

Resolving preferential flow and leakage in a confined carbonate aquifer using hydraulic testing and electrical resistivity imaging

Valentina I. Ita

The University of Toledo

James M. Martin-Hayden

The University of Toledo

Kennedy O. Doro

kennedy.doro@utoledo.edu

The University of Toledo

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Abstract

Carbonate aquifers can sustain high yields, yet understanding of flow within them is limited due to heterogeneity resulting from fractures, bedding plane partings and dissolution cavities. This study evaluates flow and transport in a confined carbonate aquifer beneath glacial deposits in northwestern Ohio, USA, by combining multiple pumping and saline tracer tests imaged with time-lapse electrical resistivity. The study was conducted using a well field consisting of three ~ 40 m deep wells and four ~ 5 and 10 m deep wells. Pumping at $18 \text{ m}^3/\text{hr}$ produced 0.02–0.20 m and 0.35–1.17 m water-level declines in shallow and deep wells respectively while the deep wells show late-time drawdown departures consistent with delayed leakage through overlying aquitard, indicating semi-confined aquifer behavior. Hydraulic conductivity estimates ranged from 10^{-4} to 10^{-6} m/s while contrasting drawdown, specific yield, and well efficiency demonstrate preferential connectivity. The first arrival of the tracer occurred within 20–22 min while calculated linear velocity, longitudinal dispersivity, and effective porosity were $2.5\text{--}2.9 \times 10^{-3} \text{ m/s}$, 2.3–2.6 m, and 0.6–1.1%, respectively. Rapid breakthrough, secondary arrival, and extended tailing indicated preferential transport with density and mobile-immobile exchange. Extending injection-well recirculation in the repeat test suppressed the early secondary peak, demonstrating how wellbore density effects in tracer experiments can mimic non-Fickian transport. Time-lapse electrical resistivity imaging detected 7–21% resistivity decrease that corroborates early and delayed tracer responses. Results of this study show that integrating hydraulic, tracer, and geophysical tests provides improved constraints on leakage, connectivity, and transport pathways in carbonate aquifers.

1.0 Introduction

Carbonate aquifers supply water to communities for domestic, agriculture, and other industrial use in many parts of the world including northwest Ohio (Coe and Raab, 2012; Stevanovic, 2019). Their productivity, however, depends on secondary permeability associated with fractures, bedding-plane partings, vugs, and dissolution-enlarged openings rather than on their primary matrix porosity (Martin-Hayden et al., 1999; White, 2002; Worthington and Ford, 2009). Consequently, groundwater wells separated by only a few to tens of meters can intersect different transmissive features within the aquifer and exhibit substantially different drawdown, specific discharge, storage response, and solute travel time (Coe and Raab, 2012; Medici and West, 2021; Worthington, 2015). Bulk hydraulic parameters assigned from a single pumping test may therefore not fully capture flow pathways that control both sustainable yield and contaminant migration within these aquifers (Butler 2005; Singhal and Gupta 2010; Maliva 2016).

Aquifer hydraulic parameter estimation via pumping and tracer tests provides complementary information due to their different sensitivity patterns and volumes tested (Dann et al., 2008). Pumping tests integrate pressure propagation across relatively large aquifer volumes and constrain transmissivity, storage, leakage, well loss, and the aquifer hydrological boundary behavior (Doro et al., 2025; Kruseman and de Ridder, 1990; Renard et al., 2009). Conservative-tracer tests, however, interrogate the connected mobile domain of the aquifer and provide estimates of travel time, velocity, effective porosity, and

dispersivity (Vandenbohede and Lebbe, 2003). In aquifers such as the carbonates characterized by secondary permeability from fractures, dissolution cavities, bedding plane, etc. (Coe and Raab, 2012), breakthrough curves can deviate strongly from the classical advection-dispersion model because of preferential flow, exchange between mobile water within the fractures and less mobile water, and density driven flow within open wells (Becker and Shapiro 2000; Massei et al. 2006; Shapiro 2019). Hence, a second tracer arrival or prolonged tailing of the tracer breakthrough curve is consequently not necessarily unique evidence of matrix diffusion (Bodin et al., 2022). Test configuration and wellbore mixing must be evaluated before transport mechanisms are assigned (Becker and Shapiro, 2003; Martin-Hayden, 2000).

Multiple hydraulic tests combining pumping and tracer tests with hydrogeophysical monitoring can reduce some of this ambiguity of transport mechanisms by adding spatial information to hydraulic and tracer concentration measurements (Singha and Gorelick, 2005). Saline tracers within groundwater are known to decrease measured bulk electrical resistivity and can therefore be imaged repeatedly using electrical resistivity methods (Binley and Kemna 2005; Day-Lewis et al. 2003; Doro et al. 2015; Linde et al. 2006). Electrical resistivity imaging (ERI) however does not provide a direct concentration measurement, and its resolution decreases with depth (Adebayo et al., 2026; Day-Lewis et al., 2005; Binley et al., 2015), but time-lapse resistivity differences can identify where and when an electrically conductive tracer plume propagates within the imaged aquifer volume (Singha and Gorelick, 2005; Kemna et al., 2002). Agreement among drawdown, tracer breakthrough, and time-lapse resistivity responses can therefore provide a stronger basis for an aquifer conceptual model compared to any single method. Divergence in results may also point to subtle characteristics of heterogeneity typical of natural systems and not just differences in methods (Singha and Gorelick, 2005).

The carbonate-bedrock aquifer of northwestern Ohio is a high-yield regional groundwater resource occurring beneath glacial and glaciolacustrine deposits (Coe and Raab, 2012; Fisher et al., 2025; Lanier et al., 2025). Recharge has been attributed to: [1] leakage through the unconsolidated glacio-lacustrine sediments mantling the bedrock, [2] lateral inflow where bedrock is shallow, [3] streambed infiltration, and [4] direct recharge where the carbonate rock is exposed (Becker et al., 2021; Breen and Dumouchelle 1991; Bugliosi 1990). In the Oak Openings Region where the study area is located, the magnitude and timing of vertical interaction, the hydraulic connection between individual bedrock wells, and field-scale transport properties remained poorly constrained (Ogunkoya et al. 2023). The Ohio Geological Survey recently released a map showing the yield and hydraulic conductivity distribution of the major aquifers in Ohio (Lanier et al. 2025, Potucek et al. 2025; Scaccia et al. 2026). They, however, acknowledge that their estimates are plagued with greater uncertainties within the carbonate aquifers in the northwestern region of the state. These uncertainties limit defensible aquifer conceptualization and numerical modeling.

Hence, this case study seeks to provide additional information on the hydraulic properties' variability and hydraulic connectivity within the carbonate aquifers in northwest Ohio with valuable insight for conceptualizing other carbonate aquifers globally. This case study tests the general hypothesis that the productive carbonate aquifer beneath glacial deposits in northwest Ohio behaves as a heterogeneous, semi-confined system in which discrete transmissive zones create preferential well-to-well connectivity

and prolonged pumping induces delayed leakage through the overlying aquitard in contrast to earlier assumed general confined aquifer model. The study tests three main predictions including: [1] identical pumping schedules applied to adjacent bedrock wells should generate contrasting drawdown, well efficiency, flow-regime, and boundary responses; [2] continuous pumping in the bedrock wells should produce small but coherent hydraulic head changes in shallow piezometers within the sediments above the confining layer and late-time drawdown behavior consistent with leakage; and [3] during forced-gradient conditions, tracer should travel rapidly through the connected mobile domain helping distinguish formation-scale transport from wellbore density effects.

We tested these predictions at the University of Toledo Stranahan Arboretum's multi-well hydrogeophysics field test site using constant-rate pumping tests with three different durations, step-drawdown tests and recovery monitoring, and two forced-gradient NaCl tracer tests monitored with time-lapse ERI. We evaluated different methods that interrogate various processes and scales, and we present a workflow that is transferable to other fractured aquifers where apparent hydraulic productivity must be reconciled with leakage, preferential transport, and test-design artifacts.

2.0 Materials and Methods

2.1 Study Site

This study was conducted at the University of Toledo's Stranahan Arboretum (STAR), Toledo, Lucas County, NW Ohio (Fig. 1). The STAR site is a 47-acre educational and outdoor research facility located within the Oak Openings ridge, a northeast-southwest trending sand ridge associated with ancestral Lake Erie (Ogunkoya et al. 2023). The surficial deposit sequence over the bedrock within the region consists of glacial till overlain by glaciolacustrine silt-clay rhythmites, littoral sand and gravel and eolian silty fine sand (Larsen et al. 2005). The thickness of surficial deposits varies regionally from exposed bedrock to more than 25 m of sediment (Bush 1966; Larsen et al. 2005; Fisher et al. 2015). The sandy sediments and locally saturated rhythmites form a shallow unconfined aquifer system with a seasonally variable water table with depth ranging from 0 m (at the surface) to > 3 m (Ogunkoya et al. 2023). The underlying clay-rich till principally serves as an aquitard over the carbonate bedrock aquifer. Silurian and Devonian carbonate units form the regional bedrock aquifer of dolomite and limestone with low primary porosity and flow within them dominated by fractures, bedding-plane partings, vugs, and dissolution features (Janssens 1977; Norris 1975). Previous regional investigations inferred that recharge to the carbonate aquifers occurs through leakage and in areas where the bedrock is hydraulically connected to shallow deposits (Breen and Dumouchelle 1991).

The STAR well field contains three bedrock wells (DWA, DWB, and DWC) and four shallow piezometers (SWA-SWD; Table 1 and Fig. 1). Bedrock-well depths range from approximately 38 to 50 m while the shallow piezometers are 5 or 10 m deep and are used to monitor the sand and rhythmites above the till. Previous studies at the STAR hydrogeophysics well field research site by Ogunkoya et al. (2023) combined geophysical measurements of electrical resistivities and refraction seismic with lithological

well-logs to produce a refined 4-layer conceptual hydrogeological model of the aquifer system differentiating the glacial till confining units from the silt clay rhythmites underlying the unconfined sand aquifers. Also, recent borehole geophysical logs and cross-borehole electrical resistivity imaging have identified permeable intervals within the carbonate aquifer separated by more massive units, including a prominent interval at approximately 39–42 m in DWA and DWC that is not found in the shallower DWB (Ita et al., in review).

Table 1
Wells at the STAR site Hydrogeophysics Well Field

Well Name	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m)	Total Drill Depth (m)	Well radius (m)
DWA	41.693371	-83.668729	195.288	~ 50	0.0762
DWB	41.693263	-83.668724	195.285	~ 38	0.1016
DWC	41.693302	-83.668593	194.993	~ 40	0.1016
SWA	41.693292	-83.668629	194.503	~ 10	0.0254
SWB	41.693292	-83.668629	194.999	~ 5	0.0254
SWC	41.693290	-83.668701	195.189	~ 10	0.0254
SWD	41.693273	-83.668688	195.164	~ 5	0.0254

2.2 Hydraulic Head Monitoring

For this study, borehole elevations were first surveyed in March 2024 using a laser transit, with measurements referenced to an established local benchmark (LBM), ensuring millimeter-scale accuracy. These elevations were used with pressure transducer readings to calculate hydraulic heads for each well. Heads were measured continuously at a 15 minute interval in all wells using DIVER data loggers (VanEssen Instrument, Hayward, CA, USA). The direction and magnitude of the hydraulic gradient at the STAR site were determined using a three-point problem approach (Johnston & Harte, 1998; MacCarthy et al., 2021). The gradient is then used to infer the direction of groundwater flow.

In addition to monitoring the hydraulic gradient at the site, head values in both the surficial and bedrock aquifers were regularly monitored throughout the study period. The head measurement datasets were then resampled to represent daily variations to capture larger seasonal fluctuations and potential influence of recharge events or nearby hydraulic activity.

2.3 Pumping Tests

We conducted multiple pumping tests by pumping at each of the bedrock wells while monitoring heads in the other bedrock wells and the four shallow piezometers. Constant-rate pumping tests were first conducted at 80 gal/min (5.05×10^{-3} m³/s) for 10, 24, and 90 hours followed by step drawdown tests using progressive pumping rates of 40, 60, 80, and 100 gal/min (2.52×10^{-3} to 6.31×10^{-3} m³/s), with

each step lasting 2 hours. For each test, we also monitored the water level recovery for over 24 h after cessation of pumping (Table 2).

For each pumping test, we used a 5-hp submersible pump installed in the pumping well at approximately 30 m below the surface. Flow rates and discharges were controlled by a valve and measured with an inline electronic flow meter. During each test, pressure transducers were installed at fixed depths in the pumping and observation wells. Water levels from the pressure transducers were corrected for barometric pressure, compared with periodic manual readings, and screened for pump-start transients and isolated sensor artifacts before use for data analysis.

Table 2
Hydraulic tests design.

Pumping well	Test	Discharge	Duration	Test period
DWA	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	10 and 24 h	October 19–21, 2023
DWA	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	90 h	June 12–16, 2024
DWA	Step drawdown	40–100 gal/min ($2.52\text{--}6.31 \times 10^{-3} \text{ m}^3/\text{s}$)	4 × 2 h	October 30, 2023
DWB	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	10 and 24 h	June 20–22, 2024
DWB	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	90 h	July 1–5, 2024
DWB	Step drawdown	40–100 gal/min ($2.52\text{--}6.31 \times 10^{-3} \text{ m}^3/\text{s}$)	4 × 2 h	July 8, 2024
DWC	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	10 and 24 h	September 20–22, 2023
DWC	Constant rate	80 gal/min ($5.05 \times 10^{-3} \text{ m}^3/\text{s}$)	90 h	August 19–23, 2024
DWC	Step drawdown	40–100 gal/min ($2.52\text{--}6.31 \times 10^{-3} \text{ m}^3/\text{s}$)	4 × 2 h	October 2, 2023

The resulting time-drawdown data from the pumping tests were inspected on linear, semi-logarithmic, and log-log plots before an analytical solution was selected (Kruseman and de Ridder 1990). Early and intermediate data that approximated confined radial flow were analyzed with the Cooper-Jacob straight-line approximation:

$$T = \frac{2.3Q}{4\pi \Delta s}$$

$$S = \frac{2.25Tt_0}{r^2}$$

2

where T is transmissivity, S is storativity, Q is discharge, Δs is drawdown change over one logarithmic time cycle, t_0 is the time intercept, and r is pumping-to-observation-well distance (Cooper and Jacob 1946). Hydraulic conductivity was calculated as $K = T/b$ using a nominal saturated bedrock thickness, b , of 25 m. These values are therefore bulk effective estimates and not interval-specific measurements.

Selected 24-h responses that departed from confined behavior at late time were also analyzed with the Hantush-Jacob leaky-aquifer solution:

$$s = \frac{Q}{4\pi T} W(u, r/B)$$

3

where

$$u = \frac{r^2 S}{4Tt}, \text{ and } L = \frac{K'}{b'} = \frac{T}{B^2}$$

4

where B is the leakage factor, K' and b' are aquitard vertical hydraulic conductivity and thickness, respectively, and L is leakance (Hantush and Jacob 1955). Leakage estimates reported here are restricted to observation-well fits; pumping-well fits were excluded because well loss and wellbore storage violate the assumptions of the analytical solution. An effective aquitard thickness of 10 m was used.

Hydraulic head recovery data were analyzed by plotting residual drawdown against $\log(t/t')$ and applying the Theis recovery approximation (Theis 1935). Step-drawdown data were analyzed using:

$$s_w = B_w Q + C_w Q^2$$

5

where $B_w Q$ represents linear aquifer loss and $C_w Q^2$ represents nonlinear well loss (Rorabaugh 1953; Hantush 1964). Well efficiency was calculated as $100B_w Q/s_w$. Aquifer Test Solver (AQTESOLV Pro v4.5) was used for analytical fitting.

We used the Bourdet derivative, $ds/d\ln(t)$ to identify changes in flow regime and possible hydraulic boundaries (Bourdet et al. 1989; Renard et al. 2009). Interpretations emphasized sustained patterns

rather than isolated derivative points. Distances to inferred boundaries were estimated with the image-well relation $r_b = (Tt_b/S)^{1/2}$, where t_b is the time at which a sustained slope change began. These distances are conceptual indicators because the inferred boundaries were not independently mapped.

2.4 Forced-Gradient Tracer Tests

Two forced gradient quasi-convergent flow field tracer tests were performed between DWC (injection) and DWB (extraction), separated by approximately 11.9 m (Fig. 1). DWB was pumped at 60 gal/min ($3.79 \times 10^{-3} \text{ m}^3/\text{s}$) for approximately 4 hours before the tracer injection to establish a quasi-steady state convergent forced gradient flow field. A tracer solution containing 18 kg NaCl dissolved in approximately 3000 L of site groundwater (nominal concentration 6 g/L) was injected into DWC at approximately 15 gal/min ($9.46 \times 10^{-4} \text{ m}^3/\text{s}$). The injection line was terminated at approximately 20 m depth. To reduce density effect which could result in the sinking of the denser saline solution, a submersible pump was used to recirculate water within DWC (LeBlanc et al. 1991). The principal design difference between tests was the post-injection recirculation period which was approximately 10 min in Test 1 and 2 h in Test 2. This controlled change was used to assess whether a secondary breakthrough response originated from formation transport or from density segregation and residual tracer within the injection well.

Groundwater electrical conductivity was measured at 15-seconds intervals in the DWB discharge line using an electrical conductivity meter. Background conductivity was approximately 903–920 $\mu\text{S}/\text{cm}$. A laboratory calibration prepared with site groundwater and 0–12 g/L NaCl solutions was used to convert measured groundwater electrical conductivity to NaCl concentration. The solute breakthrough time, peak time, recovered mass, and curve moments were calculated after subtraction of the background electrical conductivity. The recovered breakthrough curves were fitted in TRAC software using a pulse solution for radially convergent flow (Thiéry 2022). The fitted and moment-based estimates provided linear velocity, longitudinal dispersivity, and effective or kinematic porosity. Because the analytical solution assumes a homogeneous mobile domain, fitted parameters are interpreted as effective values for the connected flow path rather than properties of the entire 25-m saturated bedrock thickness.

2.5 Time-Lapse Electrical Resistivity Imaging

A 200-m ERI transect was installed crossing the well field and comprised of 80 stainless-steel electrodes at 2.5-m spacing. A dipole-dipole electrode array was used to acquire approximately 1500 apparent-resistivity measurements using a 4point light 10W resistivity system (Schwarteck, Achim, Germany). Contact resistances were first measured with values $< 2 \text{ K}\Omega$ indicating good contacts for all 80 electrodes. A current injection of minimum and maximum values of 2 and 5 cycles were used with an error limit of 2% to ensure good data quality data. A background survey preceded tracer injection with both normal and reciprocal measurements first acquired to access data error. A 10% threshold was used for filtering out bad data. Eight subsequent surveys were acquired during approximately 6 hours; each measurement sequence required approximately 33 min, with additional time for data handling.

The electrical resistivity data were inverted with ResIPy using a time-lapse difference approach (Blanchy et al. 2020). A minimum 2% error model and a target root-mean-square misfit of approximately 3 were

used. Results are reported as percentage change relative to the pre-injection model. The acquisition interval and declining depth sensitivity limit direct comparison with 1-min conductivity data; ERI anomalies are therefore interpreted as spatial corroboration of tracer influence rather than exact plume concentration.

3.0 Results

3.1 Transient hydraulic head variation and potentiometric surface

The water table in the unconfined surficial aquifer fluctuates seasonally, recharged primarily by precipitation and discharged by evapotranspiration and withdrawals from wells (Breen & Dumouchelle, 1991). For detailed context, the SWA and SWC piezometers are drilled and screened down to the lower section of the Rhythmites down to 10 m, while SWB and SWD are screened only in the sand and upper section of the Rhythmites in the shallow aquifer down to 5 m (see Table 3 – 1). Head is high, at ~ 193.5 m (above mean sea level – amsl) earlier in the year, with fluctuations in response to recharge events such as precipitation and snow melt during the winter season. This is followed by a gradual decline by mid-year (summer months) down to ~ 190.5 m amsl, and a pronounced increase as we transition back into the winter season. Notably, the 5m wells SWB and SWD were observed to dry out during the summer period (Fig. S1), as a result of the declining head seen in SWA and SWC.

In contrast, the deep wells show that the bedrock aquifer responds differently to seasonal patterns. This observation is consistent with the recharge mechanisms of carbonate bedrock aquifers previously described by Breen & Dumouchelle (1991) and Martin-Hayden et al., (1999). Hydraulic heads gradually rise (from ~ 178 to 179.5 m amsl) during the winter and early spring months (Fig. S1), reaching a peak of approximately 180.5 m before beginning to decline in the summer. By fall, heads reach their lowest levels, around 178.5 m (Fig. S1). In the bedrock aquifer, groundwater flows from the northeast toward the southwest, as indicated by the orientation of equipotential lines and the direction of the hydraulic gradient (Fig. S2). The potentiometric surface map (Fig. S2) shows a higher hydraulic head values in the northeastern portion of the site (where DWC's head is 180.22m amsl) and lower values in the southwestern portion (180.215 m amsl at DWB), confirming the inferred flow direction.

3.2 Pumping Test

3.2.1 Water level responses in surficial wells

Water level trends were continuously monitored in all shallow piezometers during pumping tests in all the bedrock wells. The hydrographs (Fig S3) reveal small scale interactions with observed drawdown magnitude across the piezometers ranging from 0.03 -0.10m drawdown. The responses observed at DWA during the pumping periods (Fig. S3) show water level declines ranging from 0.03–0.05m across the wells. This decline was followed by a rapid and nearly complete recovery immediately after pumping ceased. The 10-hour pumping event initiated the initial drawdown, after which the bedrock wells were left

to recover for approximately 24 hours. However, during this recovery period, the hydrographs (Fig. S3) indicate that water levels continued to decline rather than recover, and only began to rebound at the onset of the 24-hour pumping event. Water levels declined again toward the end of the 24-hour pumping period and reached full recovery more than 30 hours after the 24-hour test was shut off.

Pumping tests at DWB resulted in slightly greater water level declines in the surficial aquifer during the pumping periods (Fig. S3). These declines ranged from 0.05 m to 0.20 m across all four piezometers during both the 10-hour and 24-hour pumping events. The 10-hour pumping period led to a sharp decline in water levels, which became more pronounced in the latter half of the test setting in more than four hours into pumping. The aquifer was then allowed to recover for approximately 24 hours. During this period, the surficial units showed partial recovery, although water levels did not return to pre-pumping conditions. At the onset of the 24 hour pumping period, water levels began declining immediately and exhibited a brief plateau after about five hours, followed by an increase in the rate of drawdown leading to the maximum observed decline. The hydrographs however, do not capture the recovery phase following this second pumping event.

The DWC pumping test produced the smallest magnitude of drawdown in the surficial units, with declines ranging from 0.02 to 0.04m. During the 10-hour test, water levels declined slightly (less than 0.02m) before gradually increasing toward the end of the pumping period. This was followed by a recovery phase during which water levels continued to rise. However, a slight decline was observed again toward the end of the recovery period. A similar pattern occurred during the 24-hour pumping test, where an initial decline was followed by a gradual rise in water levels. Ultimately, the surficial units experienced full recovery, with water levels exceeding pre-pumping conditions.

3.2.2 Water level responses in bedrock wells

At the DWA pumping well, three constant rate pumping tests were conducted with durations of 10, 24, and 90 hours (Fig. 2). During the 10-hour test, DWA recorded a maximum drawdown of 0.61 m, while the adjacent observation wells DWB and DWC showed lower drawdowns of 0.38 m and 0.43 m, respectively. In the 24-hour test, drawdown at DWA increased to a maximum of 0.78 m. Notably, both DWB and DWC exhibited identical maximum drawdowns of 0.61 m during this test period. The 90-hour test produced the greatest drawdowns across all wells, with DWA experiencing a maximum drawdown of 1.17 m, while DWB and DWC recorded maximum drawdowns of 1.00m and 1.01m respectively.

Three constant rate tests were also carried out for pumping well DWB 90 (Fig. 3). In the 10-hour test, DWB had a rapid drawdown response, reaching a maximum of 5.76 m within the first 30 minutes. Observation wells DWA and DWC recorded maximum drawdowns of 0.39 m and 0.54 m, respectively. In the 24-hour test, the maximum drawdown in DWB increased slightly to 5.80 m, while DWA and DWC showed drawdowns of 0.58 m and 0.75 m respectively. The 90-hour test recorded the highest drawdowns across all wells, with DWB reaching 6.53 m and both DWA and DWC showing drawdowns of 0.80 m.

Similarly, three constant rate pump tests were conducted at pumping well DWC (Fig. 4). During the 10-hour test, DWC recorded a maximum drawdown of 0.60 m with observation wells DWA and DWB

recording 0.21 m and 0.45 m maximum drawdown respectively. In the 24-hour test, DWC maintained a similar drawdown of 0.58 m, with DWA reaching 0.50 m and DWB reaching drawdown of 0.58 m. The 90-hour test showed a significant and predictable increase in drawdowns across the wells, with DWC reaching 1.23 m drawdown, DWA reached 0.98 m, while DWB reached 1.08 m.

3.2.3 Estimates of aquifer hydraulic parameters from constant rate pumping test

Curve matching of the time drawdown diagnostic plots with type curves from Kruseman and De Ridder (1970) (Fig. 5) indicates that the early time data aligns primarily with the confined aquifer model, particularly in the 24 hour and 90 hour pumping tests. For the 10 hour tests, the plots fully align with the confined aquifer model, and therefore, the Cooper-Jacob straight line solution was applied for parameter estimation (Fig. 5). The Cooper Jacob analysis of the 10 hour tests yielded estimates of transmissivity (T) and storativity (S), with hydraulic conductivity (K) calculated using a saturated aquifer thickness (b) of 25m (Table 3). T values ranged from 1.02×10^{-3} to 6.93×10^{-3} m²/s, while K values ranged from 4.09×10^{-5} to 2.05×10^{-4} m/s. S values, however, varied considerably across wells with a range of 5.30×10^{-14} (Well DWB) to 2.78×10^{-2} . In the 24 hour tests, late time data begins to deviate from the confined aquifer model exhibiting drawdown responses that are more characteristic of a leaky aquifer system. This deviation is primarily as a result of changes in slope that reflects the influence of boundary effects such as recharge boundaries possibly due to delayed recharge effects from overlying hydrostratigraphic units. The time drawdown data for the 24 hour tests were analyzed using the Hantush – Jacob leaky aquifer solution (Fig. 5). This analysis provided estimates of transmissivity (T), storativity (S), specific storage (Ss), the leakage parameter (r/B'), vertical hydraulic conductivity of the aquitard (K'), and leakance (K'/b'), using an aquitard thickness (b') of 10 m due to partial saturation of rhythmites. T values were comparable to those from the 10-hour analysis, ranging from 1.98×10^{-3} to 2.14×10^{-3} m²/s. S values were more consistent, ranging from 2.64×10^{-2} to 3.44×10^{-2} . The leakage parameter (r/B') was uniform at 0.1 across wells. Ss ranged from 1.06×10^{-3} to 1.38×10^{-3} m⁻¹. K' values spanned from 1.43×10^{-7} to 1.49×10^{-6} m/s, and leakance (K'/b') remained within the same order of magnitude ranging from 6.11×10^{-6} to 9.50×10^{-6} s⁻¹. For the 90-hour pump tests, the time plots show strong variabilities and oscillations in drawdown responses especially during late times (Figs. 4 and 5). The likely cause of these oscillations is still unclear and are posited to be defects from the pressure transducers. Nonetheless, the earlier times (0–3000 minutes) aligned closely with the confined aquifer model, thus the Cooper-Jacob straight line solution was similarly applied to the early portion of the time-drawdown data. Transmissivity (T) estimates ranged from 2.66×10^{-3} to 7.77×10^{-3} m²/s, and hydraulic conductivity (K), calculated using a saturated thickness of 25 m, ranged from 1.07×10^{-4} to 3.11×10^{-4} m/s. Storativity (S) exhibited considerable variability, ranging from 5.37×10^{-6} to 1.46×10^{-2} .

Table 3
Estimated Aquifer and aquitard properties using Cooper Jacob Confined (1946) and Hantush - Jacob (1955) Leaky Aquifer Analytical Solutions.

Well	Test Duration	Pumping Well	S	T (m ² /Sec)	K (m/s)	r/B'	Ss (m ⁻¹)	K' (m/s)	K'/b'(min ⁻¹)
DWA	10 hours	DWA	-	4.69E-03	1.87E-04	-	-	-	-
DWB	10hours	DWA	2.78E-02	6.01E-03	2.41E-04	-	-	-	-
DWC	10hours	DWA	1.39E-04	5.52E-03	2.21E-04	-	-	-	-
DWA	24 hours	DWA	-	4.82E-03	1.93E-04	0.1	-	3.96E-05	2.8E-05
DWB	24hours	DWA	2.83E-02	3.14E-03	1.26E-04	0.1	1.29E-03	1.49E-06	8.93E-06
DWC	24hours	DWA	7.86E-05	7.03E-03	2.81E-04	0.1	1.06E-03	1.02E-06	6.11E-06
DWA	90 hours	DWA	-	4.37E-03	1.75E-04	-	-	-	-
DWB	90hours	DWA	1.46E-04	6.56E-03	2.63E-04	-	-	-	-
DWC	90hours	DWA	1.33E-04	5.14E-03	2.06E-04	-	-	-	-
DWA	10hours	DWB	1.73E-04	6.82E-03	2.73E-04	-	-	-	-
DWB	10 hours	DWB	-	2.72E-03	1.09E-04	-	-	-	-
DWC	10hours	DWB	1.31E-05	6.93E-03	2.77E-04	-	-	-	-
DWA	24hours	DWB	9.71E-05	8.63E-03	3.45E-04	0.1	3.07E-01	1.65E-06	9.89E-06
DWB	24 hours	DWB	-	7.03E-03	2.81E-04	0.1	-	8.72E-03	5.23E-02
DWC	24hours	DWB	8.58E-06	7.46E-03	2.98E-04	0.1	2.61E-01	2.34E-06	1.40E-05
DWA	90 hours	DWB	8.69E-04	6.10E-03	2.44E-04	-	-	-	-
DWC	90 hours	DWB	7.67E-04	6.28E-03	2.51E-04	-	-	-	-

Well	Test Duration	Pumping Well	S	T (m ² /Sec)	K (m/s)	r/B'	Ss (m ⁻¹)	K' (m/s)	K'/b'(min ⁻¹)
DWB	90 hours	DWB	-	3.07E-03	1.23E-04	-	-	-	-
DWA	10hours	DWC	3.07E-04	3.91E-03	1.56E-04	-	-	-	-
DWB	10hours	DWC	2.28E-03	6.22E-03	2.49E-04	-	-	-	-
DWC	10 hours	DWC	-	4.68E-03	1.87E-04	-	-	-	-
DWA	24hours	DWC	9.83E-05	7.01E-03	2.80E-04	0.1	1.14E-03	1.43E-07	8.61E-06
DWB	24hours	DWC	3.71E-04	4.380E-03	1.75E-04	0.1	1.38E-03	1.58E-07	9.50E-06
DWC	24 hours	DWC	-	5.43E-03	3.01E-04	0.1	-	4.87E-05	8.34E-05
DWA	90hours	DWC	1.03E-04	6.50E-03	2.60E-04	-	-	-	-
DWB	90hours	DWC	5.37E-06	7.53E-03	3.01E-04	-	-	-	-
DWC	90 hours	DWC	-	6.80E-03	2.72E-04	-	-	-	-

3.2.4 Estimates of aquifer hydraulic parameters from step drawdown tests

Step drawdown pumping tests were conducted on all three wells with observations in each (Fig. 6). However, analysis was limited to the pumping wells, as step drawdown tests are primarily used to evaluate well performance and losses specific to the pumped well. The Hantush Bierschenk graphical method was used to extrapolate the linear trends of each successive test step to obtain the incremental drawdown (Δs) at each step (Fig. 6). The cumulative drawdown (s_w) was then calculated and the values of s_w / Q were computed for each step. A plot of s_w versus s_w / Q (Fig. 7) was used to generate a linear regression line described by the equation: $s_w / Q = B + CQ$. Where the value of B is the value of the intercept which is the aquifer (linear head) loss component, and the value of C is the slope of the line representing the well (non linear) loss component (Table 4).

In Well DWA, the estimated linear and nonlinear head losses revealed that aquifer losses were the dominant component, with an average of approximately 0.30 m across all steps, compared to average well losses of 0.03 m. In contrast, Well DWB exhibited higher total drawdowns dominated by well losses which averaged 7.25 m while the average aquifer losses was 3.07 m. Well DWC showed a moderate

behavior, with aquifer losses averaging 0.30 m and well losses contributing approximately 0.17 m. Calculated well efficiencies reflected these trends. Well DWA maintained high efficiencies across all steps, ranging from 87.45% to 94.57%, indicating that the majority of drawdown resulted from aquifer losses. Well DWB displayed significantly lower efficiencies, declining from 44.94% at the lowest discharge (40 gal/min) to 24.61% at the highest discharge (100 gal/min) corresponding with an increase in CQ^2 values. Well DWC efficiencies decreased from 77.52% to 57.97% as pumping rate increased with drawdown contributions shifting gradually toward greater well losses at higher rates.

Similarly, specific capacity (Q / S_w), another metric of well and aquifer performance was also assessed during the step drawdown test. Well DWA showed the highest values (1064.18–1363.48 m^2/day), indicating strong performance. DWC exhibited relatively moderate values (747.11–1038.84 m^2/day), with slight declines across steps. In contrast to DWA and DWC, DWB had the lowest Q / S_w ranging from 53.26 to 325.61 m^2/day across the test steps. The sharp decline in DWB suggests poor well efficiency and significant head losses. These results reflect a clear contrast in performance among the wells where DWA was the most efficient, followed by DWC, with DWB performing relatively poorly.

Table 4
Step- Drawdown Test Results

Pumping Well	Step	Q (m^3/day)	Δs (m)	Q/S_w (m^2/day)	S_w / Q (m^2/day)	CQ^2 (m)	BQ (m)	$S_w = BQ + CQ^2$	$E_w = BQ/S_w \times 100$
DWA	1	218.16	0.16	1363.48	0.00073	0.01	0.17	0.18	94.57
	2	327.23	0.13	1128.39	0.00089	0.02	0.25	0.27	92.07
	3	436.31	0.12	1064.18	0.00094	0.04	0.33	0.37	89.70
	4	545.39	0.02	1268.35	0.00079	0.06	0.41	0.47	87.45
DWB	1	218.16	0.67	325.61	0.0031	2.15	1.75	3.90	44.94
	2	327.23	1.43	155.83	0.0064	4.83	2.63	7.46	35.24
	3	436.31	1.63	116.97	0.0085	8.59	3.50	12.09	28.98
	4	545.39	6.51	53.26	0.0188	13.42	4.38	17.79	24.61
DWC	1	218.16	0.21	1038.84	0.0010	0.05	0.17	0.22	77.52
	2	327.23	0.19	818.09	0.0012	0.11	0.26	0.37	69.69
	3	436.31	0.14	807.99	0.0012	0.20	0.34	0.54	63.29
	4	545.39	0.19	747.11	0.0013	0.31	0.43	0.74	57.97

3.2.5 Observed Flow Regimes and Boundary Conditions

Derivative Analysis of Drawdown Data

Derivative plot analysis of the 24-hour pumping test at DWA reveals distinct flow regime transitions indicative of aquifer heterogeneity. In well DWA (Fig. 8), the derivative declines slightly in the first 10 minutes (slope ~ -0.02), followed by a dip at exactly 10 minutes suggestive of double porosity effects. A flow regime transition occurs around 10–20 minutes, after which the derivative rises with a slope of ~ 0.5 from 20 to 300 minutes, consistent with linear flow likely due to preferential pathways. At 500 minutes, oscillations are observed on the plots and a gentle decline suggest boundary effects likely no-flow boundary. In DWB (Fig. 8), the early-time derivative exhibits a steep decline (slope ~ -1.15), likely linked to wellbore storage or flow within a highly heterogeneous zone. A subtle dip and gradual recovery indicate a double porosity behavior. Between 20 and 300 minutes, the curve continues to increase linearly likely as a result of linear flow. After 400 minutes, the derivative rises and flattens between 600 and 1000 minutes, indicating possible transition into a regime dominated by various boundary effects although there is no stable plateau observed. DWC's derivatives (Fig. 8) show a contrasting but distinct flow regime characterized by a persistent linear increase in the derivative throughout most of the test (slope ~ 0.47). This indicates dominant linear flow likely driven by a well connected fracture or permeable zone. There is no evidence of early time well bore storage or dual-porosity effects. After 1000 minutes, the curve begins to flatten, suggesting the presence of boundary effects.

Recharge and Barrier Boundary Conditions

To further evaluate the recharge and barrier boundary conditions in the pump test datasets, we applied the principle of superposition by introducing image wells. The image well method allows modelling of an imaginary well discharging or recharging at the same rate as the pumping well and positioned symmetrically across the boundaries and is used to estimate the distances (r_b) to the respective boundaries using Eq. (4) where inflection times correspond to the arrival of the image cone. The semi logarithmic time drawdown plots from the 24-hour constant rate test was analyzed for this. Time drawdown plots from the test were compared to theoretical plots (Fig. 9) from Kruseman and De Ridder (1990) to identify boundaries where characteristic slope changes at various parts of the plots are indicative of hydraulic boundaries.

Well DWB, when pumping from DWA, exhibits a noticeable deviation (steepening) from the linear trend at ~ 60 minutes suggesting the presence of a barrier boundary. A second slope change is observed at about ~ 500 minutes, indicative of a second boundary likely positioned at a farther distance from the first further constraining the flow field in the aquifer. At 1000 minutes, the drawdown curve begins to show a slight flattening which may signal the delayed influence of a recharge boundary, possibly due to leakage or drainage from overlying hydro-stratigraphic units. However, this flattening is not sustained, instead, the drawdown increases with a steeper slope, indicating the presence of a transient and limited recharge boundary. DWC pumping from DWA exhibits a very similar trend to DWB. The first barrier boundary is observed at about 58 minutes while the second boundary occurs at about 520 minutes both characterized by increased drawdowns with steepening slopes. The same weak recharge response observed in DWB appears near the 1000-minute mark indicating the influence of recharge across the observed wells. Using the image well theory, DWB's r_b at the first boundary is estimated as 59.6 m while

the second boundary is at 172.1 m. For DWC, r_b at the first boundary was estimated at 74.3 m and the second is at 218.3 m.

The observation wells pumping from DWB showed a similar but relatively distinct boundary conditions to those observed while pumping from DWA. At observation well DWA, the semi-log drawdown plot deviates from a linear trend at approximately 62 minutes, indicating the arrival of the first image cone and suggesting the influence of a nearby barrier boundary. A second inflection, occurring around 150 minutes, marks a second barrier boundary while a third deviation occurs at approximately 300 minutes. Between 300 and 700 minutes, the curve attempts to flatten, mimicking the behavior of a pseudo recharge boundary. However, this flattening is not fully achieved. Instead, the drawdown continues to increase. At approximately 1000 minutes, the curve again displays a subtle flattening characteristic of a delayed recharge boundary, though this effect remains transient as drawdowns begin to rise briefly before the pump is shut off. In DWC, a slightly different boundary response is observed. The first noticeable deviation from the initial linear drawdown trend occurs at approximately 76 minutes, indicating the influence of a barrier boundary. A second inflection point appears around 500 minutes, followed by a third at approximately 800 minutes, both suggesting additional boundary effects on the cone of depression. Around 1000 minutes, the curve exhibits a brief flattening, interpreted as a pseudo recharge condition likely due to delayed leakage or minor vertical inflow from overlying units. However, this effect is transient as drawdown resumes an increasing trend shortly afterward. At approximately 1250 minutes, a final flattening is observed, indicating interaction with a more sustained recharge boundary shortly before the pump is shut off. The estimated r_b at DWA for the first barrier boundary is 86.2m, the second at 134.2m, and the third at 189.7m. At DWC, the first barrier boundary is approximately 88.9m, the second observed boundary is at 227.7m, and the third shortly at 288.1m.

Observation well DWA, when pumping from DWC, exhibits a boundary response pattern consistent with those observed in other pumping situations. The first barrier boundary is observed approximately 50 minutes into pumping, followed by an inflection indicating a second boundary at approximately 550 minutes. The drawdown continues to increase steadily until around 1000 minutes, where a pseudo recharge effect briefly stabilizes the curve. However, this recharge boundary is transient, holding for only about an hour before the drawdown resumes its upward trend, indicating that any recharge influence is delayed. In DWB, a similar profile occurs. The first barrier boundary appears at approximately 53 minutes, the second at around 210 minutes, and a third boundary is observed at near 800 minutes. A similar pseudo recharge boundary occurs at about 1020 minutes, but this is very brief, and the drawdown begins to increase again shortly afterward. Estimated r_b in this case at the first boundary at DWA is 69.3m, the second boundary is at 230m. For DWB, the r_b at the first boundary is estimated at approximately 71.4m, the second is estimated at 142.2 m, while the third boundary occurs at 277.5m.

Hydraulic Head Recovery

The linear recovery plots (Fig. S10) show the residual drawdown trends as the wells recovered. In Well DWA, recovery occurred gradually over the monitoring period with residual drawdown decreasing steadily in both the pumping and observation wells until the well fully recovered. The residual drawdown at DWA

decreased from pumping drawdown of approximately 0.6m to baseline water level within ~ the recovery period with similar but relatively less pronounced recovery trends observed in wells DWB and DWC. Pumping from Well DWB displayed the most abrupt recovery profile among the three tests wells owing to the relatively large magnitude of drawdown recorded during the pumping period. The pumping well showed a sharp rebound with as much as 12m of residual drawdown decreasing to baseline water levels within a short period (~ 500 minutes). The observation wells had similar but much smaller magnitudes of residual drawdown that remained relatively stable levels throughout the recovery period. Pumping from Well DWC showed a similar recovery response as DWA. The residual drawdown at DWC started at ~ 0.85 m and gradually decreased to baseline pre-pumping water levels in approximately 500 minutes.

The recovery datasets were further analyzed using the Theis recovery method to obtain quantitative estimates of transmissivity (T) by plotting residual drawdown (s') against $\log(t/t')$. The T values obtained from this analysis ranged from 1.15 to $1.67 \times 10^{-4} \text{ m}^2/\text{sec}$ with an average T value of $1.45 \times 10^{-4} \text{ m}^2/\text{sec}$. Corresponding K values estimated using a saturated aquifer thickness of 25m ranged from 4.60 to $6.68 \times 10^{-6} \text{ m/sec}$. The hydraulic estimates from the recovery analysis were observed to be an order of magnitude lower than those estimated from the pumping tests.

Table 5
Estimated Aquifer properties using Theis Recovery Solution for Confined Aquifers (1935)

Well	Recovery Duration	Pumping Well	T (m ² /Sec)	K (m/s)
DWA	24hours	DWA	1.61E-04	6.44E-06
DWB	24hours	DWA	1.15E-04	4.60E-06
DWC	24hours	DWA	1.25E-04	5.00E-06
DWA	24hours	DWB	1.53E-04	6.12E-06
DWB	24hours	DWB	1.29E-04	5.16E-06
DWC	24hours	DWB	1.55E-04	6.20E-06
DWA	24hours	DWC	1.51E-04	6.04E-06
DWB	24hours	DWC	1.48E-04	5.92E-06
DWC	24hours	DWC	1.67E-04	6.68E-06

3.3 Tracer Tests

Breakthrough Curve Analysis and Estimates of Solute Transport Properties

Breakthrough curves derived from electrical conductivity measurements (Fig. 10) and corresponding calibrated tracer concentrations (Fig. 10) at DWB are presented below. In the first test (Fig. 10), the BTCs are characterized by a rapid, narrow peak, a possible second peak around 270 minutes post injection, and a flat extended tail. The second peak and subsequent fluctuations appear irregular and lack a definitive

shape; therefore, only the first peak was selected for analysis. Tracer arrival was first detected approximately 20 minutes after injection, indicated by immediate rises in both EC and concentration. Peak concentration occurred at 70 minutes, with a maximum EC of $\sim 1819 \mu\text{S}/\text{cm}$ and a corresponding tracer concentration of $0.39 \text{ g}/\text{L}$. The prolonged tailing, which extends beyond 1000 minutes, suggests a dominant diffusion-like advective process contributing to delayed tracer arrival at the observation points. This informed the decision to re-run the test. In the second test, breakthrough timing was similar, with tracer arrival observed about 22 minutes post-injection and the same peak concentration of $0.39 \text{ g}/\text{L}$. Test conditions were largely unchanged, except the recirculation pump was left to run longer for 2 hours after injection compared to just 10 minutes in the first test. Unlike the first test, the BTC did not exhibit a second irregular peak at the same time but instead showed these fluctuations much later, around 1500 minutes.

By fitting an analytical solution to the tracer BTC implemented in the TRAC program (Thi  ry 2022) an average linear groundwater velocity of $0.0029 \text{ m}/\text{s}$ and $0.0025 \text{ m}/\text{s}$ was estimated for the interval between the injection and observation wells for both tests respectively. Estimated longitudinal dispersivity (α_L) ranged from 2.3 to 2.6 m while effective (kinematic) porosity ranged from 6.38×10^{-3} (0.6%) – 1.1×10^{-2} (1.1%), with the upper bound estimated manually using Darcy's law and the lower bound obtained from TRAC. The TRAC models (Fig S13) generally showed a relatively good fit to the observed BTC particularly at the rising limbs and peak concentration parts of the curve with a model efficiency of 0.66 and 0.39 respectively for both tests indicating a good model fit. The model efficiency used in TRAC is the Nash-Sutcliffe efficiency coefficient (Nash & Sutcliffe, 1970), commonly used as a model evaluation metric in hydrology to determine how well a model's predictions matches observed data. Additionally, tracer recovery in the first test was estimated at 15.04 kg while for the second test was 65.2 kg indicating a relatively successful tracer test.

3.3.2 Time lapse Electrical Resistivity Imaging of the tracer test

The initial ERI dataset from the first tracer test, acquired five minutes prior to tracer injection, was used as the baseline resistivity model for time-lapse difference inversion. This baseline resistivity model showed an initial 0% change in resistivity. Following this, a progressive decrease in resistivity values was observed across the imaged subsurface with most of the differences observed at depths of $1 \sim 15\text{--}30 \text{ m}$. The earliest detectable decrease in resistivity occurred by ~ 53 minutes post-injection, with the maximum percentage change of 21%. By the second measurement (~ 93 minutes post-injection), the resistivity change had decreased to 14%. This reduction declined to about 8% at the third measurement (~ 133 minutes). The fourth- and fifth-time lapse (173 and 213 minutes respectively) showed a slight increase in the decline in resistivity to about 11%. A continued drop to 9% was observed at the sixth step (~ 253 minutes post-injection). Subsequently, resistivity differences increased again, reaching 14% at the seventh (~ 293 minutes). By the final measurement (~ 335 minutes post-injection), resistivity differences declined to 7%. The ERI images (Fig. 11) significantly align with observations seen on the BTC (Fig. 11) especially the early tracer breakthrough.

4.0 Discussion

4.1 A Semi-Confined, Hydraulically Heterogeneous System

The hydraulic observation results of this study support a conceptual model that lies between an ideal confined aquifer and an unconfined fractured system. Early and intermediate pumping responses were often approximated by confined solutions, but late-time departures, centimeter-scale responses in shallow piezometers, and leaky-aquifer fits indicate delayed vertical interaction with surficial units. The overlying till therefore reduces and delays recharge without completely isolating the bedrock. Similar behavior is expected where glacial aquitards contain vertical heterogeneity, discontinuities, or sufficient elastic storage to transmit a delayed pressure response (Keller et al. 1986; Strobel 1993; Li et al. 2025). The shallow responses alone are not sufficient to quantify downward flux as they are small, and seasonal with potential contribution from barometric, or other background variations. Their coherence with prolonged bedrock pumping and the late-time bedrock response, however, makes leakage a more parsimonious conceptual model than perfect confinement. The effective leakance range of 6.1×10^{-6} to $1.4 \times 10^{-5} \text{ min}^{-1}$ is conditional on the assumed 10-m aquitard and the Hantush-Jacob assumptions. It should be used for preliminary model parameterization and sensitivity testing, not as a unique measurement of till hydraulic conductivity.

Spatial variability was more pronounced than temporal variability. DWA and DWC sustained 80 gal/min with approximately 1 m or less drawdown over most test periods, whereas DWB experienced almost 6 m drawdown within 10 hours and had strong nonlinear well loss. Yet drawdown propagated among all wells. The system is therefore hydraulically connected at the pressure-response scale but not uniformly connected to transmissive openings near each well. The deeper permeable interval identified in DWA and DWC (Ita et al., in Review) provides an independent geological explanation for their greater specific capacity and efficiency.

The one- to two-order magnitude difference between hydraulic conductivity estimates via pumping test and recovery method reflect differences in the flow processes that the two different approaches are sensitive to (Butler, 2005; Cheng and Chen, 2007; Zdankus, 1974). Pumping during a forced gradient preferentially samples the most transmissive connected features and is increasingly influenced by boundaries and leakage (Butler, 2005). Recovery includes a changing gradient and redistribution among fractures, matrix storage, and adjacent units (Zdankus, 1974). Analytical solutions that assume homogeneity translate those different processes into different effective parameters. Numerical models should therefore represent the pumping-derived values as connected-pathway behavior and use the lower recovery values and observed variability to define uncertainty or less mobile domains.

4.2 Preferential Transport and the Interpretation of Tracer Test Results

Results of the tracer first arrival within approximately 20 min and effective porosity below 1.1% demonstrate that a small, connected fraction of the nominal saturated thickness carried most of the

forced-gradient transport. This finding is consistent with the drawdown and step drawdown-test evidence that the bedrock aquifer can transmit large quantities of water through discrete pathways even though most of the rock volume contributes little mobile porosity (White 2016).

The breakthrough curves also illustrate a tracer test BTC interpretation challenge with fractured-rock tracer testing. A secondary peak and long tail are commonly assigned to multiple fracture pathways or diffusion into and out of less mobile rock volumes (Becker and Shapiro 2000; Massei et al. 2006). Those processes may contribute to the tail, but the controlled recirculation change showed that the early second peak was sensitive to injection-well operation. Extending recirculation suppressed the peak at approximately 270 min, indicating that dense tracer remaining in the open well probably migrated vertically before entering a second transmissive interval. Without the repeat test, this experimental artifact could have been mistaken for a formation-scale dual-porosity signature. The broader lesson here is that anomalous breakthrough should be tested against plausible wellbore processes before a complex transport model is adopted. Density contrast, injection depth, open interval, circulation duration, and the time required to displace the injection volume should be documented and, where possible, varied in a repeat test. Persistent tailing after wellbore effects are reduced provides stronger evidence for a broad travel-time distribution or mobile-immobile exchange than a double peak alone.

The electrical conductivity measurements had a high temporal resolution and provided the basis for quantitative transport estimates. The time-lapse ERI on the other hand contributed a different type of evidence. It showed that bulk electrical resistivity changes occurred within the imaged subsurface and persisted after the principal peak passed the extraction well. The renewed anomaly near the delayed concentration response further supports a transport process involving more than a single narrow pulse. The comparison also defines the limitations of ERI. Survey duration prevented detection of the earliest arrival, and inversion regularization broadened and reduced anomaly amplitudes (Kemna et al 2002). Resistivity change cannot be converted uniquely to concentration without petrophysical calibration and accounting for temperature, porosity, and background salinity (Singha and Gorelick, 2005). For this reason, ERI is used in this study as a complementary indicator of plume influence rather than a stand-alone tracer mass-balance method.

4.3. Transferable Implications for Broader Aquifer Characterization

This case study demonstrates a combined aquifer testing approach applicable to other fractured carbonate aquifers. Multiple-duration pumping tests distinguished early connected-pathway behavior from later leakage and boundary effects. Step drawdown pumping tests separate aquifer productivity from well construction or near-well loss. Repeated tracer tests with controlled wellbore mixing evaluate whether anomalous arrivals are reproducible formation responses while time-lapse electrical resistivity imaging was used to test whether point-scale breakthrough interpretations are spatially plausible.

The results of this study also have implication for water-resource management and water-quality assessments particularly within the carbonate aquifer in northwest Ohio (Potucek et al., 2025). High well

yield does not necessarily imply uniform aquifer properties, and a low-permeability aquitard does not guarantee complete protection of the bedrock aquifer. The occurrence of preferential flow can produce rapid transport between connected wells within the aquifer system, while delayed leakage can create a slower pathway from shallow units. Hence, the use of models that assign a single hydraulic conductivity and porosity to the full saturated thickness of the aquifer unit would combine these distinct behaviors and could underestimate both early contaminant arrival and long-term exchange.

Conclusions

Results from combined pumping tests and tracer tests imaged with repeated electrical resistivity imaging in this study showed that the studied carbonate aquifer is highly productive but cannot be represented as a homogeneous, perfectly confined aquifer system. Adjacent wells exhibited strongly contrasting drawdown and efficiency, while pressure propagated non-uniformly throughout the well field. Late-time pumping behavior and small responses in shallow piezometers were consistent with delayed leakage through the glacial aquitard. Pumping and recovery analyses produced different effective hydraulic conductivities, emphasizing that analytical parameters depend on the tested flow regime and connected volume.

Forced-gradient tracer tests identified a rapid connected well DWC to DWB pathway with first arrival time of 20–22 min, effective velocity of $2.5\text{--}2.9 \times 10^{-3}$ m/s, dispersivity of 2.3–2.6 m, and effective porosity of 0.6–1.1%. Extended recirculation eliminated the early secondary peak observed in the first test, showing that density segregation within an injection well can imitate a non-Fickian formation response. Persistent tailing nevertheless indicates a broad distribution of travel times and possible mobile-immobile exchange. The time-lapse ERI data independently corroborated early and delayed tracer influence but was limited by acquisition time and inversion resolution.

The use of multi-duration pumping tests, controlled repeated tracer tests, and time-lapse electrical resistivity imaging where possible should be combined for aquifer characterization in these carbonate aquifers and their results should be interpreted together when information on leakage, preferential flow, and wellbore artifacts is required. This integrated approach provides a more defensible conceptual model for predicting yield and contaminant transport in fractured carbonate aquifers.

Declarations

Competing Interests:

The authors declare no competing interests

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Author Contribution

KOD and VII acquired funding for this research, KOD, VII and JMH conceptualized, designed the study and interpreted the results of this study. KOD and VII acquired and processed the data, KOD and JMH supervised the student and managed the research project, VII wrote the first draft of the manuscript while JMH and KOD reviewed and edited it prior to submission.

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Data Availability

The data supporting the findings of this study can be provided by the corresponding author upon a reasonable request.

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Figures

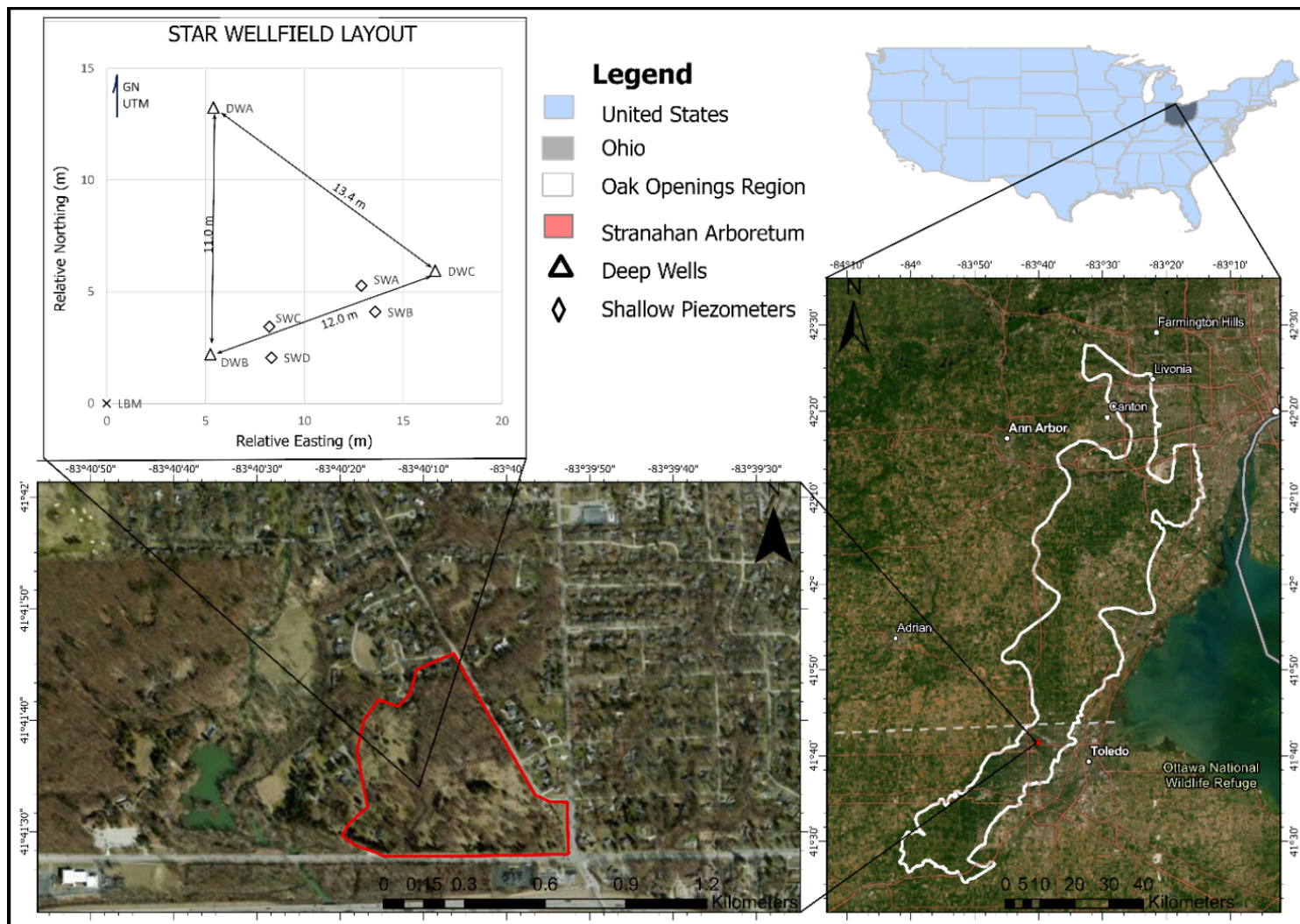


Figure 1

Location of study site showing the Hydrogeophysics well field (top left) within the Stranahan Arboretum site represented with a yellow outline (bottom left). The Outline of the Oak Opening Ridge (bottom right) within northwest Ohio (top right) is also outlined.

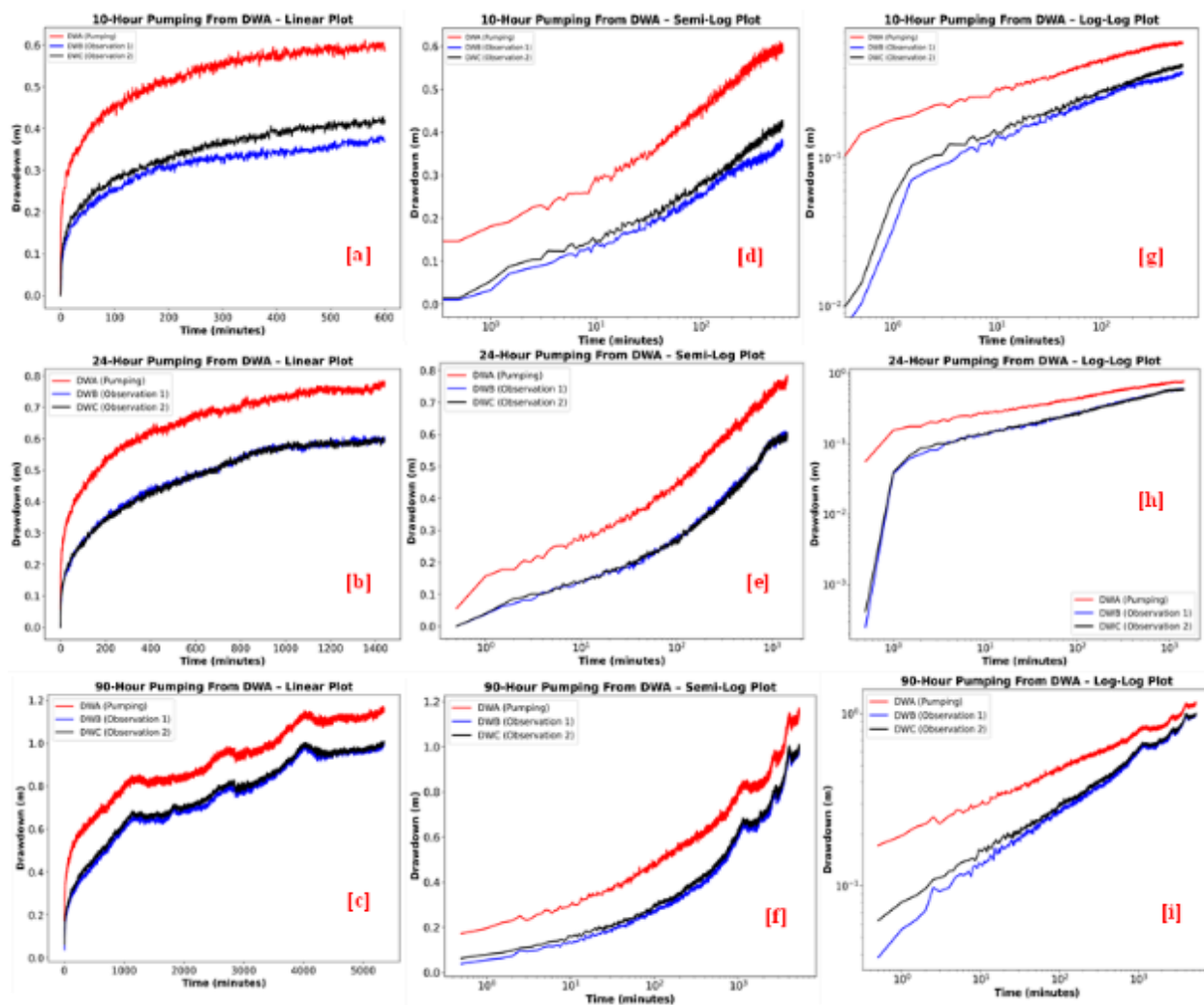


Figure 2

10-, 24- and 90-hour time-drawdown plots during pumping at DWA (Pumping well in red, DWB in blue and DWC in black). Linear plots [a-c], semi log[d-f], log – log [g-i].

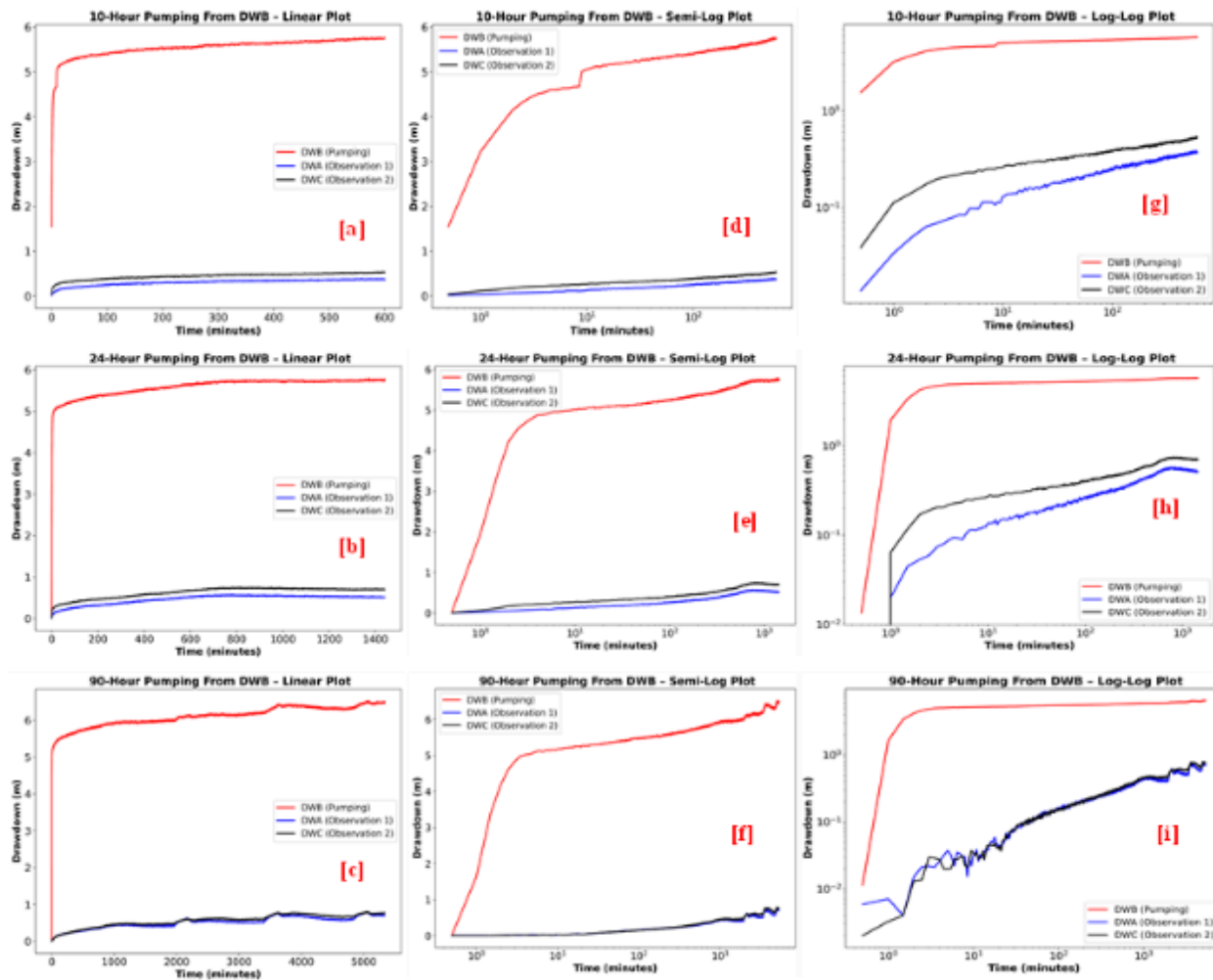


Figure 3

10-, 24- and 90-hour time-drawdown plots during pumping at DWB (Pumping well in red, DWA in blue and DWC in black). Linear plots [a-c], semi log[d-f], log – log [g-i].

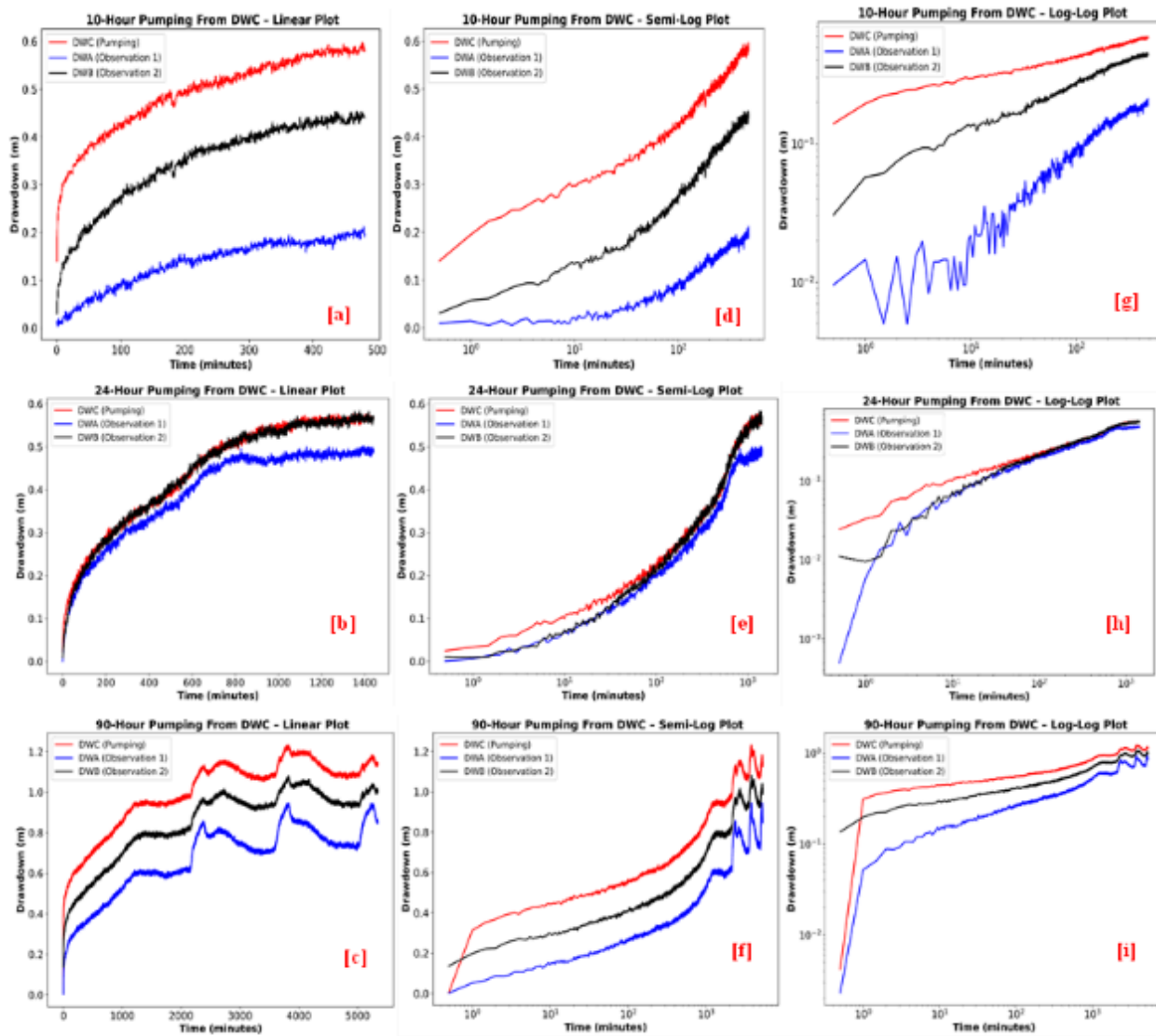


Figure 4

10-, 24- and 90-hour time--drawdown plots during pumping at DWC (Pumping well in red, DWA in blue and DWB in black). Linear plots [a-c], semi log[d-f], log – log [g-i].

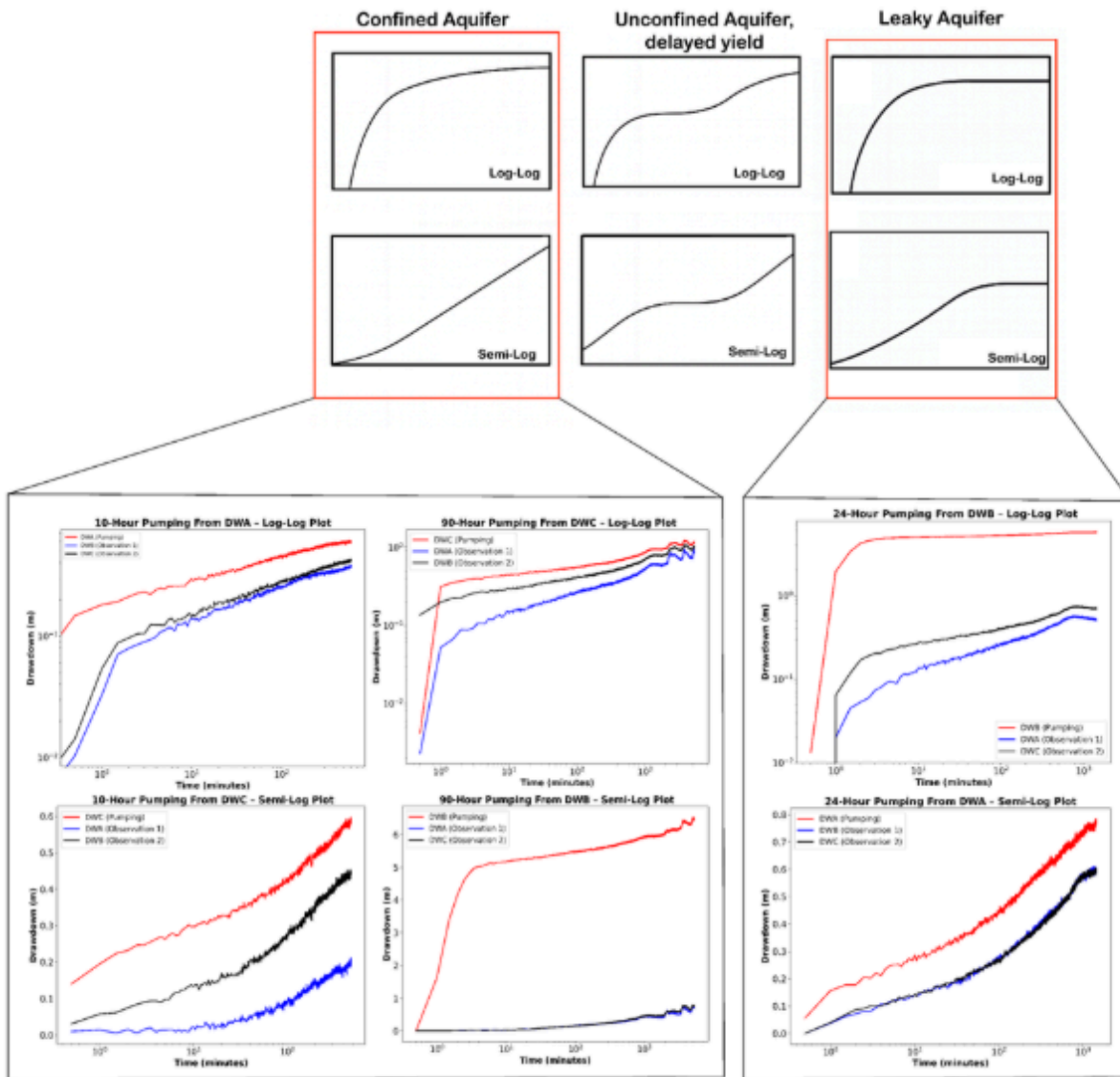


Figure 5

Selected pumping test curves matched with diagnostic curves adapted from Kruseman and De ridder, 1970. Diagnostics curves are presented in top of panel with red boxes highlighting models that match with our results.

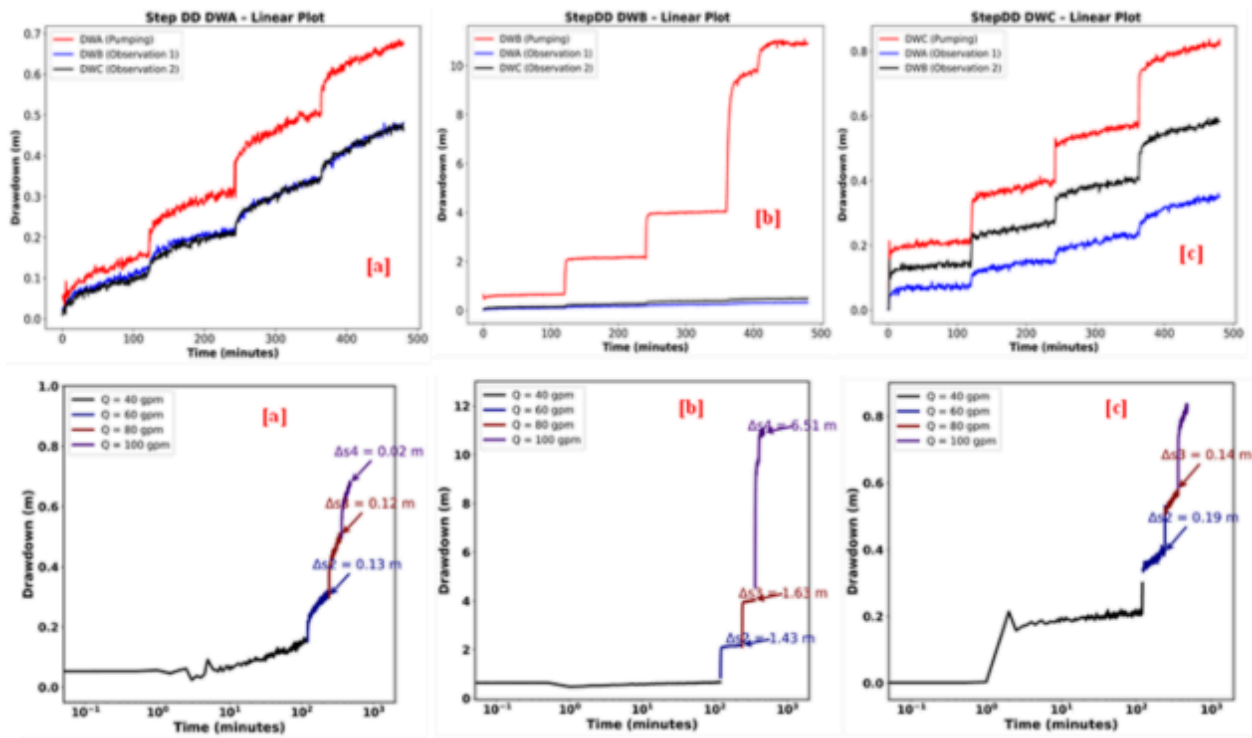


Figure 6

Step drawdown linear plots. (Pumping well in red, DWA in blue and DWB in black). Linear plots [a-c], semi log[d-f], log – log [g-i]. Extrapolated time-drawdown plots from pumping wells showing incremental drawdown at each step for incremental drawdown. Plots labelled; a = DWA, b = DWB, c = DWC].

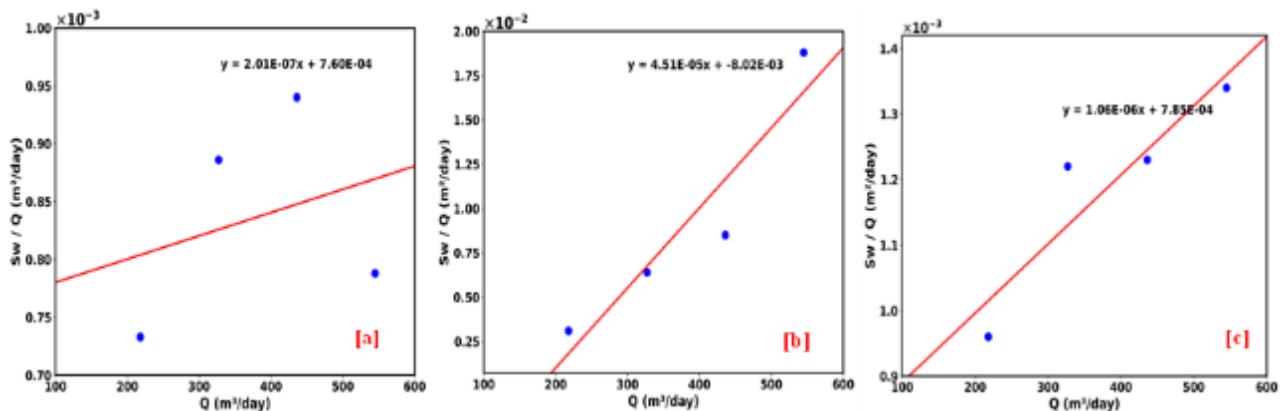


Figure 7

Sw/Q vs Q showing linear regression equation corresponding to aquifer and well loss components. Plots labelled; a = DWA, b = DWB, c = DWC].

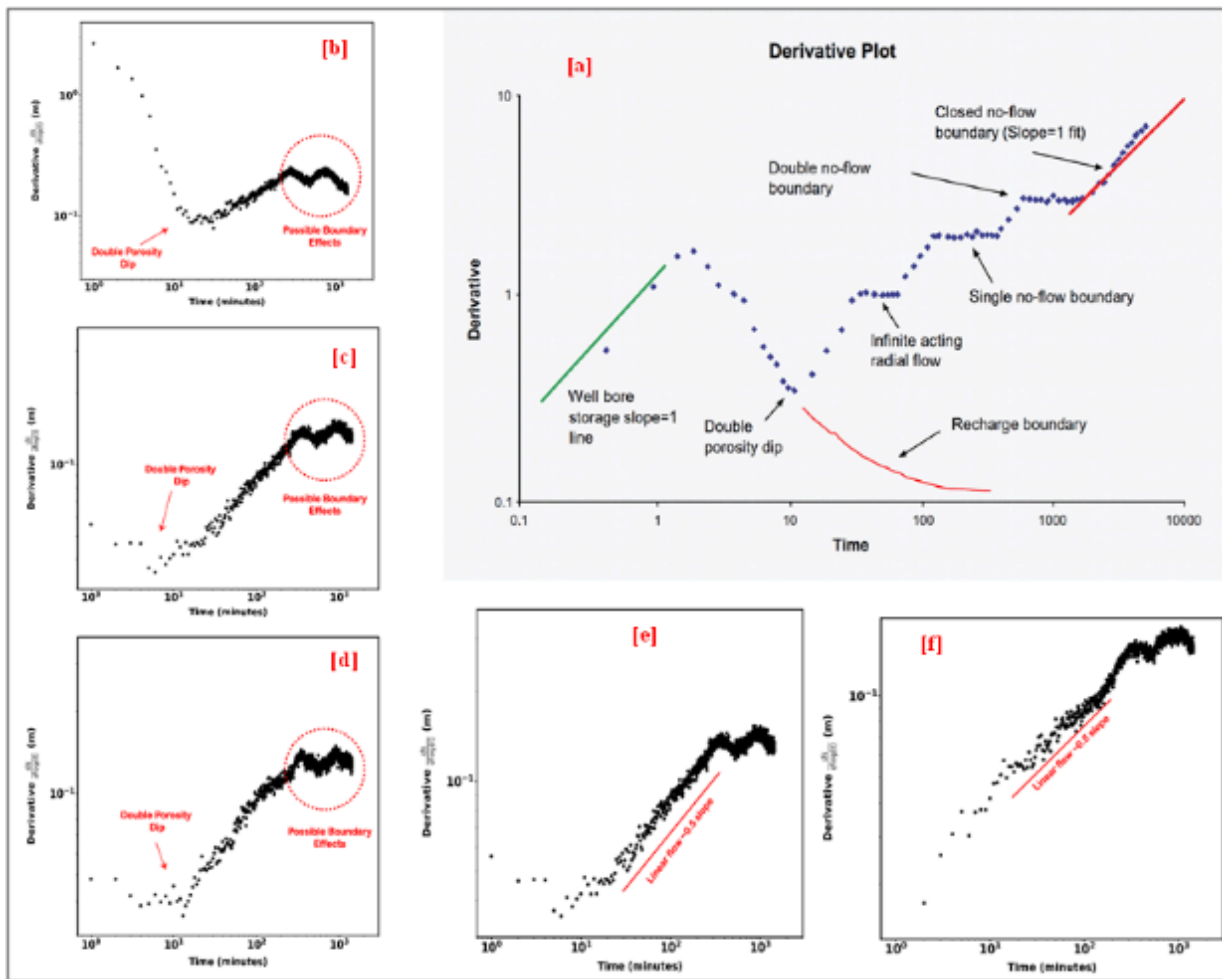


Figure 8

Selected log-log derivative plots with annotated identified flow regimes. Top right [a] is a typical derivative curve adapted from Van Tonder et al., (2002). Left and bottom plots are [b] DWB, [c] DWA at DWB tests; [d] DWA [e] DWB [f] DWC at DWC tests.

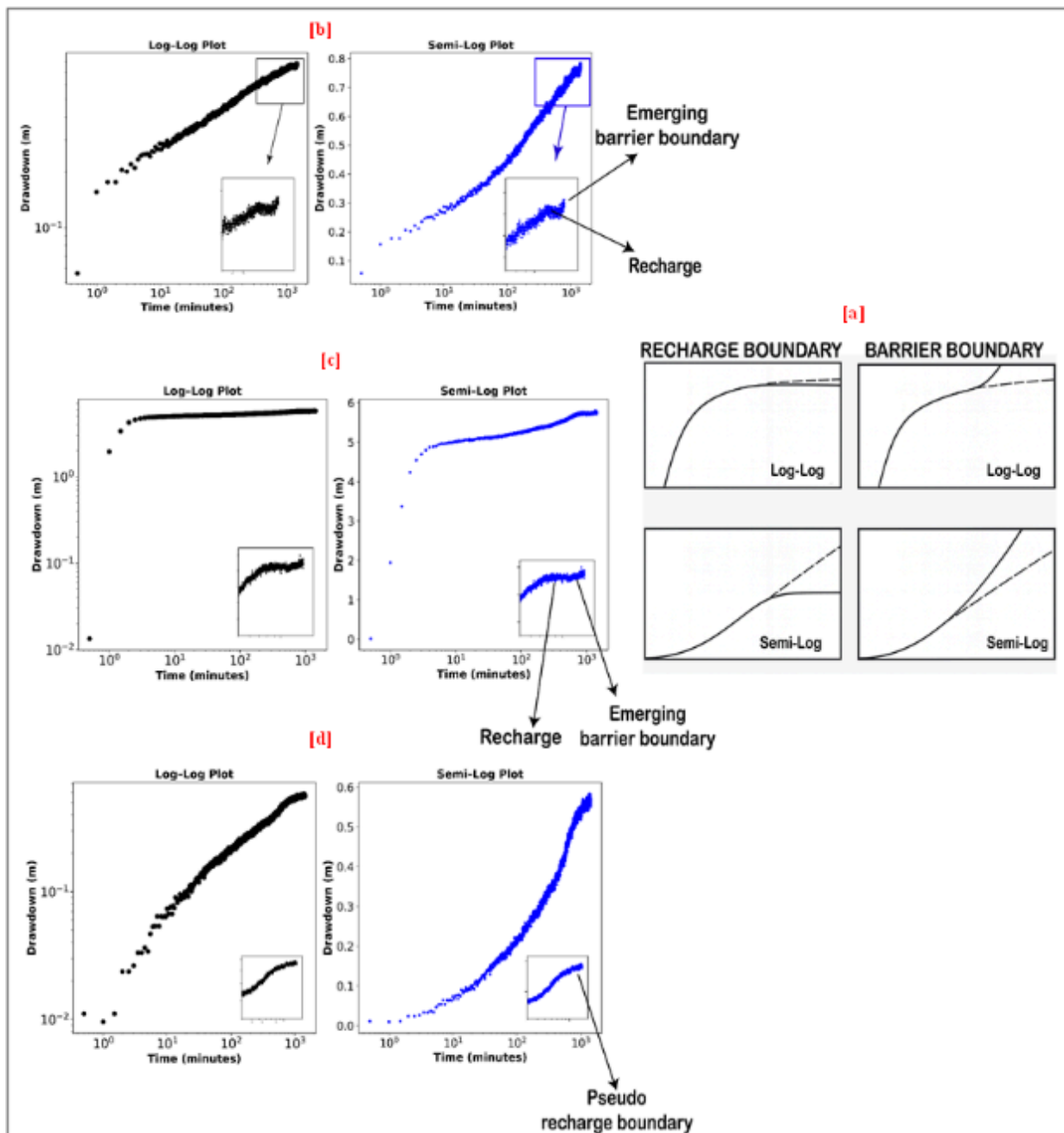


Figure 9

Selected log-log & semi-log plots of pumping wells with annotated boundary conditions. Right panel [a] are theoretical boundary conditions adapted from Kruseman and De Ridder (1970). Left panels are [b] DWA, [c] DWB [d] DWC.

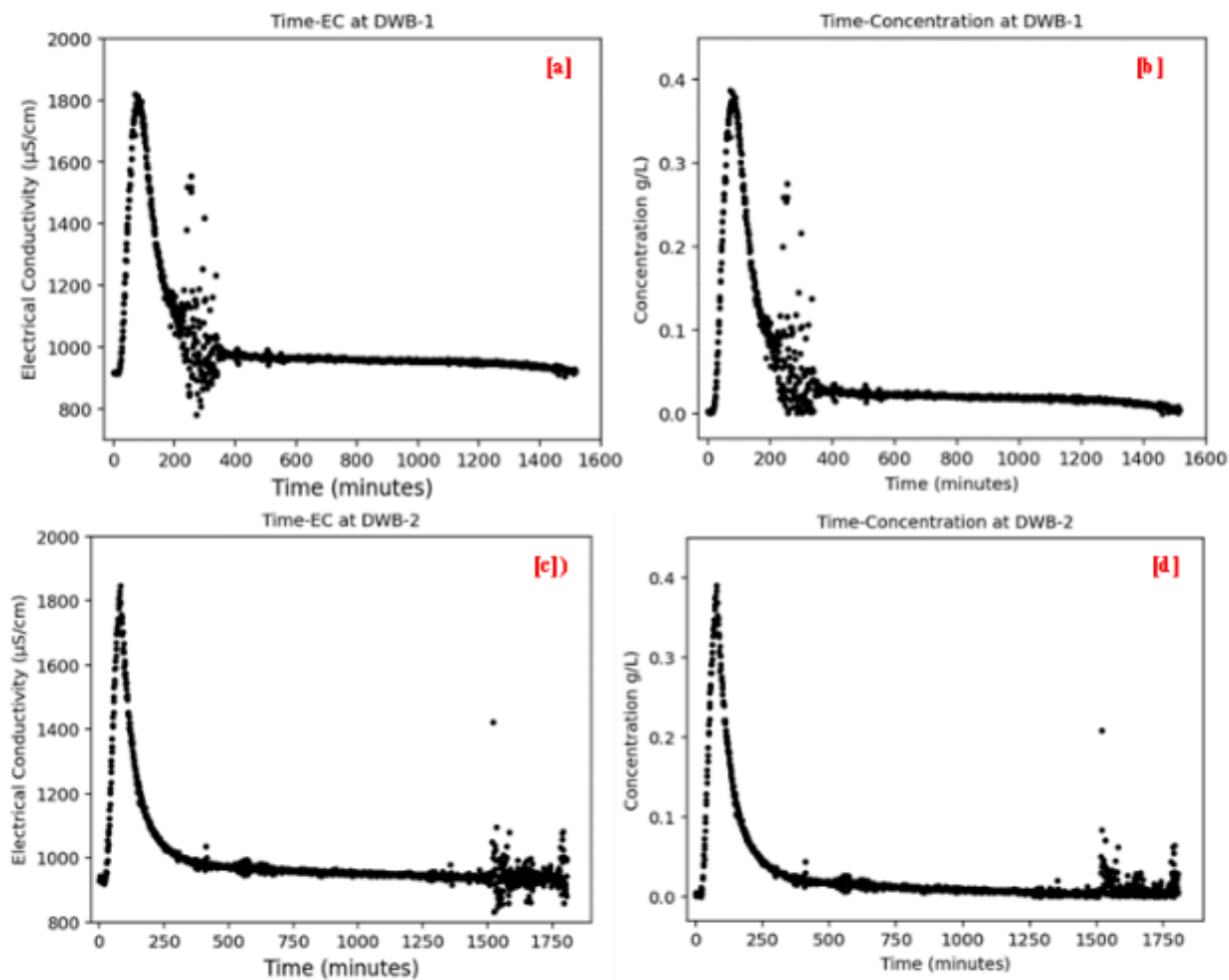


Figure 10

Linear time - breakthrough curves for extraction well - DWB [a] Time – EC, [b] Time-Concentration during first test; [c] Time – EC, [d] Time – Concentration during second test.

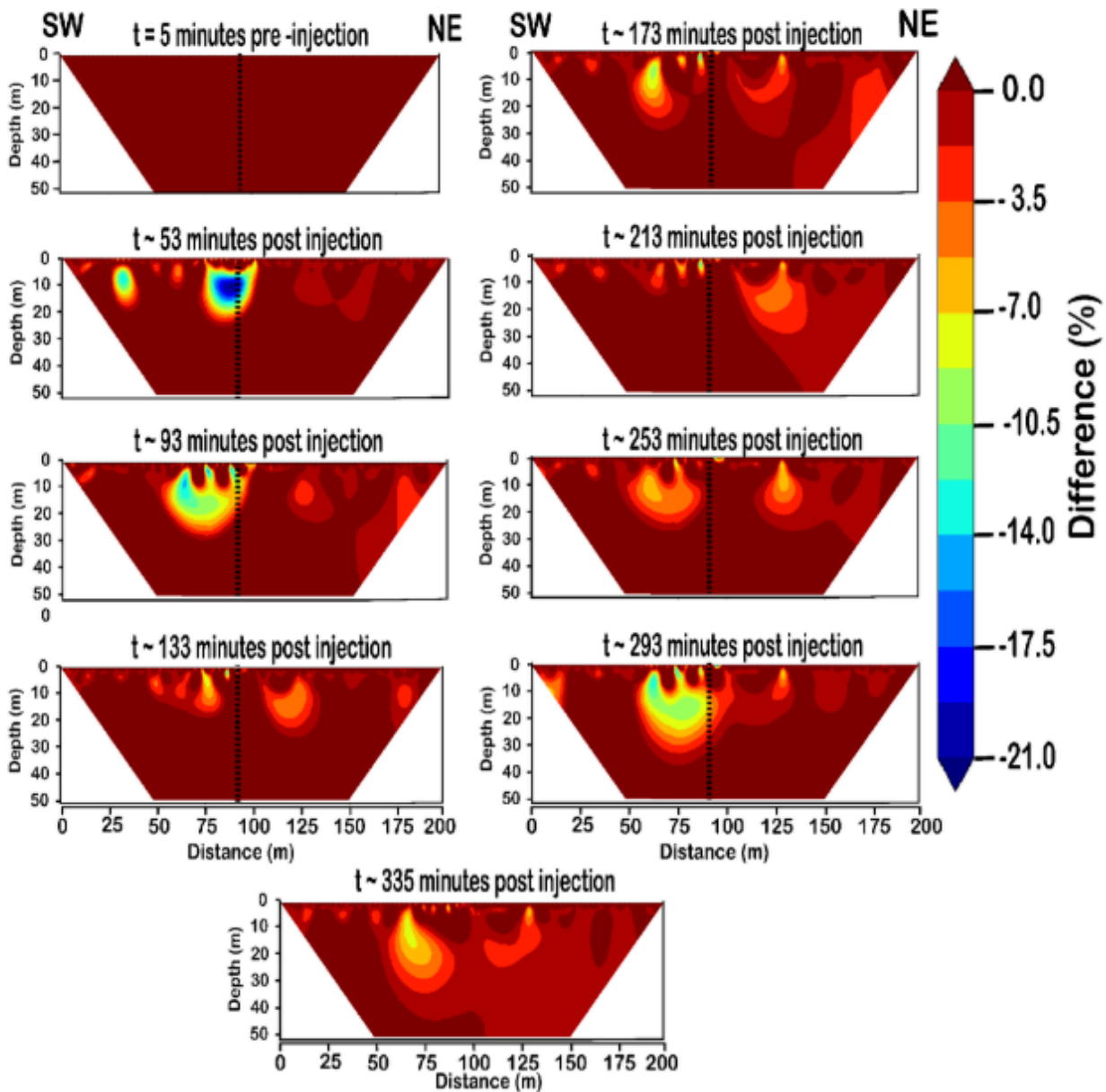


Figure 11

Time-lapse electrical resistivity images showing the resistivity changes following tracer injection. Dotted line across tomogram indicates well position across ERI line.

Supplementary Files

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