditions. It is physically realistic to expect the steady-state results to provide a conservative upper bound on the potential drawdowns; however, the reported steady-state drawdowns are small fractions of the transient results.

Scenario	Winnipeg Sandstone drawdown (m)	Red River Carbonate drawdown (m)
1 0% re-injection Shale degradation Steady-state	0.9	0.9
2 50% re-injection Shale degradation Steady-state	0.4	0.4
3 0% re-injection No shale degradation Steady-state	1.2	0.9
4 0% re-injection Shale degradation Transient	18.4	6.2
5 50% re-injection Shale degradation Transient	9.2	3.0

Section 5
Summary of peer review findings

The Rural Municipality of Springfield (RM of Springfield) has retained me to advise the municipality on the proposed groundwater aspects of the Vivian Sand Project to be developed by Sio Silica (previously CanWhite Sands Corp.). My role as hydrogeology peer reviewer for the RMSF involves identifying issues of potential concern for the RM of Springfield. These issues will be conveyed to the Manitoba Clean Environment Commission, which will in turn advise the Province of Manitoba. The ultimate decision to approve the proposal, and the conditions that may be attached to that approval, rest with the Province.

1. The material presented in *Hydrogeology and Geochemistry Assessment Report* does not alleviate my concerns that the site investigations have not adequately characterized the essential elements of the site and the potential impacts to groundwater resources in the RM of Springfield.

2. Creating a slurry of the Winnipeg Sandstone and extracting silica sand is expected to result in the development of horizontal arrays of "rooms and pillars" in the Winnipeg Sandstone. Referring to the response to RMSF-IR-010, the "rooms" refer to the combined voids created at each well cluster, and the "pillars" refer to zone of intact sandstone between the well clusters. Reference is made in the response to the loss of strength of the sandstone. Elsewhere in the responses, the proponent refers to pilot testing that has been conducted but there is no indication of whether the loss of strength was assessed during the pilot testing. It is indicated in the response to RMSF-IR-009 that "Some collapse of the overlying strata may occur but collapse is *expected* to be limited and not to spread to the surface." It is not clear from the project documentation whether this is an assumption, or data have been collected and analyzed to support this expectation. In the absence of data, it may be more appropriate to assume that the operations will result in a mass of loose sand with the potential for progressive, large-scale collapse of the overlying strata.

3. I support the indication that the following additional formal documents will be prepared:

   - Waste Characterization and Management Plan;
   - Groundwater Monitoring and Impact Mitigation Plan;
   - Water Management Plan; and
   - Progressive Well Abandonment Plan.

4. I support the indication that although the complete project has an anticipated lifespan of 24 years, the current proposal will extend only for 4.5 years (nominally half of 2021, and 2022 through 2025). This will provide an opportunity to assess the impacts of mining and the annual rehabilitation prior to the full scale-up of operations. I recommend that a formal report on the first year of performance during operations also be required.

5. If the proposal is approved, a detailed monitoring program will have to be implemented to ensure that widespread collapse of the units overlying the Winnipeg Sandstone is not occurring. The monitoring program will have to include an early-warning system that will halt operations if widespread collapse does occur and propagates to the ground surface.

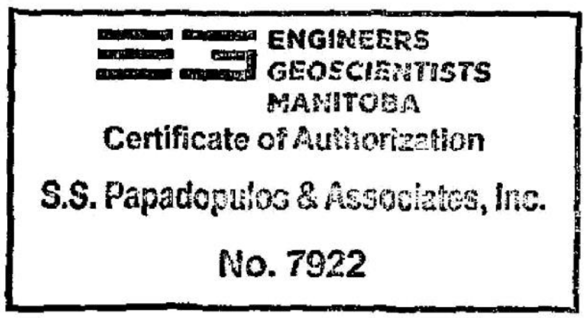
   The monitoring program required to validate the assumptions of the analyses must include monitoring of groundwater levels in the Winnipeg Sandstone, the Carbonate Aquifer, and detailed geotechnical monitoring of ground movements.

6. The practices adopted for well abandonment will be of particular concern for this project, as the wells will extend across and may connect the otherwise isolated Red River Carbonate and Winnipeg Sandstone. In my experience, improperly abandoned wells have acted as preferential pathways for the migration of surface contamination into deeper aquifers. It is suggested on Page iv of the Executive Summary of the *Vivian Sand Extraction Project – Environmental Act Proposal* that well drill cuttings may be included in the materials used to seal wells. It is also suggested on Page vii that calcified sand ("overs") may be used in well sealing activities. I caution against using drill cuttings and "overs" for this purpose. Wells should be sealed with bentonite and/or grout to surface to ensure that over the long term they can never act to connect the two aquifers. Furthermore, wells that are no longer in operation should be sealed in a continuous abandonment program rather than being left as open holes until groups of wells are abandoned.

Section 6
Signature page

This report was prepared by Mr. Christopher J. Neville, M.Sc., P.Eng., Chief Hydrogeologist of S.S, Papadopulos & Associates, Inc.

January 12, 2023



Section 7
References

AECOM, 2021a: CanWhite Sands Corp.: Vivian Sand Extraction Project Environmental Act Proposal, prepared by AECOM Canada Ltd., Winnipeg, Manitoba, July 23, 2021.

AECOM, 2021b: Vivian Sand Extraction Project – Hydrogeology and Geochemistry Assessment Report, July 2021.

Cooper, H.H., Jr., and C.E. Jacob, 1946: A generalized graphical method for evaluating formation constants and summarizing well-field history, *Transactions of the American Geophysical Union*, vol. 27, no. 4, pp. 526-534.

Morton, F.I., 1975: Potential evaporation – significance and measurement, in Report Series No. 42, pp. 9-12, Research Program, Environment Canada, Hydrology Research Division, Summaries of Progress and Short Progress Reports, Inland Waters Directorate, Water Resources Branch, Ottawa.

Meteorological Division, Department of Transport, 1957: Mean Annual Precipitation, 1921-1950, Atlas of Canada 3rd edition, compiled from information supplied by the, current publisher Natural Resources Canada, https://open.canada.ca/data/en/dataset/53377276-6db5-5ad6-82e6-dc9b7c70a321.

Theis, C.V., 1935: The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, *Transactions of the American Geophysical Union*, 16th Annual Meeting, Part 2, pp. 519-524.

APPENDIX

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

AREAS OF EXPERTISE

- Quantitative Interpretation of Hydrogeologic Data
- Groundwater Flow Modeling
- Solute Transport Modeling
- Peer review
- Litigation Support and Expert Testimony
- Professional Instruction

SUMMARY OF QUALIFICATIONS

Mr. Neville directs the Canadian operations of S.S. Papadopulos & Associates, Inc. from its Waterloo, Ontario office. His primary area of expertise is the quantitative analysis of groundwater flow and solute transport. He synthesizes hydrogeologic data, evaluates groundwater resources, develops regional and site-scale analyses of groundwater flow and solute transport, and evaluates remedial measures.

Mr. Neville has developed and documented large-scale three-dimensional numerical models for industrial, mining, and government clients, and has reviewed numerous site-specific hydrogeologic analyses and groundwater modeling codes. He has extensive experience in the development of work plans for groundwater projects and in directing groundwater modeling studies. He serves as a senior peer-reviewer and provides technical support for litigation. Mr. Neville is actively involved in the development of professional short courses in the interpretation of pumping tests and groundwater modeling, and he has assisted in teaching graduate courses at the University of Waterloo.

YEARS OF EXPERIENCE: 30+

EDUCATION

MSc, Earth Sciences (Hydrogeology), University of Waterloo, 1992
MEng, Course work for Geotechnical Engineering, University of Alberta, 1985–1987
BEng, Civil Engineering, McGill University, 1985

REGISTRATIONS

Professional Engineer
Ontario (PEO) #100013705
Manitoba (EGM) #48048

PROFESSIONAL HISTORY

S.S. Papadopulos & Associates, Inc., Senior-Staff Hydrogeologist to Chief Hydrogeologist, 1993 –1996, 1999 to present
Conestoga-Rovers & Associates, Inc. Senior Hydrogeologist, 1998
Klohn-Crippen Consultants Ltd. Senior Hydrogeologist, 1997
University of Waterloo Dept. of Earth Sciences, Research Assistant, Research Associate in Hydrogeology, 1987–1992

REPRESENTATIVE EXPERIENCE

INTERPRETATION OF HYDROGEOLOGIC AND GEOCHEMICAL DATA

- **Hanford Nuclear Reservation, Washington** — Provided senior technical review of the interpretation of slug tests in the 100 Area, the FR 3 area, and the BC 5 area. Provided technical review of the design and testing program for groundwater withdrawal wells in the 200 ZP 1 area. Reviewed the results of preliminary step drawdown tests of well EW 1. Directed and reviewed the interpretation of well development data and slug testing (100-Area). Interpreted step test and constant-rate pumping test data. Provided internal senior review of probabilistic analyses of horizontal and vertical groundwater velocity in the 100 Area. Directed, reviewed and documented the interpretation of RUM aquifer tests. Directed the interpretation of Cr (VI) column data and the development of nonequilibrium transport models to predict the progress of remediation.
- **Reid Gardner Generating Station, Moapa, Nevada –** Developed and documented the technical approach for estimating horizontal and vertical hydraulic gradients from monitoring data collected at the Reid Gardner Generating Station (RGS) site. Applied an extended version of Darcy's Law to accommodate variations in water density.
- **Onondaga,** New York — Developed a solute-transport analysis to estimate Darcy flux through lakebed sediments from concentration profiles.

- **Region of Waterloo,** Middleton Street Well Field — Interpreted hydraulic testing data for a municipal well field in fractured-karstic rock.
- **Schlage Lock Company,** Colorado Springs, Colorado — Modified and applied an axisymmetric finite-difference model for the interpretation of aquifer pumping tests.
- **Chem-Dyne Site,** Hamilton, Ohio — Developed and applied models for the interpretation of stepped-rate aquifer tests.
- **Texas-Eastern Gas Transmission Company,** Houston, Texas — Prepared a closure plan for a pump-and-treat remediation system of a BTEX plume in fractured porous-media.

SENIOR PEER REVIEW

- **Hanson Brick Co., Oakville,** Ontario, Canada — Provided senior peer review for the Region of Halton for the assessment of a proposed shale quarry.
- **Nelson Quarry, Burlington,** Ontario, Canada — Provided senior peer review for the Region of Halton for the assessment of a proposed expansion of a dolostone quarry.
- **Ontario Ministry of the Environment** — Served on the peer review panel for the development of guidance documents for Source Water Protection.
- **Credit Valley, Toronto and Region, and Central Lake Ontario Conservation Authority (CTC) Source Water Protection Region,** Canada — Served as senior peer review for the development of water budget studies and water quantity risk assessment.
- **Lake Erie Source Water Protection Region,** Canada — Served on a peer review panel for the development of water budget studies and water quantity risk assessment for the Long Point, Kettle Creek, and Catfish Creek Conservation Authorities.
- **York-Peel-Durham-Toronto (YPDT) Oak Ridge Moraine Groundwater Model,** Ontario, Canada — Provided senior peer review for the development and application of a large-scale regional groundwater flow model of the Oak Ridge Moraine area.
- **Waste Management Canada Richmond Landfill,** Ontario, Canada — Provided senior peer review for the analysis of the impacts of landfill expansion.
- **Arkell Spring Grounds, City of Guelph,** Ontario, Canada — Provided senior peer review in the analysis of impacts of increased water takings.
- **Vancouver Wharves Berth 1 Site,** Canada — Provided senior peer review for the modeling of measures to remediate groundwater contaminated with heavy metals.
- **CH2M HILL-Canada, Alder Creek Groundwater Study, Region of Waterloo** — Provided senior peer review in the development of the Alder Creek regional groundwater flow model.
- **Region of Waterloo** Ontario, Canada — Reviewed the delineation of capture zones for municipal supply wells in the Waterloo Moraine.
- **Smithville Phase IV,** Ontario, Canada — Reviewed groundwater-flow and solute-transport models for the evaluation of remedial alternatives for the Smithville PCB contamination site.

GROUNDWATER FLOW MODELING FOR WATER RESOURCES DEVELOPMENT AND PROTECTION

- **Region of Waterloo,** Ontario — Directed the groundwater modeling to support the updated characterization of the Middleton Street wellfield.
- **Region of Waterloo,** Ontario — Directed the groundwater modeling to support increased takings from the Blair Road wellfield.
- **Region of Waterloo,** Ontario — Directed the development of a groundwater model to support an application for additional water takings in the Cambridge East area.
- **Itapúa,** Paraguay — Directed the development of a regional groundwater flow model of the Guaraní transboundary aquifer for the region adjacent to the Paraná River in eastern Paraguay.
- **Prey Veng and Svay Rieng Provinces,** Cambodia — Directed the development of a regional groundwater flow model of southeastern Cambodia for the evaluation of the feasibility of the development of large-scale groundwater withdrawals for irrigation.
- **Town of Colgan,** Ontario — Developed a regional groundwater flow model to delineate a wellhead protection area for a proposed new municipal supply well.
- **Region of Waterloo,** Middleton Street Well Field — Directed the development of groundwater modeling analyses to support the delineation of capture zones and the estimation of the sustainable yield of the well field.
- **Region of Waterloo,** Greenbrook Well Field — Developed analyses to predict water-level recoveries following the shutdown of the well field.
- **Region of Waterloo,** Cedar Creek Groundwater Study — Directed the development of a groundwater model to evaluate groundwater resources and to anticipate the potential effects of large-scale gravel extraction.
- **Region of Waterloo,** Mannheim Well Field — Directed the delineation of capture zones for municipal supply wells.
- **Town of Marathon,** Ontario — Directed the development of a groundwater model to delineate wellhead protection areas for municipal wells.
- **Denver, Colorado – Directed groundwater modeling to estimate potential inter-aquifer flows during operation of a proposed geothermal system at the Colorado State Capitol.**
- **Itapúa,** Paraguay — Directed the development of a regional groundwater flow model of the Guaraní transboundary aquifer for the region adjacent to the Paraná River in eastern Paraguay.
- **Prey Veng and Svay Rieng Provinces,** Cambodia — Directed the development of a regional groundwater flow model of southeastern Cambodia for the evaluation of the feasibility of the development of large-scale groundwater withdrawals for irrigation.

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

GROUNDWATER FLOW AND SOLUTE TRANSPORT MODELING TO SUPPORT THE DESIGN AND EVALUATION OF REMEDIAL MEASURES AT CONTAMINATED SITES

- **SABIC (National Methanol Company) Ibn Sina,** Saudi Arabia — Developed the site conceptual model and directed the analysis of the migration and fate of MTBE.
- **Glenn Springs Holdings, Inc. (Occidental Chemical Corporation), Hyde Park Landfill,** Niagara Falls, New York — Directed the development of a large-scale groundwater model to evaluate capture of contaminated groundwater and to optimize remedial actions. Assignments included the development of work plans for data collection and interpretation, the supervision of hydraulic testing and analysis, and supervision of groundwater modeling.
- **Gurabo,** Puerto Rico — Directed numerical flow- and solute-transport modeling conducted to evaluate the performance of a pump-and-treat system.
- **Massachusetts Military Reservation,** Cape Cod — Developed an analysis to predict the extent of groundwater mounding due to the re-injection of treated groundwater.
- **Schlage Lock Company, Colorado Springs,** Colorado — Developed a groundwater model to assist in the evaluation of alternative pump-and-treat designs for remediation of a PCE plume.
- **Pacific Gas & Electric Company,** California — Developed and documented a groundwater flow and transport model for simulating the evolution of a plume of chromium-contaminated groundwater. Developed and documented analyses for the evaluation of remedial pumping alternatives.
- **Oregon Department of Environmental Quality,** Portland — Developed and applied a method of analysis for optimizing the placement of recovery wells for remediation of a large plume of TCE-contaminated groundwater and for protection of the City of Portland's emergency water supply.
- **Eastman Kodak Company,** Rochester, New York — Assisted in the development of a regional groundwater model that had automatic telescopic mesh refinement capabilities. Developed a user manual for the model, and provided a training course to enable Kodak staff to evaluate proposed remedial measures at the facility. Directed the updating of the model.
- **Pyrite Canyon Group,** California — Developed numerical air-flow and groundwater-flow models to assist in the evaluation of remedial measures at the Stringfellow Acid Pits. Conducted analyses for feasibility studies of remediation of shallow organic contamination, using dewatering and soil vapor extraction. Developed analyses for evaluating the performance data from a horizontal well constructed in fractured bedrock and for predicting the long-term efficacy of the well for plume remediation.

TECHNICAL SUPPORT FOR THE GROUNDWATER ASPECTS OF INFRASTRUCTURE DEVELOPMENT

- **Toronto Spadina Yonge Subway Extension** — Provided peer review of dewatering requirements and interpretation of hydrogeologic tests for the Steeles West and Finch West stations.
- **Eglinton Crosstown LRT, Toronto** – Conducted analyses to support the 30% design for the proposed Bathurst, Dufferin, Caledonia and Keele Stations. Analyses included the interpretation of hydraulic tests, estimation of groundwater pressures on Support of Excavation, estimation of groundwater inflows to station box excavations and analytical and numerical modeling to support the design of groundwater control measures. Assisted in the development of the work plan for supplemental investigations to guide the estimation of dewatering requirements.
- **San Manuel Band of Mission Indians, Highland, California** –Developed a groundwater model to assist in the evaluation of the potential effects of alternative methods of construction of the MWD Arrowhead East tunnel on the water resources of the San Manuel Tribe. Conducted an extensive follow-up studies to establish the model as a reliable tool for reconstructing past conditions and predicting future changes in groundwater conditions in the vicinity of the San Manuel Indian Reservation.

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

LITIGATION SUPPORT

- **Reko Diq Mine,** Pakistan — Served as water resources expert to the government of Pakistan and provided testimony at the International Centre for Settlement of Investment Disputes, London, UK (ICSID Case no. ARB/12/1). Provided expert opinion of the predictions of potential declines in groundwater levels the proposed Reko Diq project. Conducted independent analyses of the data from 21 days of pumping in the Fan Sediments northwest of the proposed mine.
- **Timbro Ranch,** Colorado (Colorado Water Court consolidated cases 2013CW3144 and 2014CW3134 — Developed on behalf of Denver Water independent interpretations of data collected during pumping tests to support a non-tributary water assessment.
- **Pinnacle Heights Golf Course,** Orangeville, Ontario — Provided expert opinion on the reliability of groundwater modeling conducted to evaluate the potential impacts of irrigation pumping for a proposed golf course.
- **Thomson Facility,** Marion, Indiana — Provided expert opinion on the groundwater velocity at the site. The analysis was developed within a stochastic framework.
- **Homestead Golf Course,** Michigan — Reviewed the environmental impact of a proposed golf course development adjacent to a sensitive river.
- **Cities of Vaughn and Pickering,** Ontario — Evaluated the design calculations for proposed municipal waste landfills having complex liners. Reviewed the methods for predicting leakage through composite geomembrane liners, and reviewed the methods to predict the development of groundwater mounds due to failure of leachate collection systems. Performed benchmarking of the solute transport code POLLUTE.
- **Duntroon Quarry Expansion, Singhampton,** Ontario — Served as expert witness for the Niagara Escarpment Commission for the assessment of hydrogeologic aspects of the proposed extension of the Duntroon Quarry. Prepared expert witness reports and provided testimony for the Joint Board under the *Consolidated Hearings Act*.
- **Nelson Quarry Expansion,** Burlington, Ontario — Served as expert witness for Halton Region for the assessment of hydrogeologic aspects of the proposed extension of the Nelson Quarry. Prepared expert witness reports and assisted counsel in preparation of cross-examination for the Joint Board under the *Consolidated Hearings Act*.
- **MAQ Highland Quarry,** Singhampton, Ontario — Directed the Experts Meeting and prepared the *Statement of Agreed Facts* for the proposed MAQ Highland Quarry.

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

HYDROGEOLOGY TRAINING

- **Critical Thinking in Aquifer Test Interpretation** — Developer and instructor of a professional short course on hydrogeologic testing. The course has now been taught over 35 times in Canada, the United States, Brazil and China.
- **International Ground-Water Modeling Center, Colorado School of Mines,** Golden, Colorado — Provided professional short courses in MT3D solute transport modeling.
- **Environment Institute for Continuing Education** — Developed and presented Internet-based seminars.
- **Midwest Geosciences** — Presented short-course lectures. Developed and presented Internet-based seminars on the interpretation of aquifer tests.
- **Kingdom of Cambodia Ministry of Water Resources and Meteorology** — Provided training for groundwater modeling expertise in Cambodia.
- **Eastman Kodak Company,** Region of Waterloo — Developed and led training courses for site-specific models and technology transfer.

LANGUAGES

French, Portuguese, Spanish

AWARDS AND HONORS

Citation for Leadership Recognition, National Ground Water Association, 2018

Graduate Scholarship, University of Waterloo, 1990

Citation for Reviewing Excellence, Water Resources Research, 2005

PROFESSIONAL SOCIETIES

International Association of Hydrogeologists

National Ground Water Association

American Geophysical Union

Canadian Geotechnical Society

American Society of Civil Engineers

International Mine Water Association

APPOINTMENTS

2007 – present:	Co-Chair of the Kitchener-Waterloo Hydrogeology Seminar Series
2016 – 2017:	Chair of the National Ground Water Association Groundwater Advisory Panel Group #2 (Stepwise modeling)
2015:	Co-Technical Chair of the IAH-CNC Waterloo 2015 Hydrogeology Conference
2010 – 2013:	Canadian Geotechnical Society, Chair of the Hydrogeology Division
2006 – 2009:	University of Waterloo, Department of Earth Sciences, Adjunct Lecturer
1999 – 2009:	Canadian National Chapter of the International Association of Hydrogeologists, Vice President

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

PUBLICATIONS AND PRESENTATIONS

BOOKS

Neville, C., and V. Bedekar, 2016. Chapter 17: Simulation of Flow and Transport in Fractured Rocks: An Approach for Practitioners. in *Groundwater Assessment, Modeling, and Management*. M. Thangarajan and V.P. Singh, eds. Boca Raton, FL: CRC Press, pp. 269-282.

Cohen, H., and C. Neville, 2006. Chapter 8: Fate, Transport, and Modeling of Perchlorate in Groundwater. in *Perchlorate: A Scientific, Legal, and Economic Assessment*. 1st ed., E. Hagstrom, ed. Tucson, AZ: Lawyers & Judges Publishing Company, pp. 267-294.

THESES

Neville, C.J., 1992. An Analytical Solution for Solute Transport with Multiprocess Nonequilibrium Sorption. MS thesis: Department of Earth Sciences, University of Waterloo, Ontario.

PEER-REVIEWED JOURNAL PAPERS

Neville, C.J., 2022. Alternative Interpretation of the Pressure Front Displacement Pulse for Pumping Tests in Confined Aquifers, *Hydrological Processes*, doi/10.1002/hyp.14744.

Neville, C.J, and C.B. Andrews, 2020. Containment of Sources of Groundwater Contamination: Analysis of Mass Fluxes, *Groundwater*, vol. 58, no. 2, pp. 183 188.

Priebe, E.H., F.R. Brunton, D.L. Rudolph, C.J. Neville, 2019. Geologic Controls on Hydraulic Conductivity in a Karst-Influenced Carbonate Bedrock Groundwater System in Southern Ontario, Canada, *Hydrogeology Journal*, v. 27, no. 4, pp. 1291-1308.

Wang, X., and C.J. Neville, 2019. A Semi-Analytical Solution for the Transport of Solutes with Complex Sequences of First-Order Reactions, *Computers and Geosciences*, v. 123, pp. 121-136.

Neville, C.J, and X. Wang, 2018. Analysis of solute transport from a source with finite leachable mass, *Groundwater*, v. 56, no. 6, pp. 1002 1006.

Priebe, E.H., C.J. Neville, D.L. Rudolph, 2017. Enhancing the spatial coverage of a regional high-quality hydraulic conductivity dataset with estimates made from domestic water-well specific-capacity tests, *Hydrogeology Journal*, https://doi.org/10.1007/s10040-017-1681-2, 14 p.

Neville, C.J., 2017. Comment on “Automatic estimation of aquifer parameters using long-term water supply pumping”, *Hydrogeology Journal*, v. 25, pp. 2207-2209.

Priebe, E.H., C.J. Neville, and F.R. Brunton, 2017. Discrete, High-Quality Hydraulic Conductivity Estimates for the Early Silurian Carbonates of the Guelph Region, Ontario Geological Survey, Groundwater Resources Study 16, 50 p.

Priebe, E.H., C.J. Neville, and F.R. Brunton, 2014. Evaluating the influence of geological features on hydraulic conductivity variability in Early Silurian carbonate rock aquifers of the Guelph Region, in Summary of Field Work and Other Activities 2014, Ontario Geological Survey, Open File Report 6300, pp. 35-1 to 35-8.

Neville, C., 2013. Discussion of A Constant-Head Pumping Test Method Using Direct-Push Equipment for In Situ Hydraulic Conductivity Measurements, by T. Kobayashi, N. Onoue, S. Oba, N. Yasufuku and K. Omine, *Géotechnique*, v. 63, no. 6, pp. 525-527.

Neville, C., 2013. Discussion of Shape Factors of Cylindrical Piezometers in Uniform Soil, by V. Silvestri, G. Abou-Samra, and C. Bravo-Jonard, *Groundwater*, v. 51, no. 2, pp. 168-169.

Neville, C., 2013. Discussion of Estimation of Degradation Rates by Satisfying Mass Balance at the Inlet, by V. Batu, *Groundwater*, v. 51, no. 1, p. 8.

Neville, C., and G. van der Kamp, 2012. Using Recovery Data to Extend the Effective Duration of Pumping Tests, *Ground Water*, v. 50, no. 5, pp. 804-807.

Bedekar, V., C. Neville, and M. Tonkin, 2012. Source Screening Module for Contaminant Transport Analysis Through Vadose and Saturated Zones, *Ground Water*, v. 50, no. 6, pp. 954-958.

Neville, C., and J. Zhang, 2010. Benchmark Analysis of Solute Transport with Multiaquifer Wells, *Ground Water*, v. 48, no. 6, pp. 884-891.

Karanovic, M., C. Neville, and C. Andrews, 2007. BIOSCREEN-AT: BIOSCREEN with an Exact Analytical Solution, *Ground Water*, v. 45, no. 2, pp. 242-245.

Neville, C., and C. Andrews, 2006. Containment Criterion for Contaminant Isolation by Cutoff Walls, *Ground Water*, v. 44, no. 5, September-October, pp. 682-686.

Neville, C., and M. Tonkin, 2004. Modeling Multiaquifer Wells with MODFLOW, *Ground Water*, v. 42, no. 6, pp. 910-919.

Guyonnet, D., and C. Neville, 2004. Dimensionless Analysis of Two Analytical Solutions for 3-D Transport in Groundwater, *Journal of Contaminant Hydrology*, v. 75, pp. 141-153.

Andrews, C., and C. Neville, 2003. Ground Water Flow in a Desert Basin: Challenges of Simulating Transport of Dissolved Chromium, *Ground Water*, v. 41, no. 2, pp. 219-226.

Yager, R., and C. Neville, 2002. Review of "GFLOW 2000: An Analytical Element Ground Water Flow Modeling System", *Ground Water*, v. 40, no. 6, pp. 574-576.

Neville, C., M. Ibaraki, and E. Sudicky, 2000. Solute Transport with Multiprocess Nonequilibrium: A Semi-Analytical Solution Approach, *Journal of Contaminant Hydrology*, v. 44, pp. 141-159.

Neville, C.J., 1994. Discussion of "Recommendations for Usage of SURFER to Gridding Model Results," by C. Shan and D.B. Stephens, *Ground Water*, v. 32, no. 6, p. 1037.

CONFERENCE PUBLICATIONS

Wang, X, and C.J. Neville, 2017. Response to pumping in a two-aquifer system, in *Proceedings of GeoOttawa 2017*, 7 p.

Priebe, E.H., C.J. Neville, and D.L. Rudolph, 2017. Improving the spatial density of a regional hydraulic conductivity dataset with estimates made from domestic water well information (abstract), in *Regional-Scale Groundwater Geoscience in Southern Ontario: An Ontario Geological Survey, Geological Survey of Canada, and Conservation Ontario Open House*, Geological Survey of Canada, Open File 8212.

Priebe, E., C. Neville, and F. Brunton, 2015. Evaluating the influence of regional stratigraphic architecture on hydraulic conductivity variability in Early Silurian carbonate rock aquifers, Guelph Region, southern Ontario (abstract). *Waterloo 2015*, International Association of Hydrogeologists – Canadian National Chapter, October 29, 2015, Waterloo, ON.

Wang, X., and C. Neville, 2015. Benchmarking mod-PATH3DU for complex problems, in Proceedings of *MODFLOW and More 2015: Modeling a Complex World*, IGWMC, Colorado School of Mines, Golden, CO, 5 p.

Muffels, C., X. Wang, M. Tonkin, and C. Neville, 2015. mod-PATH3DU: A groundwater path and travel-time simulator for both unstructured-grid (USG) and structured grid versions of MODFLOW, in Proceedings of *MODFLOW and More 2015: Modeling a Complex World*, IGWMC, Colorado School of Mines, Golden, CO, 4 p.

Zhang, J., and C.J. Neville, 2013. Identification of topographically-controlled groundwater systems, in Proceedings of the *International Symposium on Regional Groundwater Flow: Theory, Applications and Future Development*, June 21-23, 2013, Xi'an, China, pp. 143-146.

Priebe, E., C. Neville, and F. Brunton, 2015. Evaluating the influence of stratigraphic architecture on Kh variability in the Guelph Region, ON. *Waterloo 2015*, International Association of Hydrogeologists – Canadian National Chapter, October 29, 2015, Waterloo, ON.

Khambhammettu, P., C.J. Neville, and M.J. Tonkin, 2011. Analysis of the Migration of Bio-Amended Water through the Vadose Zone for In-Situ Remediation of Hexavalent Chromium, MODFLOW and MORE 2011, June 7, 2011, Colorado School of Mines Golden, Golden, CO.

Khambhammettu, P., C.J. Neville, and M.J. Tonkin, 2011. An Analysis of Migration of Bio-Amended Water for In-Situ Remediation of Hexavalent Chromium Through the Vadose Zone (Abstract). *2011 Ground Water Summit*, National Ground Water Association, May 2, 2011.

Bedekar, V., C.J. Neville, and M.J. Tonkin, 2010. Analysis of Contaminant Transport through the Vadose and Saturated Zones for Source Screening. *Fall Meeting 2010*, American Geophysical Union, Abstract No. H53C-1059 and poster.

Neville, C.J., 2009. Contaminant Isolation by Cutoff Walls: Reconsideration of Mass Fluxes. *GeoHalifax 2009: 62nd Canadian Geotechnical Conference & 10th Joint CGS/IAH-CNC Groundwater Conference*, September 20–24, 2009, Halifax, Canada, 7 p.

Neville, C.J. and G. van der Kamp, 2009. A General Method for Using Recovery Data for Pumping Tests in Complex Hydrogeological Settings. *GeoHalifax 2009: 62nd Canadian Geotechnical Conference & 10th Joint CGS/IAH-CNC Groundwater Conference*, September 20–24, 2009, Halifax, Canada, 7 p.

Neville, C., and J. Zhang, 2008. Benchmark Analyses of Solute Transport with Multi-Aquifer Wells. *MODFLOW and More 2008: Ground Water and Public Policy Conference*, May 18-21, 2008, International Ground-Water Modeling Center, Colorado School of Mines, Golden, CO.

Neville, C.J., 2006. Rehabilitation of the Specified-Concentration Boundary Condition for Solute Transport. *MODFLOW and More 2006, Managing Ground-Water Systems*, May 22-24, 2006, International Ground Water Modeling Center, Colorado School of Mines Golden, CO, pp. 667–672.

Tsou, M.-S., K. Tu, J. Kool, C. Neville, and S. Young, 2003. Comparison of Three Numerical Simulation Models for Chain-Decay Transport Simulation at a Closed AFB in Texas. *MODFLOW 2003*, September 17-19, 2003, International Groundwater Modeling Center, Colorado School of Mines, Golden, CO.

Williams, J., C. Neville, J. Keizer, and G. Luxbacher, 2002. Characterization of Discrete Flow Zones by Packer Testing, Hyde Park Landfill Site. *2002 National Ground Water Association (NGWA) Northeast FOCUS Ground Water Conference*, October 3-4, 2002, Burlington, VT.

Sorel, D., C. Neville, M. Rafferty, K. Chiang, and C. Andrews, 2002. Hydraulic Containment Using Phytoremediation and a Barrier Wall to Prevent Arsenic Migration. *Proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds,* May 20-23, 2002, Monterey, CA, A. Gavaskar and A. Chen, eds, Battelle Press.

Neville, C., S. Sayko, M. Kuhl, R. Passmore, G. Luxbacher, M. Mateyk, J. Williams, and B. Trytten, 2002. Identification of Groundwater Flow Zones with Borehole Geophysics and Flowmeter Profiling, Hyde Park Landfill Site, Niagara Falls, New York. *Proceedings of the 2002 Fractured-Rock Aquifers Conference,* March 2002, National Ground Water Association, Denver, CO.

Andrews, C., and C. Neville, 2001. Groundwater Flow in a Desert Basin: Complexity and Controversy. in *Proceedings of MODFLOW 2001 and Other Modeling Odysseys*, September 11-14, 2001, International Groundwater Modeling Center, Colorado School of Mines, Golden, CO, pp. 770-775.

Neville, C., and M. Tonkin, 2001. Representation of Multiaquifer Wells in MODFLOW. *Proceedings of MODFLOW 2001 and Other Modeling Odysseys*, September 11-14, 2001, International Groundwater Modeling Center, Colorado School of Mines, Golden, CO, pp. 51-59.

Cohen, H., M. Tonkin, and C. Neville, 2000. Determination of Hydraulic Conductivity Distribution in a Heterogeneous Glacial Sand Aquifer: Correlation between Estimates Based on Impeller Flow Meter Data and Grain-Size Distributions. *Society for Sedimentary Geology / International Association of Sedimentologists (SEPM/IAS) Research Conference, Environmental Sedimentology: Hydrogeology of Sedimentary Aquifers*, September 24-27, 2000, Santa Fe, New Mexico.

Neville, C., and J. Markle, 2000. Interpretation of Constant-Head Tests: Rigorous and Approximate Analyses. *Proceedings of the First Joint IAH-CNC/CGS Groundwater Specialty Conference*, October 15-18, 2000, Montreal, QC.

Guo, W., and C. Neville, 1998. Adaptation of MODFLOW for Transient Air Flow Simulation. *roceedings of the MODFLOW 98 Conference*, October 1998, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Neville, C., M. Riley, and C. Zheng, 1998. Implicit Modeling of Low-Permeability Features: An Appraisal for Solute Transport. *Proceedings of the MODFLOW '98 Conference*, October 1998, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO.

Guo, W., C. Neville, and C. Zheng, 1995. Numerical Simulation of Air Flow and Advective Transport Using MODFLOW. *1995 Spring Meeting*, American Geophysical Union, Baltimore, MD. *Eos*, v. 76, no. 17, S130.

Neville, C., N. Guiguer, and M. Rivett, 1992. A Review of Batch Flush Models for Pump-and-Treat Remediation. *Aquifer Restoration: Pump-and-Treat and the Alternatives*, AGWSE 1992 Education Program, Las Vegas, NV.

PRESENTATIONS

Neville, C.J., 2009. Contaminant Isolation by Cutoff Walls: Reconsideration of Mass Fluxes. *GeoHalifax 2009: 62nd Canadian Geotechnical Conference & 10th Joint CGS/IAH-CNC Groundwater Conference*, Halifax, Canada, September 20–24, 2009.

Neville, C. J., 2008. Flow in Fractured Rock: Implications of Long Open Interval Wells. Presentation at the Kitchener-Waterloo Hydrogeology Seminar Series, Canadian Geotechnical Society/International Association of Hydrogeologists, March 5, 2008.

Neville, C.J., 2006. Rehabilitation of the Specified-Concentration Boundary Condition for Solute Transport. *MODFLOW and More 2006, Managing Ground-Water Systems*, International Ground Water Modeling Center, Colorado School of Mines Golden, CO, May 22-24, 2006.

Neville, C.J., 2003. Contributions of Edward A. Sudicky in Analytical Solutions in Fractured-Porous Media. *2003 Annual Meeting*, Geological Society of America, Seattle, WA, November 2–5, 2003.

Neville, C., S. Sayko, M. Kuhl, R. Passmore, G. Luxbacher, M. Mateyk, J. Williams, and B. Trytten, 2002. Identification of Groundwater Flow Zones with Borehole Geophysics and Flowmeter Profiling, Hyde Park Landfill Site, Niagara Falls, New York. *2002 Fractured-Rock Aquifers Conference,* National Ground Water Association, Denver, CO, March 2002.

Riley, M., and C. Neville, 2001. Natural Attenuation in Tidal Zones. *National Ground Water Association Northwest Focus Conference*, Portland, OR, February 2001.

Neville, C., M. Riley, and C. Zheng, 1998. Implicit Modeling of Low-Permeability Features: An Appraisal for Solute Transport. *MODFLOW '98 Conference*, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, October 1998.

RESEARCH REPORTS

Neville, C.J., 1992. Contaminant Recovery Test Site: Summary of Geostatistical Analyses of Core Data. Technical Note, Waterloo Centre for Groundwater Research.

Neville, C.J., 1991. A Numerical Study of Hydraulic Communication Around Packers in Uncased Boreholes. Prepared for Solinst Canada Ltd. Waterloo Centre for Groundwater Research.

Kaiser, P., D. Chan, D. Tannant, F. Pelli, and C. Neville, 1987. Numerical Simulation of Room 209 Instrument Ring, Interim Technical Report. Prepared for Atomic Energy of Canada. Pinawa, Manitoba. Department of Civil Engineering, University of Alberta, Canada.

CHRISTOPHER J. NEVILLE, M.SC., P.ENG.

Chief Hydrogeologist

DOCUMENTATION OF GROUNDWATER MODELING SOFTWARE

Wang, X., and C.J. Neville, 2016. User's Guide for DECAY, Analytical Solution for One-Dimensional Solute Transport with Multispecies Subject to First-Order Decay Reactions. S.S. Papadopulos & Associates, Inc.

Neville, C.J., 2004. MPNE1D Analytical Solution: User's Guide. Version 4.1. S.S. Papadopulos & Associates, Inc.

Neville, C.J., 1998. ATRANS: Analytical Solutions for 3D Transport from a Patch Source. Version 2. S.S. Papadopulos & Associates, Inc.

Zhang, Y., C. Zheng, C. Neville, and C. Andrews, 1996. ModIME User's Guide: An Integrated Modeling Environment for MODFLOW, PATH3D, and MT3D. Version 1.1. S.S. Papadopulos & Associates, Inc.

Neville, C.J., 1992. Analytical Solutions for Transport with NAPL Sources. Technical Report (computer program and documentation), Waterloo Centre for Groundwater Research, Canada.

Neville, C.J., 1992. GA83: A Program for Computing the Effective Hydraulic Conductivity and Macrodispersivity Tensor for Three-Dimensionally Heterogeneous Aquifers Using the Stochastic Theory of Gelhar and Axness [1983]. Technical Report (computer program and documentation), Waterloo Centre for Groundwater Research, Canada.

Neville, C.J., 1992. Notes on the De Hoog Routine for the Numerical Inversion of Laplace Transforms: Analytical Solutions. Technical Report (computer program and documentation), Waterloo Centre for Groundwater Research, Canada.

Neville, C.J., 1992. Notes on the De Hoog Routine for the Numerical Inversion of Laplace Transforms: Discrete Numerical Solutions. Technical Report (computer program and documentation), Waterloo Centre for Groundwater Research.