Modelling the Groundwater Flow of the Carbonate Aquifer during Pump Tests of Two Wells in East St. Paul, Manitoba

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ABSTRACT
The upper carbonate aquifer is a highly fractured limestone formation that is the main supply of drinking water for the Rural Municipality of East St. Paul, Manitoba. There have been several pump tests conducted in the region to determine the capacity of wells drilled into the aquifer. A 3D numerical model was developed using commercially available finite element software to simulate groundwater flow during two pump tests in the East St. Paul region. Four numerical approaches were used to model the pump tests in the fractured aquifer: 1) continuum, 2) minor fracture network, 3) major fracture network, and 4) major fracture network coupled with continuum. The size of study area, material properties, and fracture network density were modified in simulations to understand how they impacted drawdown in the wells. The numerical modelling in this paper provided meaningful conclusions that should be built upon in future studies to model groundwater flow in the East St. Paul region.

RÉSUMÉ
L'aquifère carbonaté supérieur est une formation de calcaire fracturé qui fournit l'eau potable pour la municipalité rurale manitobaine de East St Paul. Après la réalisation de plusieurs tests de pompes dans la région, nous pouvons déterminer la capacité des puits forés dans l'aquifère. Un modèle numérique à trois dimensions a été développé en utilisant des éléments fini disponibles commercialement pour stimuler les courants d'eaux souterraines dans la région de East St Paul. Quatre approches ont été utilisées dans la modéliser les tests de pompes: 1) un continuum, 2) un réseau de fracture mineur, 3) un réseau de fracture majeur, et 4) un réseau de fracture majeur combiner avec un continuum. La grosseur de la région étudiée, les propriétés matérielles ainsi que les puits de fractures ont été modifiés avec des simulations pour mieux comprendre leurs impacts sur les rabattements des puits. Le modèle numérique présenté dans ce document démontre des conclusions significatives qui devront appuyer des études futures concernant le modèle des eaux souterraines dans la région de East St Paul.

1 INTRODUCTION

Modelling groundwater flow in fractured rock is challenging, mainly due to high variability of the fracture network and difficulties obtaining knowledge of its geometry. Information on the fracture network, directly from observations and sampling or indirectly from pump test data, can aid tremendously in developing these models. There are several numerical approaches to model fractured rocks, each with varying levels of complexity. Understanding the suitability and limitations of each modelling approach for a specific region allows for more accurate modelling of the regional groundwater flow.

1.1 Study Region

The rural municipality (RM) of East St. Paul (ESP) is located directly northeast of Winnipeg. Geology in the region is relatively consistent due to its formation under proglacial Lake Agassiz. The soil is primarily high-plastic clay with silt deposits, underlain by a layer of glacial till. The average thickness of the clay and till are 12 and 6 m, respectively (Render, 1970). Beneath the till is a 75 m thick carbonate formation, composed of limestone and dolomite (Render, 1970). The structure of the carbonate aquifer varies significantly with depth and the upper 15 m is characterized by fractures, referred to as the upper carbonate. Joints and fractures in the upper carbonate greatly increase its permeability. The upper carbonate is a karstic aquifer and geochemical processes have further increased the permeability of the aquifer. Fractures usually do not exceed 2.5 cm, but major joint openings greater than 0.3 m have been observed (Render, 1970).

One exception of the subsurface conditions in the region is the Bird's Hill Esker; a deposit of sand and gravel located east of ESP. Groundwater levels there are high and groundwater flows radially outwards (Stantec, 2004). This causes groundwater in the carbonate aquifer in ESP to flow westward towards the Red River. The carbonate aquifer is the main supply of well water to ESP because of its high permeability and good quality (Stantec, 2004). The capacity of wells connected to the carbonate aquifer varies across ESP due to changes in the fracture network.

1.2 Pump Test Information

Two pump tests were part of investigations to identify suitable well locations to expand the municipal water supply system for the growing water demand in the RM. The first pump test was performed on municipal Pump Well 7 (PW7), located in the south of the RM (Figure 1). Water was pumped for 48 hours, beginning on February 25, 2004. The second pump test was performed on a municipal pump well located near Bray Road (Bray Well) in the northern part of the RM (Figure 1). Water was pumped for 72 hours, beginning on March 13, 2012.

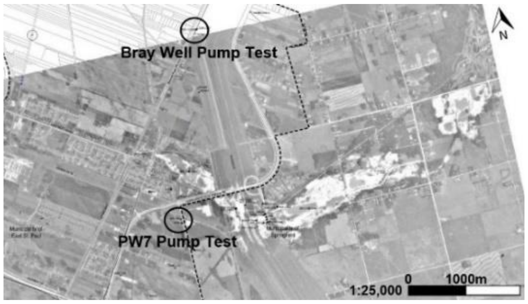

Figure 1. Map of East St. Paul with pump test locations (modified from Stantec, 2004).

2 OBJECTIVES

The research objectives for this paper were:

1. Develop a numerical model to simulate the groundwater flow during pump tests of Bray Well and Pump Well 7 in the East St. Paul region.
2. Investigate the accuracy and effectiveness of four approaches to model the two pump tests. The modelling approaches that were investigated were: 1) continuum, 2) minor fracture network, 3) major fracture network, and 4) major fracture network coupled with continuum.

3 METHODOLOGY

This section explains the methods that were used to develop the numerical model, followed by an explanation of the modelling approaches.

3.1 Model Development

The numerical model was developed using the finite element modelling software FEFLOW 7.0 (DHI-WASY GmbH, 2007). It was a 3D, fully-saturated model that simulated transient water flow. Model limits were established along the Red River on the west and the Red River Floodway on the east (Figure 2). The north and south model limits were aligned perpendicular to potentiometric head contours (Figure 2). Model limits aligned this way allows the application of no-flow boundaries to be reasonable approximations. The total area of the model is 47.3 km^2. Topographic data obtained from EarthExplorer (United States Geological Survey, 2017) via SRTM satellite imagery was downloaded and imported to FEFLOW.

Subsurface stratigraphy of the model was determined using well logs (Province of Manitoba Groundwater Management, 2017). The stratigraphy was split into four layers (from shallowest to deepest): clay, till, upper carbonate, and lower carbonate. The thickness of the upper carbonate layer in the model ranged from 13 to 19 m, which agreed with reports stating an average upper carbonate thickness of 15 m (Render, 1970). The thickness of the clay and till layers also agreed with thicknesses reported by Render (1970). The bottom of the lower carbonate (lower limit of the model) was set to a constant elevation of 180 m. Although the lower carbonate extends deeper than 180 m, the entire layer did not need to be included in the model because flow through the lower carbonate is insignificant due to its low permeability.

The model domain was discretized into 3D triangular layered elements. The mesh was refined 10x at the wells and 3x at the domain limits to account for head gradients that would be encountered at these locations (Figure 3).

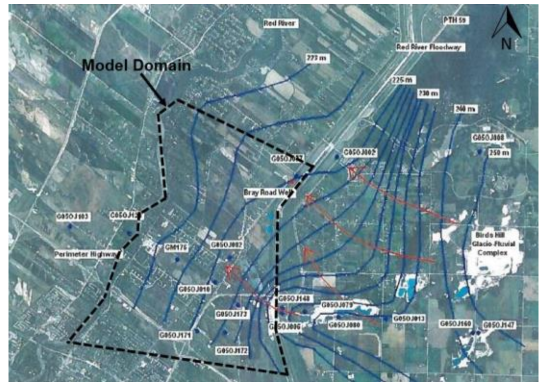

Figure 2. Potentiometric surface in the East St. Paul region with model domain (modified from Friesen Drillers, 2012).

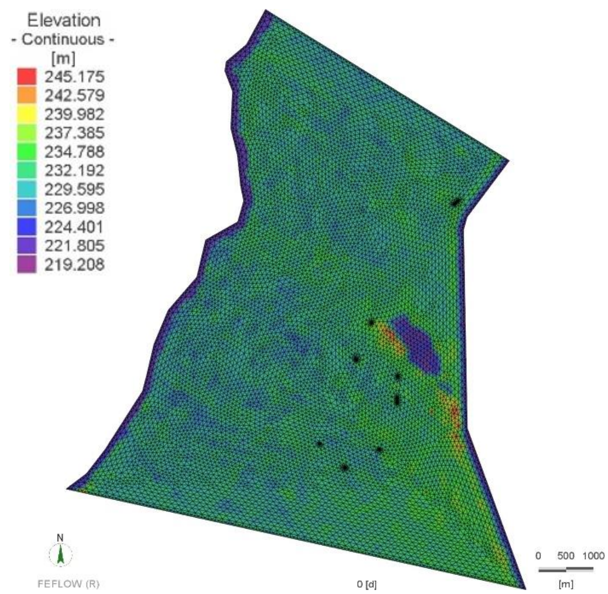

Figure 3. Elevation data and mesh discretization of the ground surface.

3.1.1 Model Input Parameters

Hydraulic conductivities of the clay and till were both 1x10^{-11} m/s. The fractured bedrock was much more permeable, with hydraulic conductivities ranging from 1x10^{-9} m/s deep underground to 5x10^{-4} m/s at the top (Table 1). Initial hydraulic properties of the upper carbonate aquifer were taken from investigation reports for the two pump tests (Stantec, 2004 and Friesen Drillers, 2012). Properties of the clay, till and lower carbonate were found in literature. Horizontal and vertical hydraulic conductivity were always assumed to be equal.

Table 1. Material properties.

Parameter	Value	Unit
Clay horizontal hydraulic conductivity[1,2,5], K_H	$1x10^{-11}$	m/s
Clay vertical hydraulic conductivity[1,2,5], K_V	$1x10^{-11}$	m/s
Clay specific storage[5], S_S	$6.5x10^{-3}$	m^{-1}
Till horizontal hydraulic conductivity[2], K_H	$6.1x10^{-11}$	m/s
Till vertical hydraulic conductivity[2], K_V	$6.1x10^{-11}$	m/s
Till specific storage[2], S_S	$9.91x10^{-3}$	m^{-1}
Lower carbonate horizontal hydraulic conductivity[5], K_H	$1x10^{-9}$	m/s
Lower carbonate vertical hydraulic conductivity[5], K_V	$1x10^{-9}$	m/s
Lower carbonate specific storage[5], S_S	$1x10^{-7}$	m^{-1}
Upper carbonate horizontal hydraulic conductivity (Bray area)[3], K_H	$5.9x10^{-4}$	m/s
Upper carbonate vertical hydraulic conductivity (Bray area)[3], K_V	$5.9x10^{-4}$	m/s
Upper carbonate specific storage (Bray area)[3], S_S	$9.5x10^{-7}$	m^{-1}
Upper carbonate horizontal hydraulic conductivity (PW7 area)[4], K_H	$4.7x10^{-4}$	m/s
Upper carbonate vertical hydraulic conductivity (PW7 area)[4], K_V	$4.7x10^{-4}$	m/s
Upper carbonate specific storage (PW7 area)[4], S_S	$4.3x10^{-6}$	m^{-1}
Upper carbonate fracture specific storage[5]	$4x10^{-6}$	m^{-1}

[1] (Render, 1970)
[2] (Grisak & Cherry, 1975)
[3] (Friesen Drillers, 2012)
[4] (Stantec, 2004)
[5] (AQTESOLV, 2017)

3.1.2 Boundary and Initial Conditions

Based on flow level data of the Red River at ESP (Environment and Natural Resources of Canada, 2017), a constant-head boundary condition of 221.0 m was applied along the west limit of the model. No water level data was available for a constant-head boundary condition along the Floodway.

Groundwater levels from wells in the region (Province of Manitoba Groundwater Management, 2017) were inputted to the model and the head distribution between the wells was interpolated using inverse distance weighting interpolation. The interpolated head conditions were unrealistic and caused steep head gradients throughout the model. This generated groundwater flow and caused drawdown in the wells during preliminary simulations with no pumping, making the initial conditions unsuitable. The head contour discrepancy is likely due to the low amount of data points for the interpolation and unknown subsurface conditions that the model did not include.

To overcome the unstable head conditions from the well data, the potentiometric surface from 2012 was used to calibrate the model's initial conditions. Head values at nodes in the upper carbonate along the Floodway were recorded and used as a constant-head boundary along that edge. The model was simulated (without pumping) until a quasi-static condition. The results of this simulation (Figure 4) reasonably represented the 2012 potentiometric surface. The head values throughout the model at the quasi-static condition were used as the initial head conditions for the Bray Well pump test simulations.

Because potentiometric contour maps from 2010 and 2012 showed minor differences, it was assumed that the potentiometric surface in ESP in 2004 would be similar to 2012. Additionally, the Red River water level was the same in 2004 and 2012. Based on this, the boundary and initial conditions from the Bray Well pump test in 2012 were applied to the PW7 pump test in 2004.

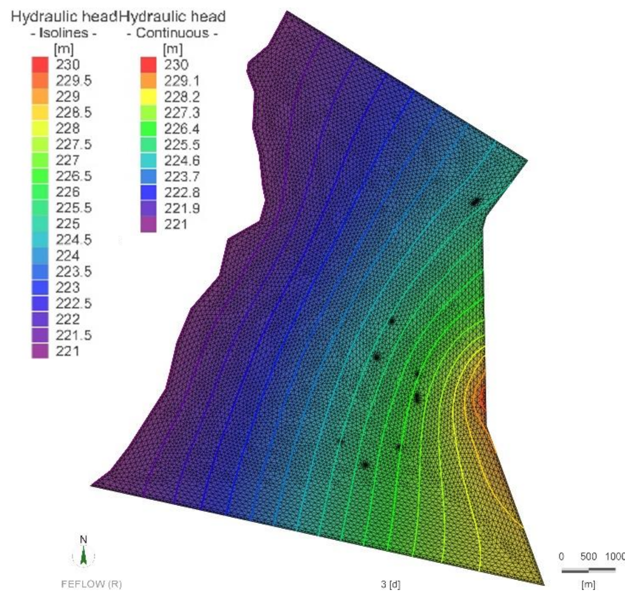

Figure 4. Initial head conditions based on the 2012 potentiometric surface.

3.2 Modelling Approaches

Four modelling approaches were used to model the drawdown behaviour during the pump tests:

1. Continuum;
2. Minor fracture network;
3. Major fracture network; and
4. Major fracture network coupled with continuum.

Certain material properties of the upper carbonate were modified in simulations while others remained constant. All material properties of the clay, till, and lower carbonate were constant through all simulations (Table 1). The fractures were defined in FEFLOW as 1D plane non-phreatic elements and flow in the fracture networks was characterized by the Hagen-Poiseuille cubic flow law. The geometric input parameter was the cross-sectional flow area (A) and the frictional input parameter was the hydraulic aperture (b). Table 2 outlines the properties that were held constant and the properties that were modified.

Table 2. Upper carbonate properties for different modelling approaches.

Modelling Approach	Constant Parameters	Modified Parameters
Single Continuum	$S_{S\text{-matrix}} = 9.5\text{x}10^{-7}$ m^{-1}	K
Minor Fracture Network	$S_{S\text{-matrix}} = 1\text{x}10^{-7}$ m^{-1} $K = 1\text{x}10^{-9}$ m/s b = 0.025 m $S_{S\text{-frac}} = 4\text{x}10^{-6}$ m^{-1}	A
Major Fracture Network	$S_{S\text{-matrix}} = 1\text{x}10^{-7}$ m^{-1} $K_{matrix} = 1\text{x}10^{-9}$ m/s b = 0.3 m $S_{S\text{-frac}} = 4\text{x}10^{-6}$ m^{-1}	A
Major Fracture Network with Continuum	$S_{S\text{-matrix}} = 9.5\text{x}10^{-7}$ m^{-1} b = 0.3 m $S_{S\text{-fracture}} = 4\text{x}10^{-6}$ m^{-1}	K, A

For the continuum approach, the specific storage was constant for each pump test (Table 1). This was based on preliminary simulations where the specific storage was modified by orders of magnitude and the drawdown results were unaffected. The hydraulic conductivity of the elements in the study area was modified (Figures 6a and 7a). Outside of that area, the hydraulic conductivity of the matrix remained constant (Table 1).

For the minor fracture networks, all edges of elements in the study area were assigned to a discrete feature element (Figures 6b and 7b). Material properties of the lower carbonate were applied to the matrix in the study area. Material properties outside of the fracture network area were left as specified in Table 1. During preliminary simulations of the minor fracture network, aperture and cross-sectional area of the fractures were both modified to determine their effect. The simulations showed that modifying the aperture and area had the same effect on drawdown; the magnitude of the drawdown varied but the shape of the drawdown curves was the same. This allowed for one of the parameters to be held constant to simplify the problem from two variables to one. Hydraulic aperture of the minor fracture network was set to 0.025 m, the typical maximum fracture size in the upper carbonate aquifer (Render, 1970). The specific storage in the fractures was held constant at $4\text{x}10^{-6}$ m^{-1} and cross-sectional area was modified. Minor fracture networks for the PW7 pump test were of similar density as the Bray Well pump test.

For the major fracture networks, arbitrary element edges connecting the wells with each other and the surrounding area were assigned to a discrete feature element (Figures 6c, 7c, and 10). Lower carbonate properties were assigned to the matrix material in the fracture network area and material properties outside of the fracture network area were left as specified in Table 1. Hydraulic aperture of the major fractures was set to 0.3 m, the size of major joint openings observed in the upper carbonate (Render, 1970). The cross-sectional area of the major fractures was modified in simulations.

For the major fracture network coupled with continuum approach, hydraulic conductivity of the continuum matrix and cross-sectional area of the fractures were modified during simulations. All other properties were constant based on reasoning discussed above. In addition, the size of the continuum and fracture network areas for each approach were modified to study the impact on the drawdown (Figures 6, 7, and 9).

3.2.1 Bray Well Pump Test Modelling Details

The pumping rate of the Bray Well pump test was 28.97 L/s and the test duration was 72 hours. The simulation used adaptable time-stepping with a maximum time-step of 0.01 day. Groundwater levels were observed in nine observation wells (excluding the pump well). Most of the observation wells were private or located outside the model domain, so only observation well SD-4432 was included in the model (Figure 5). The distance between the pump well and observation well was approximately 90 m.

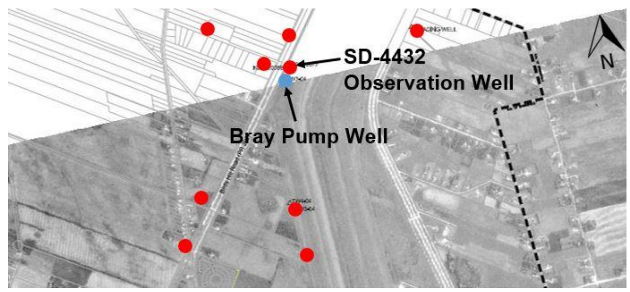

Figure 5. Map of pump well (blue) and observation wells (red) for Bray Well pump test (modified from Stantec 2004).

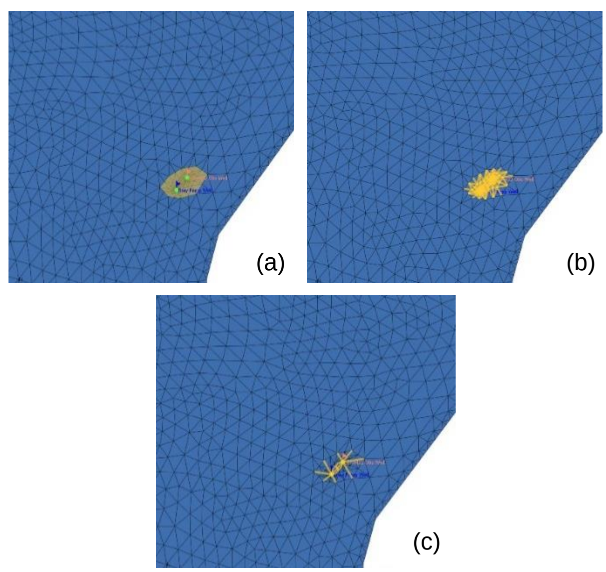

Figure 6. Bray Well pump test Area 1 element features for: (a) continuum, (b) minor fracture network and (c) major fracture network.

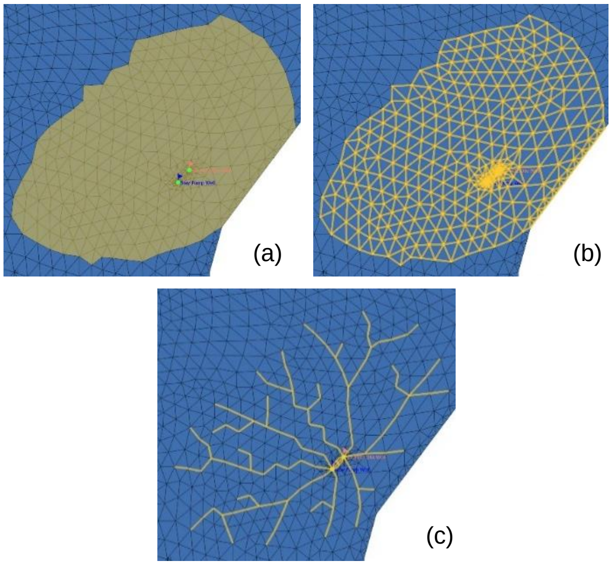

Figure 7. Bray Well pump test Area 2 element features for: (a) continuum, (b) minor fracture network and (c) major fracture network.

3.2.2 Pump Well 7 Pump Test Modelling Details

The pumping rate of the PW7 pump test was 28.5 L/s and the test duration was 48 hours. The pumping stopped 26 hours into the test for 20 minutes due to an issue with the pump. The simulation used adaptable time-stepping with a maximum time-step of 0.01 day. Groundwater levels were observed in nine observation wells (excluding the pump well). Most of the observation wells were located outside the model domain, so only three observation wells were included in the model: SD-126559, SD-4185, and RW4 (Figure 8).

The distance from the pump well to SD-126559, SD-4185, and RW4 were 85, 1080, and 1510 m, respectively. The study area for the pump test was split into three areas for the specific observation wells (Figure 9). Feature elements and material properties for each modelling approach were uniquely assigned to the different areas to account for differences in the fracture network. The network of the major fractures was also modified to determine its impact on the drawdown results (Figure 10).

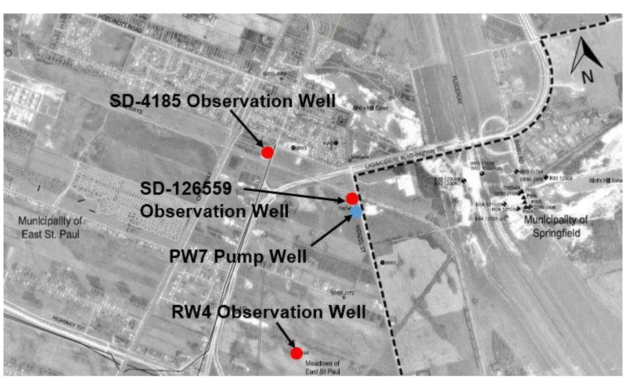

Figure 8. Map of pump and observation wells for PW7 pump test (modified from Stantec, 2004).

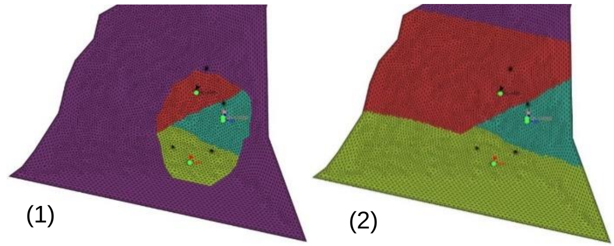

Figure 9. Areas 1 and 2 for PW7 pump test.

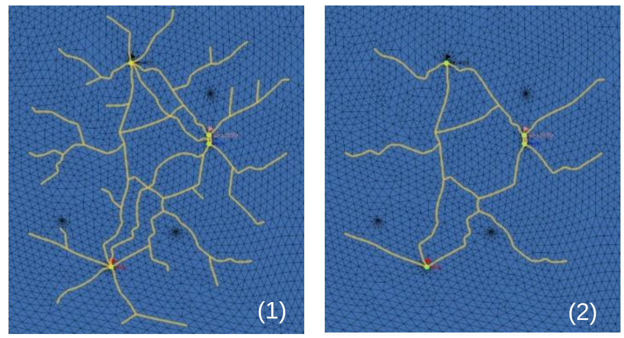

Figure 10. Major fracture networks for PW7 pump test.

4 RESULTS AND DISCUSSION

Several simulations were run for each approach until a near-optimal drawdown was generated. Table 3 is included at the end of the section to provide a concise overview of the strengths and weaknesses of each modelling approach.

4.1 Bray Well Pump Test Results

Drawdown behaviour for the single continuum was quite different for Areas 1 and 2 (Figure 11). Drawdown for Area 1 was more gradual and the drawdown recovery was not accurately modelled. Area 2 was able to capture the rapid drawdown and recovery at the start and end of the test for the pump well, but failed to accurately model the observation well.

The minor fracture network approach did not fully capture the rapid drawdown and recovery, but the overall behaviour was reasonably modelled (Figure 12). Area 2 better resembled the actual drawdown in both wells. The major fracture network (Figure 13) did not simulate the drawdown as well as the minor fractures. The plots of the two approaches had similar shape, but major fractures could not separate drawdown in the wells because of their high connectivity.

The major fracture network with continuum was the best performing modelling approach for the Bray Well pump test (Figure 14). The option to modify both the continuum and fracture properties allowed for more precise control of the groundwater flow in the area and accurate modelling of the drawdown in both pump and observation wells. One drawback is that the major fracture network with continuum took more time and effort to set up and optimize compared to the other approaches.

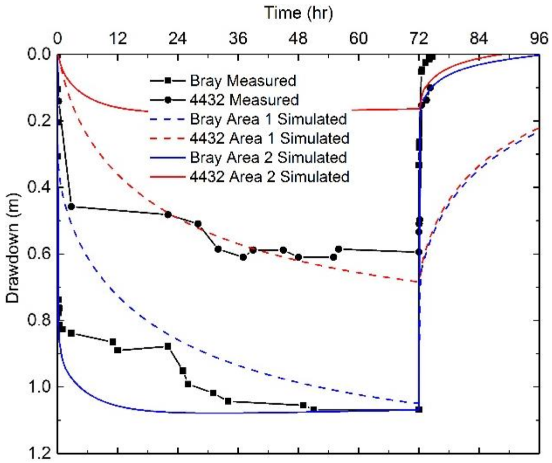

Figure 11. Bray Well pump test continuum results.

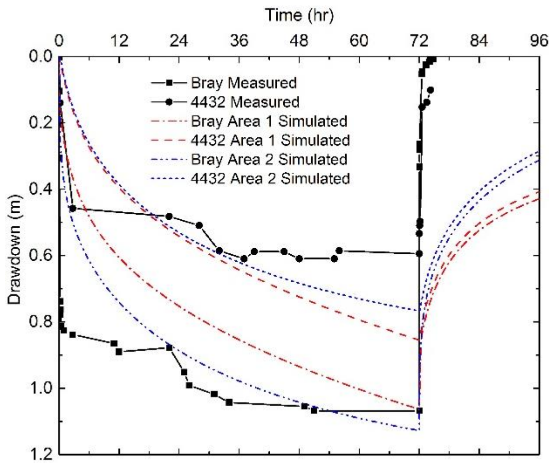

Figure 12. Bray Well pump test minor fracture network results.

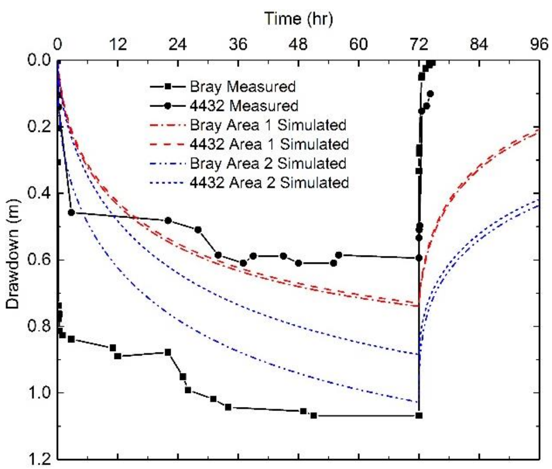

Figure 13. Bray Well pump test major fracture network results.

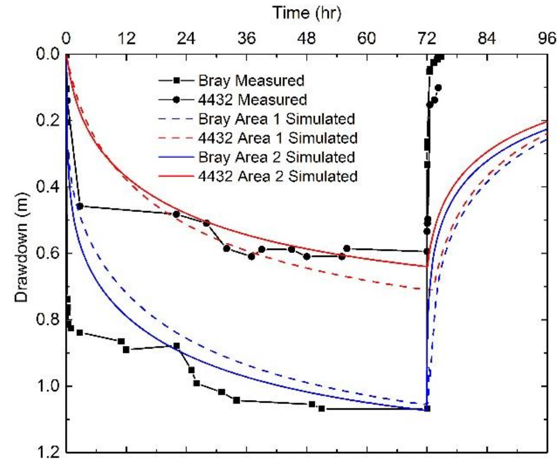

Figure 14. Bray Well pump test major fracture network with continuum results.

4.2 Pump Well 7 Pump Test Results

Continuum was the best modelling approach for the pump well because it was able to accurately capture the rapid drawdown and recovery (Figure 15). Alternatively, the continuum models were ineffective at modelling drawdown in wells at longer distances. The multiple continuum approach marginally improved the accuracy compared to single continuum (Figure 15).

Drawdown behaviour for a single minor fracture network was (Figure 16) a slight improvement to single continuum, but drawdown at the observation wells was still not accurate. Multiple minor fracture networks significantly improved the accuracy of the simulated drawdown at the observation wells, but did not fully capture the rapid recovery at the end of the 3-day simulation (Figure 16). Overall, multiple minor fracture networks performed well compared to the other approaches.

The major fracture network approach was not successful in modelling drawdown, particularly at the long-distance observation wells (Figure 17). Multiple major fracture networks improved the drawdown results and was the only approach to successfully model the recovery in wells SD-126559 and RW4. The increase in water level at the start of the major fracture network simulations was because there was high connectivity between wells and the heads in the pump well were initially higher than in SD-126559 and RW4. It is also likely that modifying the material properties in each simulation altered the groundwater regime and caused a minor transient condition at the start of the pump tests, which impacted drawdowns. This would particularly interfere with the observation wells furthest from the pump well because they are less impacted by drawdown in the pump well.

The major fracture network with continuum approach was not effective for the PW7 pump test because the study area (Area 1) was not large enough and the surrounding region interfered with drawdown in the pump well (Figure 18).

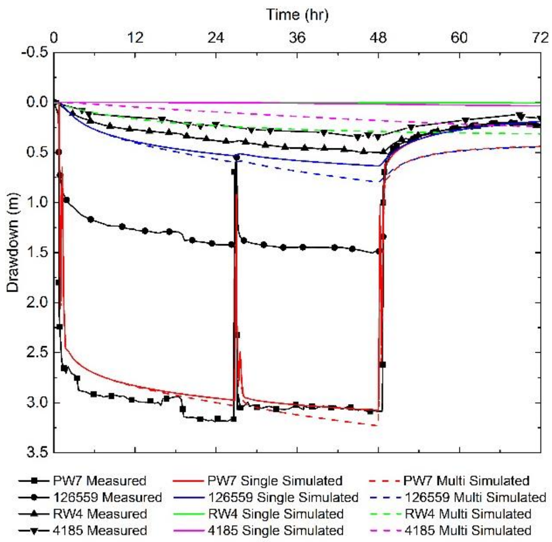

Figure 15. PW7 pump test continuum results.

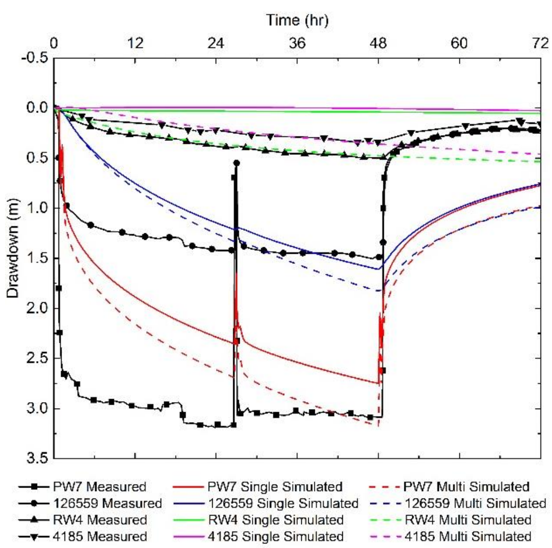

Figure 16. PW7 pump test minor fracture network results.

Using multiple areas and fracture networks improved the results for each approach. Specifying the material properties of the area surrounding each well gave more flexibility to the modelling and allowed for more accurate drawdown simulations. Approaches using multiple areas required more time for calibration and optimization.

The two major fracture networks were compared using the same material and fracture properties to understand the impact of the fracture network density on the drawdown (Figure 19). Behaviours were similar for each well but overall the less dense fracture network more accurately captured the drawdown behaviour. This is likely because the denser fracture network had more inflow to the observation wells from the additional fractures. The less dense network had less interference from the surrounding elements and the drawdown in the pump and observation wells was more connected, leading to more accurate results.

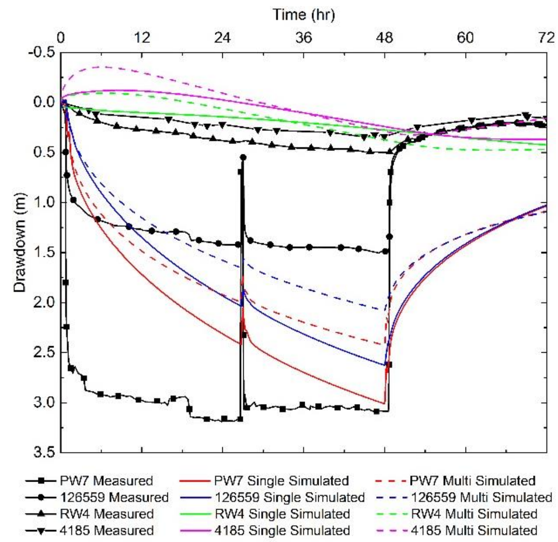

Figure 17. PW7 pump test major fracture network results.

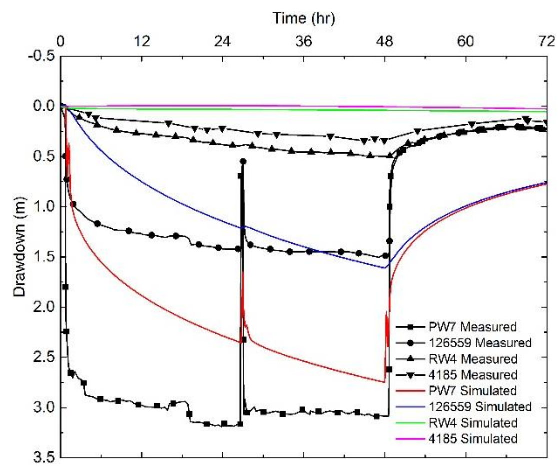

Figure 18. PW7 pump test major fracture network with continuum results.

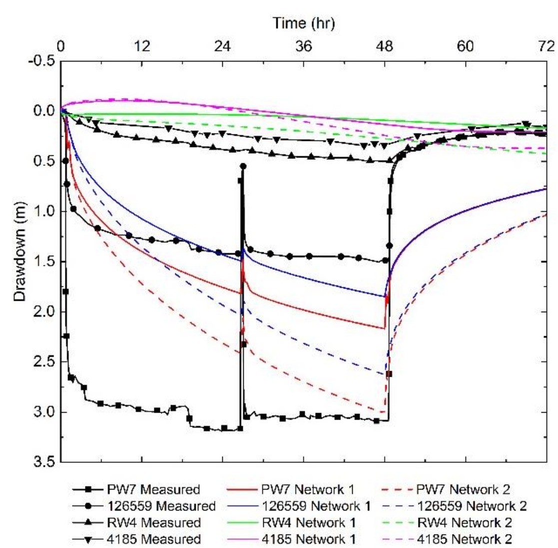

Figure 19: Comparison of PW7 pump test major fracture network 1 and 2 results.

Table 3. Strengths and weaknesses of the modelling approaches.

Modelling Approach	Strengths	Weaknesses
Continuum	• Simple and fast • Captured rapid drawdown and recovery in pump wells	• Ineffective at longer distances • Underestimated drawdown at observation wells
Minor Fracture Network	• Reasonably simulated behavior at all wells • Easy model to set up	• Fails to capture rapid drawdown and recovery in pump well
Major Fracture Network	• Simulates recovery at long distance observation wells reasonably well	• Failed to capture rapid drawdown and recovery in pump well • Longer time to set up model • Must define fracture network without knowledge
Major Fracture Network Coupled with Continuum	• Versatile approach – able to focus on pump or observation wells • Reasonably simulates behavior at all wells	• More time and work to set up model • Most variables and takes longer to calibrate • Does not fully capture recovery

5 CONCLUSION AND RECOMMENDATIONS

A numerical model was developed using FEFLOW to investigate the effectiveness of four modelling approaches to simulate pump tests of two wells in a fractured rock aquifer. Several characteristics such as size of the study area, material properties, and fracture network density were modified to understand their impact on the drawdown results. The analysis led to four main conclusions:

1. The major fracture network coupled with continuum was the best performing modelling approach for the Bray Well pump test, but did not perform well for the PW7 pump test due to size limits of the fracture area.
2. The minor fracture network approach performed strongly for both pump tests and is an appropriate approach to model the fractures in the ESP region.
3. Using multiple areas surrounding each well to specify material properties improved the accuracy of the drawdown results compared to a single area for all wells. Multiple areas however requires more time for calibration.
4. Larger areas in which material properties are modified and less dense fracture networks generally improved accuracy of the simulated drawdown.

This research served as a base study to initiate groundwater modelling in the ESP region. There were some limitations of the numerical modelling and issues encountered that if resolved could improve the results. Following are four recommendations for future work:

1. Run all simulations without pumping until a quasi-steady state is reached. Modifying fracture networks and material properties between simulations changes the groundwater regime and can interfere with drawdown in the wells if initial conditions are not at a steady state.
2. Model the pump tests using a multiple discrete fracture network approach – a minor fracture network across the area with major fractures connecting wells. Major fractures between wells could improve the rapid drawdown and recovery accuracy, which was lacking in the minor fracture network approach.
3. Extend the model domain near the Bray Well to eliminate the possibility of boundary condition interference along the Floodway.

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