A field and numerical study of a tracer test in a gypsum formation beneath a road

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ABSTRACT
Gypsum dissolution has the potential to create karst and sinkholes which can damage infrastructure. A dye tracer test was conducted between a sinkhole in the Harcus Drain, and a gypsum quarry in the RM of Alonsa, Manitoba, Canada. The aim of this study was to provide insight into the ongoing dissolution along the drain by analyzing groundwater flow properties. Groundwater regionally flows east to Lake Manitoba, however, locally from the drain it flows north toward the quarry. Analysis of tracer breakthrough curves suggested that there is a hydraulic connection between the drain and the quarry, likely resulting from gypsum excavation. As a consequence, dissolution of a gypsum formation in the Harcus Drain, and perhaps, under South Leifur Road are resulting in damage to infrastructure.

RÉSUMÉ
La dissolution du gypse a le potentiel de créer des karsts et des gouffres pouvant endommager les infrastructures. Un test de colorant a été effectué entre un trou dans le drain de Harcus et une carrière de gypse dans la municipalité rurale d'Alonsa, Manitoba, Canada. Le but de cette étude était de fournir un aperçu de la dissolution en cours le long du drain en analysant les propriétés d'écoulement des eaux souterraines. L'eau souterraine s'écoule à l'est vers le lac Manitoba, mais, localement, elle s'écoule vers le nord en direction de la carrière. L'analyse des courbes de pénétration du traceur a suggéré qu'il existe un lien hydraulique entre le drain et la carrière, probablement dû à l'excavation du gypse. En conséquence, la dissolution d'une formation de gypse dans le drain de Harcus, et peut-être sous South Leifur Road, endommage les infrastructures.

1 INTRODUCTION

Portions of the Rural Municipality (RM) of Alonsa, Manitoba, Canada are underlain by a thick gypsum formation located at a shallow depth (Lapenskie and Bamburak 2015). Sinkholes have been observed in the area for at least 25 years (Bamburak 2015). Lapenskie and Bamburak (2016) created isopach maps of gypsum in the area and suggested that groundwater related gypsum dissolution is associated with karst development, including sinkholes. In 2014, a sinkhole formed in the Harcus Drainage Ditch, 100 m south of a gypsum quarry. This sinkhole is causing damage to infrastructure including roads, and presents a potential risk to traffic.

Karst systems are heterogeneous, and create a challenge for the characterization of groundwater flow. Tracer tests are generally regarded as being the most reliable and efficient means of gathering subsurface hydraulic information for karst aquifers (Field 1999). Qualitative tracer tests establish a positive connection between a source and monitoring locations while quantitative tracer tests provide further information on site characteristics, including solute transport parameters (Field 1999).

The aim of this study is to quantitatively characterize the flow between the Harcus Drain sinkhole and the gypsum quarry located in the RM of Alonsa, and to create a groundwater flow model which is calibrated to provide quantitative properties of the karst system. Kuechler et al. (2004) indicated that gypsum dissolution is dependent on saturation and the Darcy velocity. Thus, we can derive information about the formation rate of karst from the flow data. Data from this study will be used in subsequent geochemical studies into gypsum dissolution at the study site.

2 SITE DESCRIPTION

The study area is located around the Harcus Drainage Ditch and a gypsum quarry located west of Lake Manitoba in quarter section NE-27-20-10W1 and SE-22-20-10W1 in the RM of Alonsa (Figure 1). Gypsum has been mined at the site since 1978 and quarries approximately 100,000 tonnes of gypsum annually (Bamburak 2015). In 2014, Manitoba and Saskatchewan, including the RM of Alonsa experienced a wet year with above average precipitation and an elevated water table that led to a state of emergency. High runoff from the 2014 flood event challenged the local drain capacity, resulting in breakouts from the drain onto adjacent farmland. Water flowed in the drain at a depth of 0.75 m to 1.0 m from early June until early November. When water levels decreased to around 0.30 m, a sinkhole became visible, with water estimated to be draining into the sinkhole at 20 L/s (Gurke 2015). The road adjacent to the ditch was closed to heavy traffic. The water was believed to be draining toward the gypsum quarry, located approximately 100 m north of the sinkhole in the Harcus Drain (Figure 1). The depth of water in the drain is indicative of the hydraulic gradient between the drain and quarry.

Attempts were made to stabilize and remediate the drain (Gurke 2015). A temporary diversion channel was constructed diverting flow south of the sinkholes and back into Harcus Drain to the east. However, 3 small sinkhole formed in the new channel. A total of 8025 gallons of bentonite gel was injected into the sinkhole in early 2015, based on expert advice (Gurke 2015). The site was contoured with 1 cm limestone, capped with approximately 20 cm of clay, lined with a ditch liner and covered in rip rap. In the summer of 2017, slumping was once again visible in the Harcus Drain.

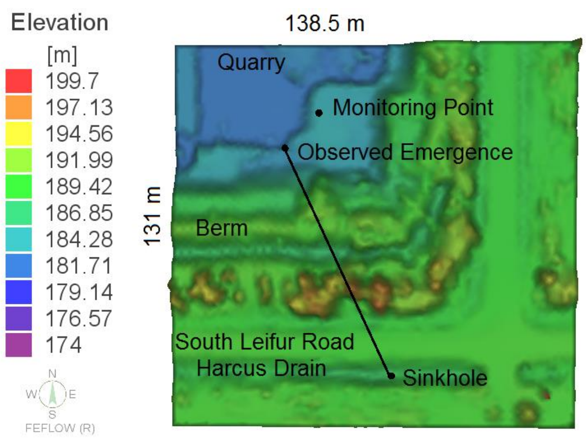

Figure 1. The study area. Inflow marks the location of the sinkhole and tracer injection, outflow the location of the fluorometer monitoring. Emergence is the point the tracer was first visible. The black line indicates the model location.

3 GEOLOGY

The study area is located on the eastern edge of the Western Canadian Sedimentary Basin, which stretches from the Rocky Mountains to eastern Manitoba, and includes the smaller Williston Basin. The Upper Amaranth formation of Jurassic age out crops near the site. The Amaranth formation is characterized by evaporites, gypsum, red shale and sandstone (Bezys and McCabe 1996). The Upper Amaranth evaporite member is the source of gypsum in the study area. At the study site, approximately 6 m of pleistocene glacial till overlies approximately 7.5 m of gypsum and anhydrite-bearing formations (Lapenskie and Bamburak 2016). The anhydrite in the formation can be converted to gypsum, causing a 30-60% increase in volume, creating significant permeability due to loosening of the formation and disturbance of the sedimentary bedding planes (Bamburak 2015).

4 METHODS

4.1 Field Test

With permission from the Government of Manitoba, a tracer test was conducted at the study site from 31 October to 2 November 2017, based on methods described in Field (1999) and Carleton et al. (1999). Weather and runoff were stable the week before and during the experiment, with no water flowing in the Harcus Drain. The injection site, or inflow, was located in the drainage ditch near the location of the sinkhole that formed in 2014 on the south side of South Leifur Road and a fluorometer was set up at the monitoring site, or outflow, located within the quarry (Figure 1). The distance between the inflow and detection system was approximately 100 m. A slug of 3750 L of potable water along with 535 g of Rhodamine-WT was added to the drainage ditch near the sinkhole between 1:14 pm and 1:44 pm on 31 October 2017. The water infiltrated into the ground at approximately 126 L/min. To encourage flow, a second injection of 5678 L of water was added on 1 November 2017 between 10:18 am and 10:42 am, approximately 21 hours after the beginning of the test. During the second injection, water infiltrated into the ground at approximately 189 L/min. Monitoring continued until 2 November 2017 at 10:03 am.

4.2 Measurements

A Turner 10AU-005-CE Fluorormeter S/N 1100297 was used for detecting Rhodamine-WT concentration at the outflow location (Figure 1). The fluorometer was calibrated using standards and background water from the quarry prior to the beginning of the test. The sampling interval was set at 2 minutes. The Fluorometer was not functional between 8 and 20 hours into the test due to a pump failure. Additional samples were for verification purposes and ion analysis were taken from the fluorometer outflow in amber plastic bottles and stored in dark and cool conditions.

Quantitative values were calculated for a number of parameters.

Mean residence time $\bar{t}$ (hours) was calculated as (Field 1999):

$$\bar{t} = \frac{\int_0^\infty tC(t)Q(t)dt}{\int_0^\infty C(t)Q(t)dt} \qquad [1]$$

where t is time (s), C is concentration (mg/m^3) and Q is discharge (m^3/s).

Mean residence time standard deviation σ_t (hours) was calculated as (Field 1999):

$$\sigma_t = \left(\frac{\int_0^\infty (t-\bar{t})^2 C(t)Q(t)dt}{\int_0^\infty C(t)Q(t)dt}\right)^{1/2} \qquad [2]$$

Mean tracer velocity $\bar{v}$ (m/hr) was calculated as (Field 1999):

$$\bar{v} = \frac{\int_0^\infty \frac{x}{t} C(t)Q(t)dt}{\int_0^\infty C(t)Q(t)dt} \qquad [3]$$

where x is tracer migration distance (m), which is the 1.5 times the distance.

Percent mass recovered M_o (%) was calculated as (Field 1999):

$$M_o = t_c \sum_{i=1}^{n} Q_i C_i \qquad [4]$$

Flow system volume V (m^3)was calculated as (Field 1999):

$$V = \bar{Q}\bar{t} \quad [5]$$

where $\bar{Q}$ is average discharge (m^3/s).

Longitudinal dispersion D_L (m) was calculated as (Field 1999):

$$D_L = \frac{\sigma_t^2 \bar{v} x}{2\bar{t}^2} \quad [6]$$

The hydraulic head at the ditch was not measured, as there was no well at the location. Therefore, the hydraulic gradient between the drain and quarry was estimated. No significant precipitation was registered on site in during the experiment.

The electrical conductivity was measured on a number of samples collected from the pit prior to testing, injected potable water and samples during the test from the fluorometer outflow (Figure 2). The values were compared to the conductivity of a Gypsum standard, assuming the conductivity is mainly contributed by gypsum.

4.3 Model Concept

A groundwater flow model was built to provide a better estimation of flow parameters occurring in the study area. Wendland and Himmelsbach (2002) modeled the interaction between a sandstone formation and a single fracture with a pyranine tracer. Similar to their work, a coupled model of porous and fracture flow was chosen to simulate the formation. The specific discharge q (m^2/s) can be given by the Darcy equation:

$$q = -K \cdot \nabla \cdot \left(\frac{p}{\rho g} + z\right) \quad [7]$$

where K is hydraulic conductivity (m/s), ρ is fluid density (kg/m^3), g is acceleration due to gravity (m/s^2), p is the hydrostatic pressure (Pa) and z is elevation (m).

The Hagen-Poiseuille equation was used to simulate flow through the fracture. The hydraulic aperture was estimated based on hydraulic conductivity using a parallel plate model (Singhal and Gupta 2010):

$$\alpha = \sqrt{\frac{K \cdot 12\mu}{\gamma}} \quad [8]$$

where α is the hydraulic aperture (m), K is hydraulic conductivity (m/s), μ is dynamic viscosity (m^2/s), and γ is the specific weight of water (N/m^3).

Rhodamine-WT was simulated using a simple tracer with no decay. Transient transport of dissolved solutes is governed by the advection-dispersion equation (Diersch 2002):

$$\varepsilon \frac{\delta C}{\delta t} + q \cdot \nabla C = \nabla \cdot (D \cdot \nabla C) \quad [9]$$

where ε is porosity (unitless), q is the darcy velocity vector (m/s), D is hydrodynamic dispersion (m^2/s) and C is concentration (g/m^3).

4.3.1 Model Settings and Boundary Conditions

Model calibration, consisting of fitting a modelled curve to the observed breakthrough curve was completed using a numerical groundwater flow model. A 3-D transient model was created using the finite element code FeFlow (Diersch 2014). Feflow allows the simulation of a dual porosity system consisting of matrix and fracture flow. The fracture was simulated as a single discrete fracture. The model area was approximately 60 m to the west of the fracture by 89 m between the inflow and outflow with a 3 m thickness. The model was assumed to be saturated, so the 3 m thickness was chosen based on the estimated saturated thickness. Discretization started near the inflow at 0.10 m and increases to 1.3 m. The model was divided into 6 layers 0.5 m thick. The tracer test was simulated for 2 days with an initial time step of $1x10^{-5}$ days and a maximum time step of 0.01 days.

Initial constant head boundaries were located along the Harcus Drain of 244.5 m, and at the gypsum quarry of 244 m. A well boundary condition was used to simulate the injections of water into the formation that occurred during the tracer test. Both the well boundary condition and the mas-concentration boundary condition were applied using time series. The Rhodamine-WT was simulated as a tracer using a mass nodal sink/source boundary condition.

The fracture thickness and hydraulic aperture were used to calibrate the fluid flow. Hydraulic head was assumed not to increase past surface level. The flow parameters along with molecular diffusion, longitudinal diffusion and transverse diffusion were used to calibrate the tracer breakthrough curve. The concentration of Rhodamine-WT was reduced 100 times for input into the model because of the large water of body the tracer emerged into, which was not simulated in the model. For the selected calibration, the following parameters were used: hydraulic gradient 0.5 m, fracture thickness 0.003 m, hydraulic aperture 0.003 m, diffusion $1x10^{-5}$ m^2/s, longitudinal dispersivity 1.2 m, transverse dispersivity 1 m.

4.3.2 Sensitivity Analysis

A sensitivity analysis was conducted to analyze the reaction of the system to changes in hydraulic gradient, hydraulic conductivity, transverse and longitudinal dispersivity, diffusion, and fracture width.

5 RESULTS

Rhodamine-WT was visible near the emergence point on 1 November 2017 at 8:15 am, 19 hours into the test (Figure 1). The fluorometer first detected elevated concentrations at approximately 20 hours with a concentrations exceeding 5 ppb, extending until 25 hours. This curve peaked at 23.4 hours with a concentration of 99.2 ppb.

A second peak, assumed to be associated with the second injection, occurred at approximately 29 hours, extended until approximately 39 hours and peaked at 32 hours with a concentration of 84 ppb (Figure 2). Unfortunately, the time period just before the first peak was not recorded due to a pump failure. Both breakthrough curves had similar peaks and durations. Noise in the sampler made the distinction of the exact time of emergence difficult.

Based on the first curve, travel time was calculated as 4.5 m/hour, comparable to the visually observed value of 4.3 m/hour. Mean residence time was 31.7 hours and the flow system volume is 228 m^3 (Equations 1-6, Table 1). Assuming that flow was predominantly through fractures and karst this indicates that for each meter length of travel there was 2.4 m^2 of openings in the 6 m of gypsum. Total tracer recovery was 21.5%, based on the assumption that discharge into the outflow was the same as infiltration into the inflow. The longitudinal dispersivity was calculated as 18 m, based on a residence time standard deviation of 7.54 hours. Using the travel time of 4.2 m/day and equation 8, the estimated hydraulic aperture was estimated at 3.81×10^{-5} m.

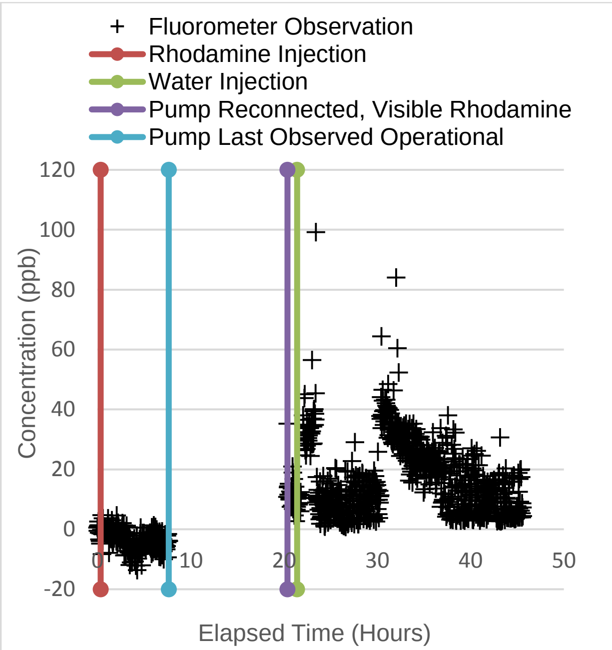

Figure 2. Results from the fluorometer observed at the outflow for Rhodamine-WT concentration as well as major events during the Tracer Test.

Based on the second peak, assuming the test started during the second injection, travel was time around 8.4 m/hour, mean residence time was 11.4 hours and flow system volume was 129 m^3. These values represent the fastest travel time and shortest mean residence time. The difference in values from the first injection of water and tracer to the second injection of water may indicate that the system experienced different saturation conditions between the first and second injection, likely dry before the first test and partially saturated before the second injection. However, flow through the matrix and water may have contributed as well.

The water in the quarry immediately before the tracer test began had a concentration equivalent to 2.6 g/L of pure gypsum, however may have contained other minerals and the potable water used in the test had a concentration of 0.82 g/L. Concentration initially decreased at 10 and 20 hours and then sharply increased back to background values (Figure 3).

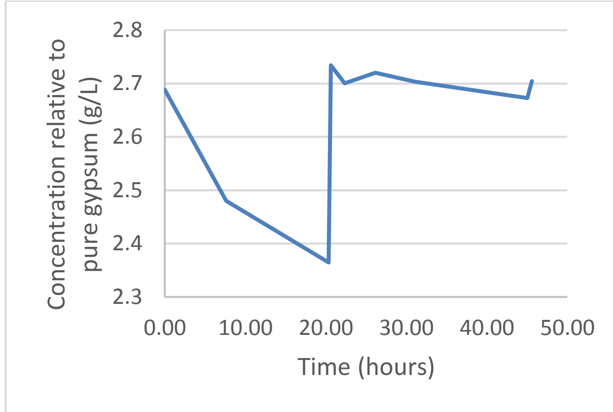

Figure 3. Concentration in samples relative to pure gypsum.

Table 1. Tracer test results

Characteristics	Units	Value
Inflow Coordinates	14U NAD 1893	561955189 mN 516624.46 mE
Outflow Coordinates	14U NAD 1893	5619641.99 mN 516599.43 mE
Simulation Time	days	1.875
Rhodamine-WT Injected	mg/L	141
Inflow Rate 1	m^3/day	181.44
Duration 1	hours	0.768 – 1.272
Inflow Rate 2	m^3/day	272
Duration 2	hours	21.84 – 22.25
Formation Thickness	m	6
Travel Distance	m	95.5
Mean tracer velocity	m/hour	4.3 to 8.4
Mass recovered	%	21.5 (field) 22.6 (model)
Flow system volume	m^3	228 (field)
Mean residence time (field) (1)	hr	31.7 (field) 24.8 (model)
Longitudinal dispersivity (field)	m	18.3 (field) 1.2 (model)
Transverse dispersivity	m	1.0 (model)
Hydraulic Aperture	m	0.003 (model)
Diffusion	m^2/s	1e-5 (model)

In order to calibrate the tracer test model, fracture aperture and thickness were initially adjusted to obtain an appropriate breakthrough time and peak in concentration. Next longitudinal and transverse dispersion and diffusion were adjusted, controlling peak values and time. Finally concentration was reduced by 100 times to account for the reservoir. The model was unable to separate the two peaks observed in the tracer concentration, therefore they were treated as one peak (Figure 5). Calibration resulted in hydraulic gradient 0.5 m, fracture thickness 0.003 m, diffusion 1×10^{-5} m^2/s, longitudinal dispersivity 1.2 m, transverse dispersivity 1 m.

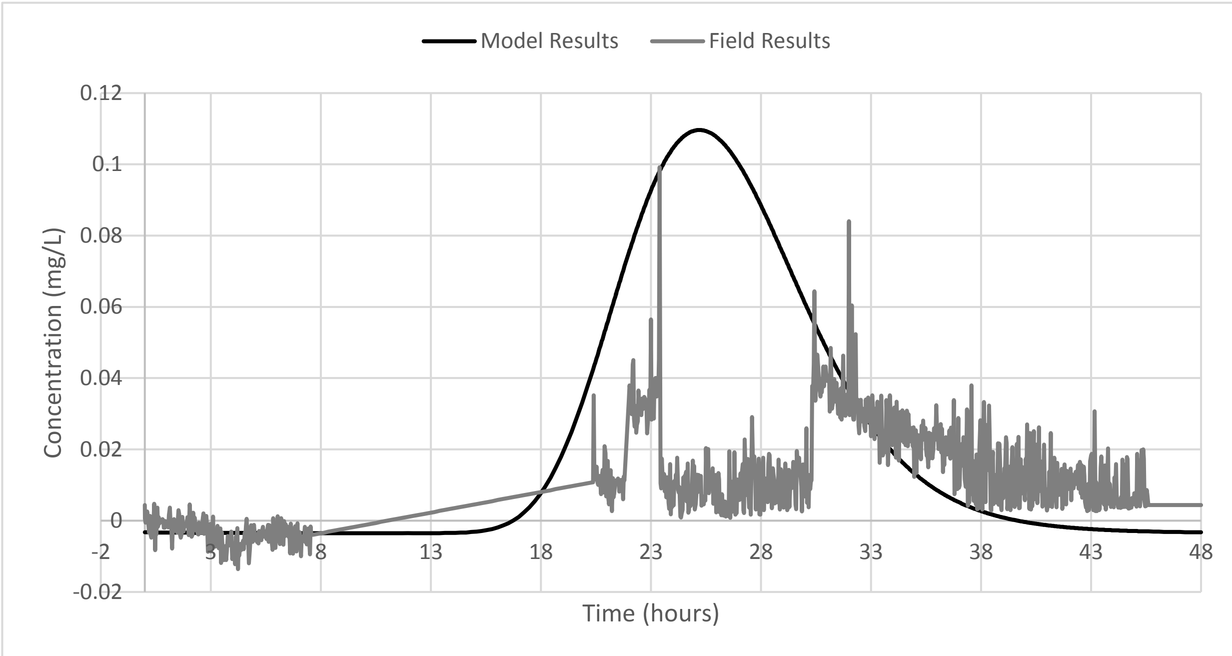

Figure 5. Comparison of observed breakthrough curve (grey) and modelled breakthrough curve (black for the tracer test, observed at the quarry. Hydraulic head difference of 0.5 m, fracture thickness 0.003 m, diffusion 1x10^{-5} m^2/s, longitudinal dispersivity 1.2 m, transverse dispersivity 1 m.

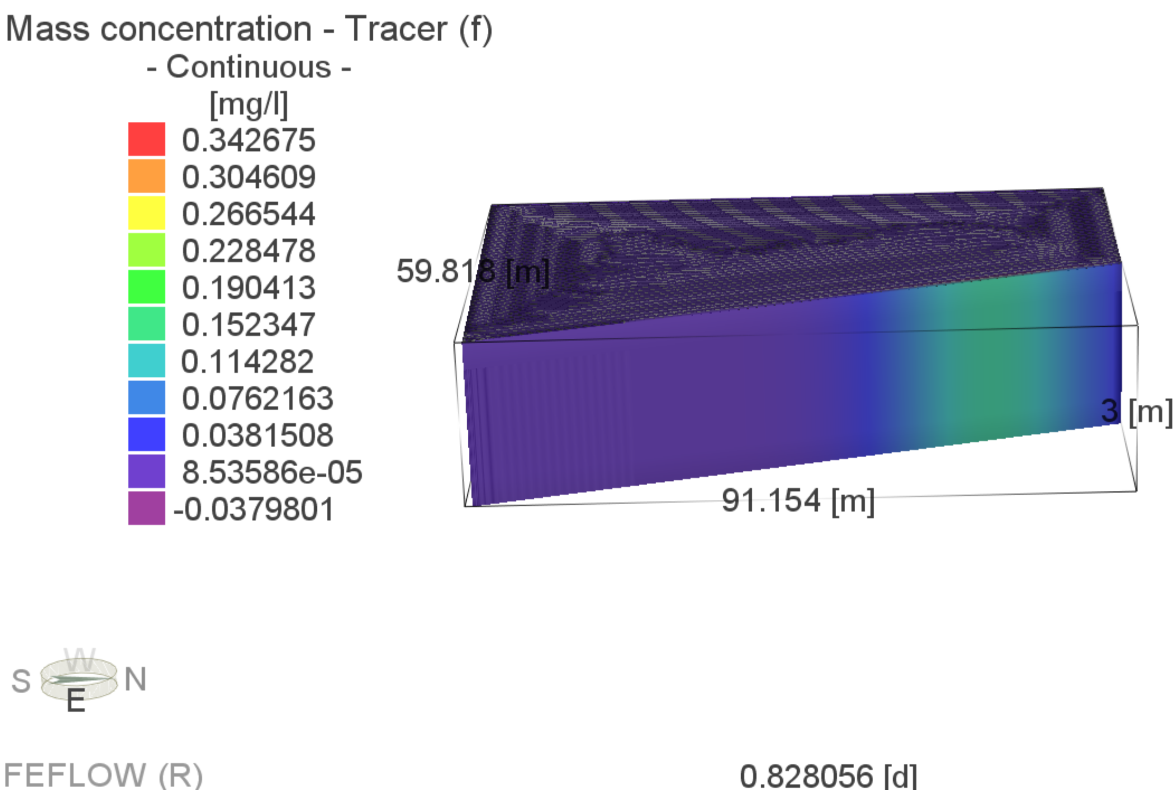

Figure 2. Tracer concentration in the fracture at approximately 19.8 hours. The left edge represents the inflow and the right edge represents the outflow.

The model was sensitive to a very low hydraulic conductivity value, resulting in no emergence of peak concentration within 2 days. Similar results could be produced with hydraulic head values of 244.5 to 246 m. Decreasing transverse dispersivity from 1 to 0.1 causes an increase in peak concentration value to 0.2 mg/L. Increasing the transverse dispersivity from 1 to 10 caused a decrease in peak concentration to 0.08 mg/L. Increasing fracture thickness causes the peak to occur earlier in the timeline, a 10 fold increase from 0.03 m to 0.003 m causes emergence to move from 19 hours to 4 hours. While decreasing fracture thickness by a factor of 10 to 0.0003 m results in no peak in 2 days. Adjusting the in and out transfer rates to $10x10^{-4}$ /d had no effect on the time or magnitude of the concentration peak. Adjusting only the out transfer rate from the discrete feature caused an increase in peak concentration to 0.016 mg/L, and slightly earlier peak. Increasing concentration to the full value resulted in similar breakthrough times, but much higher concentrations.

6 DISCUSSION

The results provide the first information on groundwater flow in the karst terrain in the RM of Alonsa. From the injection point at the sinkhole in the Harcus Drain, a north-northwest flow direction was observed toward the quarry. Flow in the regional is generally west to east, from the Riding Mountain region towards Lake Manitoba (Groundwater Management Section 2010). However, flow in the study area is from south to north, from the Harcus Drain towards the quarry. Therefore, we interpret that the quarry has caused changes in the groundwater flow pattern.

Considering the tracer mass not recovered, 78.5%, it is possible that parts of the tracer remained in the unsaturated zone, moved into conduits not connect with the quarry, was diluted in the quarry, or drained towards Lake Manitoba via different pathways. The emergence of tracer was visible 20 m south of the sampling location (Figure 1). Therefore, it is possible that the outflow into the quarry pond was significantly diluted by the open water body. The water in the quarry was approximately 2 m deep at the time of the experiment and the samples were taken at the bottom of the water column. Flow through the unsaturated zone was not taken into account due to unknown vertical flow velocities. Comparing the estimated flow system volume of 228 m^3 to the volume of the fracture of 0.9 m^3, we found a large discrepancy in the two values, which may result from flow into the matrix or other fractures, or from the quarry pond.

The two peaks observed during the tracer test indicate that flow through the karst system likely only occurs when water level surpass a certain hydraulic gradient. The first peak was the initial tracer and water injection reaching the quarry, while the second peak was a result of the second injection pushing the remaining volume of the first injection through the formation. The heights of the peaks were correlated with the volume of water injected, indicating a strong influence of hydraulic gradient. This was observed as one peak in the model because there was no pause in flow in the model. A slight change in ion concentration was observed at the same time as the first peak, indicating the freshwater was moving into the quarry.

7 CONCLUSIONS

By conducting a dye tracer test from the Harcus Drain in the RM of Alonsa, it was possible to confirm that the sinkholes drain towards the gypsum quarry, in contrast to the regional west to east flow. Quantification of flow parameters and karst system characteristics was also possible. Conductivity was estimated at 4.3 m/day between the sinkhole and the quarry. Model results suggested a fracture width of 0.003 m, longitudinal dispersivity of 1.2 m, transverse dispersivity of 1 m and diffusion of $1x10^{-5}$ m^2/s.

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