DALLAS ASR GRANT STUDY

ASR OPTIMIZATION AND EXPANSION STUDY

City of Dallas, Oregon

OWRD Grant #GB0008-09

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EXECUTIVE SUMMARY

The City of Dallas (City) has continued work on an aquifer storage and recovery (ASR) optimization and expansion feasibility study to improve understanding of the hydrogeologic conditions of the aquifer system at the City's existing ASR facility. Candidate locations for additional ASR wells have been identified and alternative operational management strategies have been assessed with the goal of optimizing recovery efficiency from the ASR system. Phase 1 of the feasibility study included a dynamic borehole survey in the City's existing ASR well (ASR-1) to identify variability in flow contribution and water quality with depth in the open borehole as a function of pumping rate. Phase 2 of the feasibility study titled "City of Dallas ASR Optimization/Expansion Study" (the grant study) was performed in conjunction with the Oregon Water Resources Department (OWRD) Conservation, Reuse, and Storage Grant Program, which was jointly funded by the City and OWRD under state grant number GB0008-09. The grant study consists of three tasks: 1) advanced well testing analyses, 2) numerical modeling, and 3) reporting.

Task 1 work included extensive analysis of data collected throughout the ASR pilot testing program and a geophysical survey at the field site to validate the conceptual model of the ASR aquifer system. Because the aquifer at depth is known only from a single point (the ASR well), derivative analysis of existing pumping and recharge data resulted in improved estimates of physical aquifer parameters and aquifer geometry. A geophysical survey provided further evidence that two near-vertical fault zones intersect in the vicinity of ASR-1, forming a key component of the ASR-system. The revised conceptual model is inclusive of a fractured confined aquifer zone of relatively high permeability connected to the two near-vertical intersecting permeable fault structures.

Task 2 work involved construction of a simple finite-element numerical groundwater model based on the conceptual model. The numerical model was calibrated with data from the ASR-1 pumping test, as well as historical ASR pilot testing water level and water quality data. The calibrated model was used to perform a series of forecasting simulations of an expanded two-well ASR system (assuming twice the current stored and recovered volume from the existing single-well system). The forecasting simulations assessed changes in recovered water quality and quantity given three potential locations for a new ASR well in the vicinity of the Water Treatment Plant (WTP) and four ASR operational management scenarios.

Forecasting simulation results for the various interacting two-well systems indicated that the addition of a new ASR well in the vicinity of ASR-1 will result in an improvement in water quality (and therefore recovery efficiency) as compared to a single well system. This improvement is due to the increased effectiveness of conditioning the saline SRV aquifer between the two wells during periods of recharge, and would not be realized if a new well was located far from ASR-1.

Simulations of a new ASR well placed near the intersection of the two fault zones identified in Task 1 exhibited the best recovery efficiency based on the quality of recovered water (21% lower TDS concentration in final recovered water compared to the single well system). However, the cost per unit

recovered volume in this scenario is expected to be relatively high compared to other scenarios due to the necessity of acquiring new land and installing conveyance pipe and electricity to potential new well locations outside the WTP site. A more cost-effective ASR expansion plan includes a second ASR well placed within the WTP property boundary as near as possible to the identified fault zones, which is forecasted to provide a similar increase in stored and recovered water volume but result in a smaller improvement in final recovered water quality (13% lower TDS concentration in final recovered water compared to the single well system).

Simulation results also indicate that different management scenarios can be used to recover a greater percentage of injected water or to recover recharged water with lower TDS concentrations as compared to the current operational scheme. For example, recovering water from the ASR system every other year is forecasted to result in improved recovered water quality, and therefore recovering water only when needed to meet peak demand would likely result in improved water quality during those recovery periods. Altering management practices to provide improvements in recovered water quality will come at the expense of recovered water quantity as a percentage of recharged volume and vice versa. However, the ability exists to alter the quality or quantity of recovered water from the ASR system as may be necessary depending upon the future needs of the City's water supply program.

Task 3 concludes the feasibility study with the results and recommendations presented in this document and its appendices.

1.0 INTRODUCTION

The City of Dallas is currently pilot testing a single-well 0.33-MGD ASR system utilizing the saline Siletz River Volcanics (SRV) as the receiving aquifer. During recharge of the ASR system, injected source water locally displaces naturally-occurring saline groundwater in the basalt aquifer. Pilot testing operations have been conducted over the past four years to evaluate the efficiency and feasibility of recovering high-quality drinking water at the City's ASR facility. Pilot testing results show that a fresh water storage zone can be developed in the SRV, that potable water can be recovered from the system, nearby shallow wells are not impacted by operations, and that recovery efficiency increases over successive pilot testing cycles. The City initiated a feasibility study to assess the best means of optimizing and expanding the ASR system in 2008, which has progressed in two phases.

Phase 1 of the feasibility study was designed to identify variability in flow contribution and water quality with depth in the open borehole as a function of pumping rate. A dynamic borehole survey technique developed by the USGS (Izbicki, 2005) was conducted at ASR-1 in July 2008. Results confirmed that ASR operations result in complex mixing between fresher source water and saline native groundwater in the aquifer. Recovered water quality has been shown to be strongly influenced by pumping rate, affecting both advective dispersion and changing the local pressure profile (the amount of saline water up-coning in the vicinity of the well). Up-coning of saline water increases mixing with injected source water in the borehole during recovery and adversely affects recovered water quality. The results from Phase 1 of the feasibility study are documented in the Year-3 ASR Pilot Testing Report (Golder, 2009).

This report presents the results of the City of Dallas Aquifer Storage and Recovery (ASR) Optimization/Expansion Study – Phase 2, funded in part by OWRD Grant #GB0008-09. Phase 2 work utilized existing data to perform advanced well testing analysis and develop a calibrated numerical groundwater flow and mass transport model. The results of well testing analysis describe the aquifer geometry and estimate physical parameters that affect injection and recovery of freshwater from the saline aquifer. The numerical model provides a technical basis for evaluating the optimization of aquifer storage and recovery in the saline SRV aquifer. This approach provided site-specific management information which could potentially improve recovery efficiency from the City's current ASR system and inform future expansion of the system to include multiple ASR wells in a cost effective manner.

The body of this report presents a general overview of the methods, results, and recommendations resulting from Tasks 1 and 2 of the Phase 2 work. Technical details of the work completed during Phase 2 of the optimization and expansion study are presented in two technical memoranda, included as appendices to this report.

2.0 SUMMARY OF PHASE 2 METHODS

Phase 2 was conducted in three tasks: 1) advanced well testing analyses, 2) numerical modeling, and 3) reporting. Task 1 generated a conceptual model of the SRV aquifer in the vicinity of ASR-1 using pressure response data collected during initial pumping tests conducted at ASR-1 and during three years of ASR pilot testing. Task 2 involved construction and calibration of a simple finite element numerical groundwater flow model using the aquifer properties estimated during Phase 1, and water level and water quality observations made during ASR pilot testing. The calibrated model was used to conduct forecasting simulations to provide a basis for determining the best location for installation of a second ASR well to increase system capacity and the potential benefits to recovered water quality and quantity that may be realized through operational management of a two-well system. Task 3 concludes the feasibility study with the results and recommendations presented in this document and its appendices.

2.1.1 Task 1 Methods

Task 1 applied advanced well test analysis software (HydroBench® and Interpret®) to aquifer response data to more accurately evaluate aquifer geometry and aquifer hydraulic properties for model construction. The programs were used to analyze measured flow rate and transient pressure response data collected during the initial 72-hour constant-rate aquifer test conducted in 2005 and during the following 3 years of ASR pilot testing cycles (ASR Cycles 1 through 7).

Because hydraulic response and field observation suggested a faulted system was one possible conceptual hydrogeologic model, a geophysical survey was conducted during Task 1 to confirm the presence and location of nearby fault zones. Seismic refraction and reflection surveys were conducted along perpendicular survey lines established in the rights-of-way of Ellendale Road and the road leading to the City water treatment plant (WTP). The surveys generated a cross-sectional seismic wave velocity profile modeling the thickness of subsurface layers beneath the surface, which were interpreted to identify potential fault zone locations and integrated into the site conceptual model. Details are provided in Attachment A – Task 1 Technical Memorandum.

2.1.2 Task 2 Methods

A finite-element groundwater flow and transport model was constructed with the software FEFLOW® using the Dallas ASR site conceptual model developed in Task 1 as the basis for model geometry, boundary conditions, and hydraulic parameters. A single-well simulation model was initially constructed to reproduce the development of a freshwater storage zone in the SRV aquifer during 3 years of ASR pilot testing (Cycles 5 through 7) at the existing ASR-1 well. The simulation model was calibrated based on water levels observed at ASR-1 and two responding observation wells, in addition to total dissolved solids concentrations of recovered water.

The calibrated simulation model was used as the basis of a dual-well forecasting model used to perform a series of predictive simulations to evaluate the potential benefits and approach for expanding the Dallas

ASR system by adding a second ASR well. Three potential locations for the new (second) well were selected for forecasting analysis with input from the City. New wells locations were chosen to be:

- Within or near the Water Treatment Plant site to maintain proximity to existing ASR infrastructure and the benefits of well interaction, including improved aquifer conditioning between the two wells;
- Near the conceptualized locations of the permeable fault zones to increase potential aquifer storage capacity; and,
- At least 100 feet from property lines (when located on existing City-owned land) to satisfy Department of Health (DOH) setback requirements.

The three new well locations are shown in Figure 1, and include:

- **ASR-2** is located near the intersection of the two conceptualized fault zones west of the Water Treatment Plant site boundary.
- **ASR-3** is located within the Water Treatment Plant site boundary on the northern side of the property.
- **ASR-4** is located near the fault trending along northern boundary of the Water Treatment Plant site.

Forecasting model simulations of a two-well ASR system were performed to evaluate the potential improvements to recovered water quality and quantity (or tradeoffs between the two) given four ASR operational management scenarios that were applied to both wells in the model. The management scenarios are summarized in Table 1, and were constructed as follows:

- **Scenario 1** (the baseline scenario) simulates a typical ASR cycle consisting of injection at a rate of 165 gpm (900 m^3/day) for 200 days, storage for 3 days, and recovery at a rate of 250 gpm (1360 m^3/day) for 50 days at each well. Scenario 1 results in an annual recharge volume of 95 million gallons and a recovered volume of 36 million gallons, recovering approximately 38% of the water injected annually.
- **Scenario 2** simulates an alternative ASR management time schedule intended to maximize recovered water quality by simulating recharge for two years with a single recovery period at the end of the second year. Injection during the two recharge periods occurs at a rate of 165 gpm (900 m^3/day) for 200 days separated by a 165 day storage period. The second recharge period is followed by a 3 day storage period and recovery at a rate of 250 gpm (1360 m^3/day) for 50 days. Scenario 2 results in a biennial (2-year) recharge volume of 190 million gallons and a biennial recovered volume of 36 million gallons, recovering approximately 19% of the water injected over two years.
- **Scenario 3** simulates an alternative ASR management rate schedule intended to maximize system efficiency with respect to the volume of water recovered as a percentage of the volume injected, while also maximizing the total volume of water injected and recovered. The recharge, storage, and recovery periods occur over the same time scales specified in Scenario 1, but injection rates were maximized within the limits of available buildup and recovery rates were adjusted within the limits of available drawdown during each simulation to obtain a 50% recovery efficiency and the maximum volume of recovered water at the well. Actual volumes are dependent on hydraulic interaction and therefore well location, and are summarized in Table 1.

- **Scenario 4** simulates the potential for long term improvement in recovered water quality due to aquifer conditioning over five successive ASR cycles. Each cycle is conducted according to the base case (Scenario 1) rate and time schedule.

Details of model construction, calibration and operation are included in Attachment B – Task 2 Technical Memorandum.

3.0 SUMMARY OF PHASE 2 RESULTS

3.1 Task 1 Results

Derivative analysis of aquifer pressure response to injection and recovery activity at ASR-1 suggested that several transmissivity zones may be present in the SRV aquifer below the study site. These zones may affect how injected water mixes with native saline groundwater through mechanical dispersion, and therefore act as one of the primary controls on the quality of recovered water.

Geophysical survey results indicate the possible location of two fault zones that may act as planar and (relatively) permeable conduits in the aquifer system. These fault zones comprise one of the modeled transmissivity zones that affect how injected water disperses within the SRV aquifer. This conceptual model is supported by observed hydraulic connection between the ASR-1 well and two (of eight) observation wells (Lowe – POLK51112; and Presser – POLK56697).

Derivative analysis and geophysical survey results were used along with existing data (e.g., Phase 1 downhole flow analysis surveys, lineament analysis, etc.) and site observations to create a refined conceptual model of the aquifer system. The conceptual model consists of three zones of transmissivity in the vicinity of ASR-1 described as follows:

- Zone 1 - a relatively localized high transmissivity zone intersected by the ASR-1 well, interpreted to be a heavily fractured shallow horizontal zone extending approximately 1000 to 2000 feet from the well and hydraulically connecting the well to a fault system.
- Zone 2 – a lower transmissivity zone compared to Zone 1, exhibiting bilinear flow conditions interpreted to result from linear flow through two intersecting permeable fault structures which form the main ASR storage zone.
- Zone 3 – the overall SRV basalt formation composed of layered marine volcanic deposits, which contributes insignificant storage volume to the ASR system and isolates most neighboring observation wells from pressure responses related to recharge and recovery activities at ASR-1.

3.2 Task 2 Results

3.2.1 Simulation Model Calibration Results

A numerical groundwater flow model simulating Cycles 5 and 7 was calibrated based on water levels observed at ASR-1 and two responding observation wells. The timing of observed water level response to ASR operations (or lack thereof) matched the observation well network data. However, the magnitude of water level change at the two responding observation wells was consistently under-predicted by the model. To address the project objectives, the model calibration focused on near-field (i.e. ASR well) response accuracy. Modeled water levels along fault zones distant from ASR-1 toward the edge of the model domain are likely influenced by model boundary conditions, and the difference between distant and

near-well accuracy does not affect the predictive capacity of ASR development scenarios in the vicinity of the City's WTP.

Simulation of the Cycle 7 pilot test period was used to calibrate the mass transport model based on recovered water total dissolved solids (TDS) concentrations observed at ASR-1. A pair of nested dispersivity zones around ASR-1 were necessary to simulate the recovered water TDS profile as closely as possible over a full-scale ASR cycle. Observed TDS concentration values were satisfactorily simulated for the first 30 days of recovery. After 30 days, the model under-predicted TDS concentrations. Further calibration efforts did not narrow the gap between simulated and observed recovered water TDS concentrations at late times, indicating additional uncertainty in aquifer geometry not addressed with advanced hydraulic analysis and the geophysical surveys conducted. Still, the final calibrated Cycle 7 model is shown to reasonably simulate groundwater flow and mass transport processes in the SRV aquifer near ASR-1 during full-scale ASR pilot testing activities through approximately 2/3 of a typical recovery phase, after which it tends to under-predict recovered water TDS concentrations. Observed response data can be used to proportionately adjust predictive analyses.

3.2.2 Forecasting Model Prediction Results

The calibrated flow and transport model was used to conduct forecasting simulations of ASR recharge and recovery cycles given several system management scenarios and adding a second ASR well to the system at three locations. Simulation results were normalized to a base case scenario representing a typical recharge-storage-recovery scheme at a single ASR well. Therefore changes in recovered water quality (final TDS concentration at the end of recovery) and quantity (recovered volume as a fraction of injected volume at the end of recovery) due to the various management scenarios and second well locations are presented as a percent change from the base case (described in Section 2.1.2) at the end of the recovery period for each scenario. Note that the total volume injected and recovered is at least twice that of the base case in all scenarios, and that improvement in recovered water TDS from a combined system is forecast in every scenario due to improved aquifer conditioning predicted to occur with a two-well system. Model parameters used in the baseline and forecasting scenarios and qualitative comparisons of simulation results are presented in Table 1.

A summary of forecasting simulation results is presented graphically in Figure 2, which compares gains in water quality and volumetric recovery given the various new well locations and management scenarios. The x-axis of Figure 2 is the change in percent recovery (as a fraction of recharge volume) for a simulated two-well system compared to the percent recovery of a baseline single well system. The y-axis of Figure 2 is the percent improvement in final water quality for a dual well system compared to the final water quality a baseline single well system. The forecasting results indicate that both recovered water quality and quantity are sensitive to the simulated management scenarios (described in Section 2.1.2). Water quality (though not recovered water quantity) is also sensitive to the simulated location of a second ASR well (locations shown in Figure 1).

- Scenario 1 simulation results predict that a two-well ASR system will result in a 12% to 21% improvement in recovered water quality compared to a baseline single-well simulation, and little improvement in recovered volume as a fraction of recharge volume (though 2 to 2.5 times as much water is recharged and recovered as compared to the baseline single well system in all forecasting simulations).
- Scenario 2 simulations predict significantly improved recovered water quality (36% to 43% increase) at the expense of percent recovered water quantity (an 18% decrease).
- Scenario 3 simulations predict an improvement in recovered water quantity (12% to 13% increase) with limited improvement in recovered water quality (0 to 10% improvement over background scenarios).

Model simulations indicate that the Dallas ASR system can be managed to provide greater recovered water quantity as a percent of injected volume or better recovered water quality as compared to a base-case operational practices to meet the future needs of the City's water supply system with different management strategies and well locations. The location of an additional well will have some effect on the magnitude of improvement in water quality; though will have little influence on recovered water quantity. A second well placed at the intersection of the two hypothesized fault zones (PW-2 location, see Figure 1) is forecast to result in recovered water quality that is 7% to 9% better than is forecasted to be realized from a second well placed at the other two modeled locations (PW-3 and PW-4 locations, see Figure 1) given the same management scenario.

4.0 ASR PROGRAM EXPANSION AND OPTIMIZATION RECOMMENDATIONS

4.1 ASR Program Expansion

The capacity of the City's ASR system may be doubled to approximately 0.66 MG/day by adding a second well to the City's ASR system. Additionally, a dual well system in which the new well is in proximity to ASR-1 is expected to condition the saline SRV aquifer more rapidly than a single well system alone, thereby decreasing recovered water TDS concentration and increasing the potential recovery efficiency of a dual-well ASR system. Model forecasts indicate that all three proposed locations should be suitable for system expansion based on their ability to provide additional system capacity.

Model forecasts indicate little difference in recovered water quality given a second well placed at either the PW-3 or PW-4 locations (see Figure 1). A new well at the PW-2 location is predicted to provide slightly better (7%) improvement in recovered water quality than a new well at site PW-3. However, this benefit is offset by the greater expenditure on capital costs (pipeline, power, etc.) and permitting required to develop a second well outside the current property footprint of the water treatment plant. The additional costs for the slight water quality improvement (compared to other sites) may not result in a good return on investment in terms of $/unit recovered water. Forecasted yield improvement was similar for each location, and therefore the PW-3 site located inside the current WTP boundary could become the City's preferred location for future expansion to a two-well ASR system.

4.2 ASR Program Optimization

Simulation results indicate that the addition of a new well will result in an improvement in water quality (and therefore recovery efficiency) as compared to a single well system due to the effectiveness of conditioning the saline SRV aquifer between the two wells during periods of recharge. Beyond this benefit, the City's ASR system can also be managed to recover a greater percentage of injected water or lower recovered water TDS concentrations as compared to the current operational scheme. In general, altering management practices to provide improvements in recovered water quality will come at the expense of recovered water quantity and vice versa. However, the ability exists to alter the quality or quantity of recovered water from the ASR system as may be necessary depending upon the future needs of the City's water supply program.

TABLES

Table 1

Forecasting Simulation Parameters and Results

City of Dallas ASR Optimization/Expansion Grant Study

Forecase Simulation Parameters

			Injection			Storage	Recovery				
			Rate	Duration	Volume	Duration	Rate	Duration	Total Volume		Combined TDS
Forecast	Well	Scenario #	(gpm)	(days)	(MG)	(days)	(gpm)	(days)	(MG)	(% Inj. Vol.)	(% improvement*)
Baseline (Single Well System)	ASR-1	1	165	200	47.5	3	250	50	18	38%	-
	ASR-2		165	200	47.5	3	250	50	18	38%	-
	ASR-3		165	200	47.5	3	250	50	18	38%	-
	ASR-4		165	200	47.5	3	250	50	18	38%	-
	ASR-1	2	165	400	95.0	168	250	50	18	19%	15%
ASR-1 + ASR-2 (Two Well System)	ASR-1	1	165	200	95.0	3	250	50	36	38%	21%
	ASR-2		165				250				
	ASR-1	2	165	400	190.1	168	250	50	36	19%	43%
	ASR-2		165				250				
	ASR-1	3	174.3	200	89.8	3	312	50	45	50%	10%
	ASR-2		137.6				312				
	ASR-1	4	165	1000	237.6	15	250	250	90	38%	48%
	ASR-2		165				250				
ASR-1 + ASR-3 (Twp Well System)	ASR-1	1	165	200	95.0	3	250	50	36	38%	13%
	ASR-3		165				250				
	ASR-1	2	165	400	190.1	168	250	50	36	19%	36%
	ASR-3		165				250				
	ASR-1	3	174.3	200	89.0	3	302.7	50	44	49%	1%
	ASR-3		134.8				302.7				
ASR-1 + ASR-4 (Two Well System)	ASR-1	1	165	200	95.0	3	250	50	36	38%	12%
	ASR-4		165				250				
	ASR-1	3	174.3	200	84.5	3	293.5	50	42	50%	1%
	ASR-4		119.2				293.5				

Notes: * at the end of the recovery period as compared to the baseline single-well scenario

Short Scenario Description

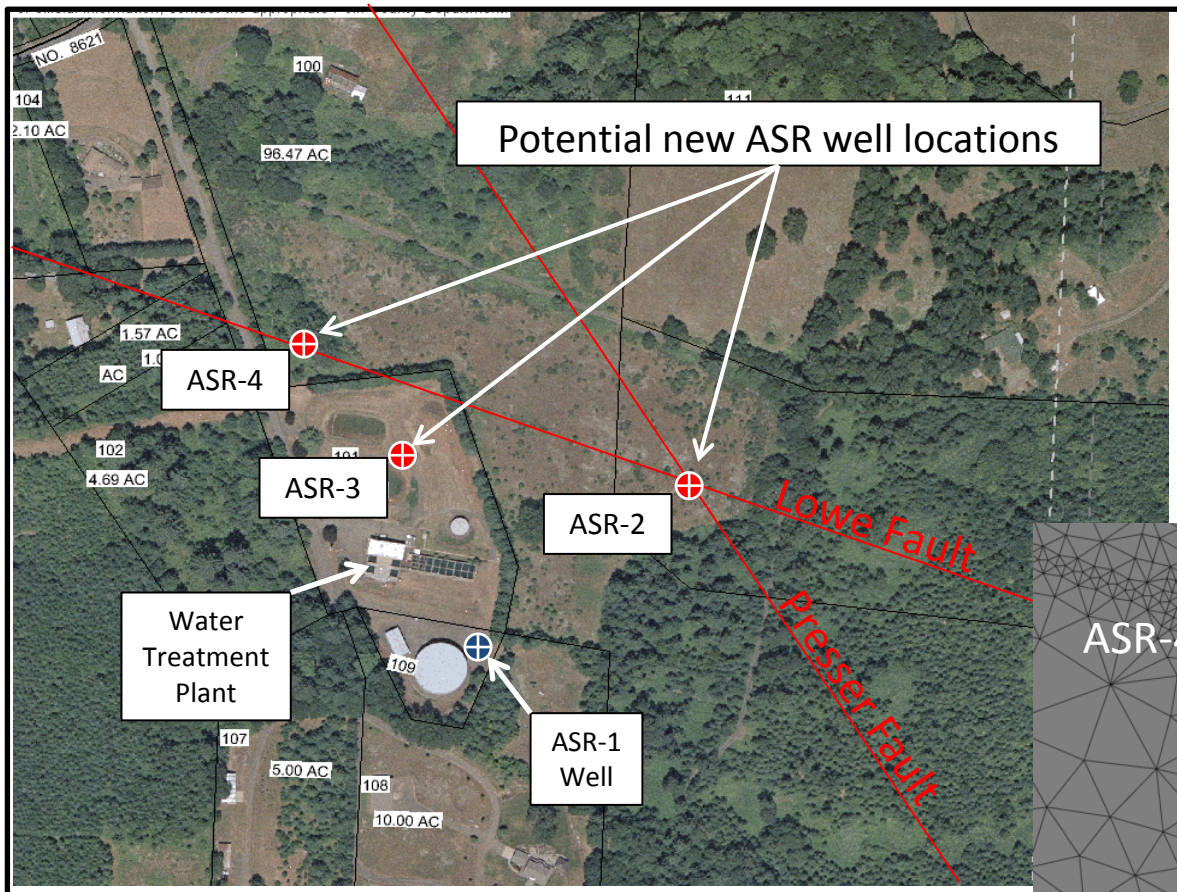
1 Typical ASR Cycle

2 Annual Recharge, Biennial Recovery

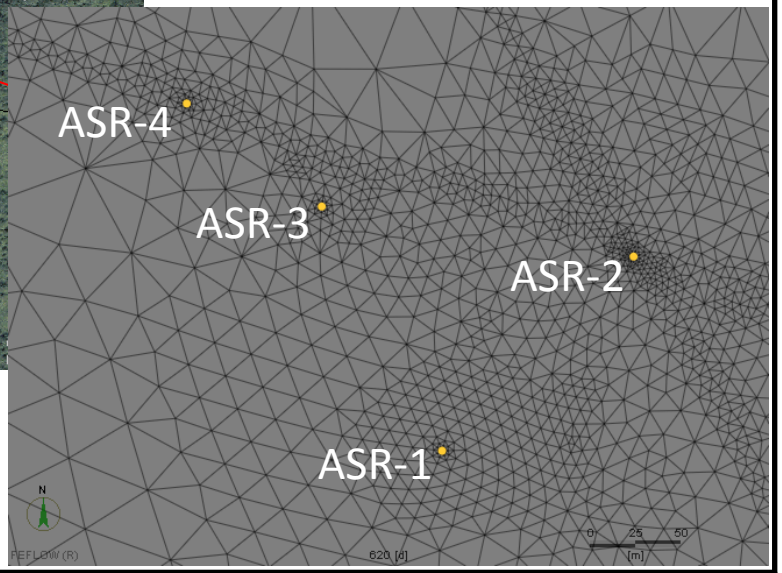
3 Rates adjusted to attain maximum injection volume and 50% recovery

4 Five consecutive annual ASR cycles (Sim.1 x 5)

FIGURES

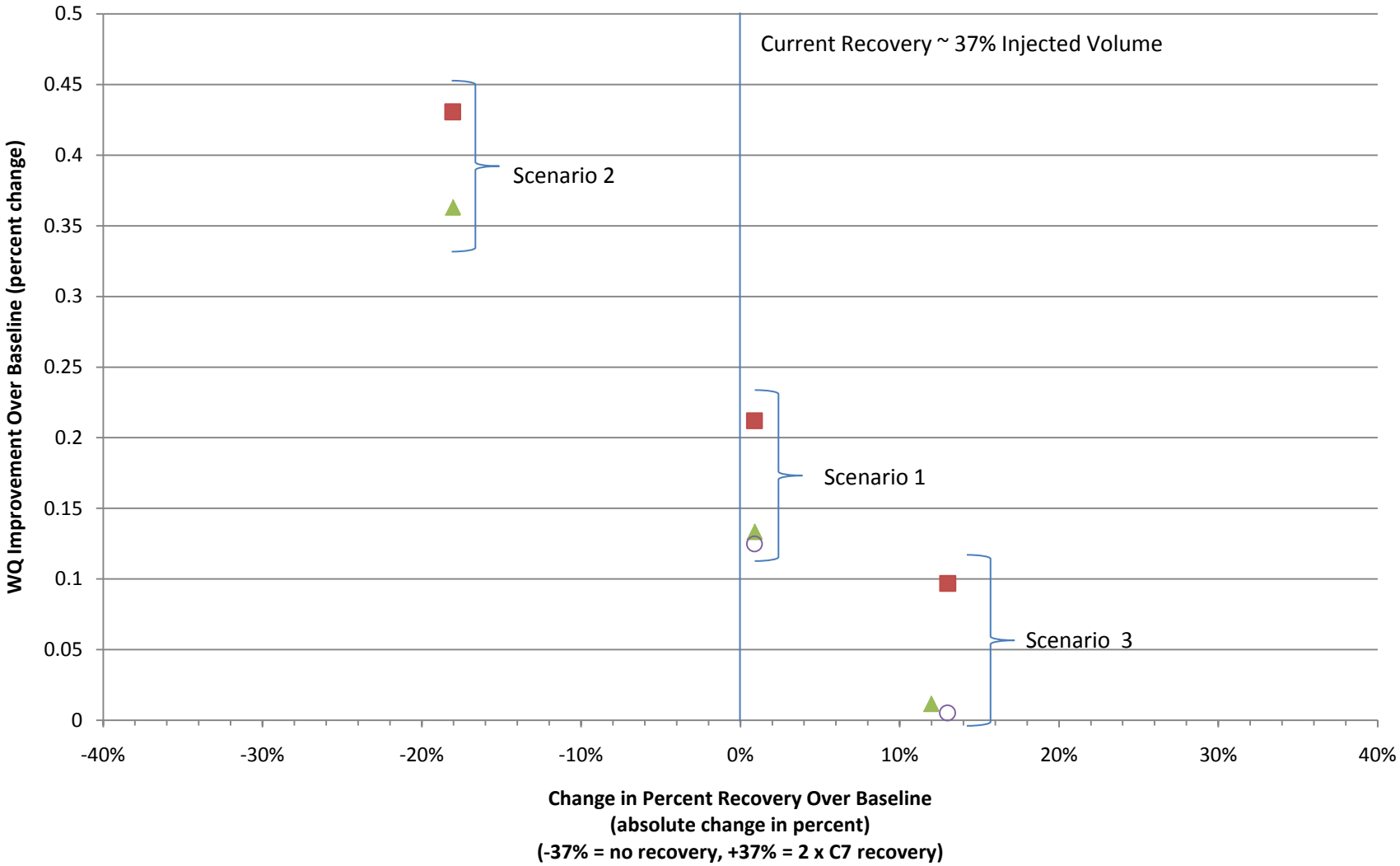


Well Representation Within Mesh



Golder Associates	Title: Potential new well locations		Drawn: SLH
			Checked: JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 053-9747400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 24, 2010	FIGURE 1

S:\Projects\2005\053-9747-400_DallasASR\OWRD Grant Work\0839747-400_Dallas Grant Study Reporting\Grant Study Report\Grant Study Report Figures and Tables.xlsx



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PW1 + PW2
PW1 + PW3
PW1 + PW4

Title	Summary of Forecasting Simulation Results	Drawn	SLH
Project Name	ASR Feasibility Grant Study	Checked	JTI
Project No.	0539747-400.04	Reviewed	PAB
Client Name	City of Dallas	FIGURE	2
Date	September 2010		

APPENDIX A

TECHNICAL MEMORANDUM
DALLAS ASR OPTIMIZATION AND EXPANSION STUDY
TASK 1 – DERIVATIVE ANALYSIS AND SEISMIC SURVEY

REPORT

CITY OF DALLAS

Appendix A

ASR Optimization/Expansion Study: Task 1

Advanced Aquifer Testing Analysis and Seismic Survey

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1.0 INTRODUCTION

This technical memorandum presents the results of advanced well testing analyses and seismic surveys performed as Task 1 of the "City of Dallas ASR Optimization/Expansion Study" (the grant study). The grant study was performed in conjunction with the Oregon Water Resources Department (OWRD) Conservation, Reuse, and Storage Grant Program, jointly funded by the City and OWRD under state grant number GB0008-09. The overall objectives of the grant study are to gain an improved understanding of the hydrogeologic conditions of the aquifer system at the City's ASR facility, identify candidate locations for additional ASR wells, and assess alternative operational management strategies to optimize recovery efficiency from the City's ASR system. Task 1 work focused on meeting the first goal of the study by using both advanced pumping test analysis techniques and field geophysical surveys to refine the conceptual model of the ASR system

Task 1 work involved derivative analysis of existing water level (pressure response) data collected from the City's existing ASR well (ASR-1) during feasibility study and pilot testing activities. Pressure response data used for this study were generated during an initial 72-hour constant-rate aquifer test conducted in 2004 and 3 years of ASR pilot testing operations performed between 2006 and 2008. Pressure data collected over the period of record were subdivided into injection/recharge and pumping/recovery data subsets, and the most complete subsets of high frequency data were selected for use in performing pressure response derivative analysis.

Derivative analysis of the pressure response measurements was conducted using the software program *HydroBench*. A conceptual model was developed for the aquifer system based on results from the derivative analyses in conjunction with observation well water level measurements collected over the course of ASR pilot testing, topography/landform analysis, and other general field observations. A preliminary discrete fracture network groundwater flow model was constructed using *MAFIC* to verify the conceptual model. The conceptual model was further verified with the results of a geophysical seismic survey conducted to confirm the presence of fault structures believed to form the storage zones of the ASR system.

2.0 METHODS AND SOFTWARE

2.1 General Description of Derivative Analysis

Derivative analysis is the process of calculating and analyzing the derivative of time series pressure response data with respect to time. As the method was originally developed by the oil industry, pressure response data were traditionally obtained from an oil well tested under transient conditions (either pumping or injection) and then sealed, with "shut-in" pressure response measured within the tested well. Derivative analysis methods can be applied to water wells, with pressure response measured as the change in water level in the well. While the term pressure response will be used in this memo for

consistency with the vocabulary of derivative analysis, it is synonymous with water level response to recharge and recovery activities conducted at ASR-1.

The derivative of pressure response data is the slope (pressure change with time) of the change in drawdown, buildup, or recovery pressure observed in a well over time. The shape of a series of point-to-point derivatives plotted on a log-log graph can be analyzed to identify possible physical aquifer characteristics controlling aquifer pressure response to testing events. Derivative analysis is a diagnostic tool used to supplement traditional curve matching techniques with a more detailed and precise evaluation of aquifer geometry, dimensions, and hydraulic parameters.

A typical sequence of pressure response events during a well test (observed in chronological order) consists of changes in water level observed in a pumping well due to wellbore storage, skin effects, infinite-acting radial flow to the well, and potential aquifer boundary effects. Other pressure response sequences resulting from specific well characteristics and aquifer conditions that control flow are also possible. Figure 1 presents conceptual diagrams of some characteristic derivative plots and the interpreted well/aquifer conditions that may cause them. This illustrates the advantage of evaluating derivative plots relative to standard pressure response plots. For further information and details regarding derivative analysis of pressure response data, refer to the following journal articles and textbooks: Horne, 1995; Spane & Wurstner, 1993; Ehlig-Economides, 1988; and Bourdet, 1983.

2.2 Data Generation for Derivative Analysis

The hydraulic data (transient pressure response, or water levels) collected as part of the City of Dallas ASR program were considered for derivative analysis. Data sets include water levels measured during the initial 72-hour constant-rate aquifer test completed at ASR-1 and during 3 years of ASR pilot testing cycles (ASR Cycles 1 through 7). The most complete pressure response data sets were imported into *HydroBench* for analysis. The aquifer test pressure response data set was selected for analysis because the pressure measurements were collected at high frequency and the type-curve and straight-line analyses previously completed (Golder, 2005) could be used for comparison with the derivative analysis results. Pressure response data sets from the initial brief ASR Cycles 1 through 5 were less complete, and were not used for derivative analysis during this study. Although some pressure response data from Cycle 6 were analyzed, the derivative analyses focused on data sets from Cycle 7 that contained the most complete pressure response records. Because the derivative analysis methodology is very sensitive to changes in flow rate, our analyses focused mainly on recovery periods when the water level in ASR-1 was re-equilibrating after recharge or recovery had ceased.

2.3 Density Effects of Saline Native Groundwater on Derivative Analysis

An assessment was completed to evaluate the relative significance of water density on the derivative analyses simulation results obtained from *HydroBench*. Native groundwater in the Siletz River Volcanics aquifer system is saline, with total dissolved solids concentration of approximately 4,250 mg/l and a

specific conductance of approximately 6,500 µS/cm measured at ASR-1 (Golder, 2005). Assuming all dissolved solids are sodium chloride (NaCl, the dominant salt in native groundwater), native groundwater at the site has an approximate density of 1,002.3 kg/m^3, as compared to the density of pure water of approximately 1,000 kg/m^3 (DeMarsily, 1986). Two *HydroBench* simulations of the constant-rate aquifer test were conducted given modeled water densities corresponding to observed saline and assumed fresh conditions. The simulation results were substantially similar, indicating that derivative analysis results are insensitive to water density values above that of pure water within the range of potential groundwater densities measured at ASR-1. Given this parameter insensitivity native groundwater and recharged water were assumed to have a density of 1,000 kg/m^3 in all *HydroBench* simulations.

2.4 Derivative Analysis using *HydroBench*

HydroBench is software package designed by a Golder Associates specifically for the derivative analysis of pressure response data from wells and boreholes where water is the ambient formation fluid. The software uses hydraulic properties of the tested wellbore and connected geologic formations to simulate pressure response derivative curves. By varying parameters to calibrate the modeled curves to match observed data the parameters of the system can be estimated. Parameters that can be calculated for the well and aquifer using *HydroBench* simulations consist of:

- Wellbore storage coefficient
- Well skin factor
- Transmissivity
- Storativity
- Flow dimension
- Initial static pressure in the aquifer
- Distance to boundary conditions (shell radius)

These parameters can be fixed to match observed values or free for the program to vary as necessary to fit the simulation. A multi-shell system can be modeled to evaluate changes in aquifer parameters (such as transmissivity) over both time and distance. The concept of a shell can be described as a radial zone of transmissivity surrounding the well.

For this study, a two-shell system with four free parameters was simulated. The simulated free parameters are summarized in Table 1, and included the following:

- The transmissivities for two shells
- The radius of the inner shell of transmissivity
- The initial/final static aquifer pressure of the Cycle 7 injection scenario
- The well skin factor (to fit the early-time shape of the derivative curve)

The wellbore storage coefficient was given a fixed value of 1.35 x 10^{-5} m^3/Pa, calculated based on the dimensions of the borehole and the specific weight of water. The storativity was assigned a fixed value of 2.2 x 10^{-4} for the 72-hour constant-rate pumping test simulation and a value of 1.6 x 10^{-4} for the Cycle 7 recovery simulation. These storativity values were adjusted manually to allow for the best-fit of the simulated derivative curve in HydroBench while maintaining storativity values consistent with fractured basalt aquifer systems.

The flow dimension, defined as the path water travels through the aquifer to the well, was assigned a fixed value of 1.5. The flow dimension value was assessed based on the late-time slope of the pressure derivative curve plotted on a log-log scale. The relationship between derivative curve slope and flow dimension has been described by Barker (1988). A derivative curve slope of zero corresponds with 2-dimensional flow (radial planar flow, e.g. a classic cone of depression) and a slope of ½ corresponds with 1-dimensional flow (linear flow, e.g. flow along a dominant fault structure to a well penetrating otherwise impervious material). The derivative plots analyzed in this study exhibit slopes of approximately ¼, relating to a flow regime between planer and linear. This so called bi-linear fractional flow dimension (dimension = 1.5) may be envisioned as linear flow to the well through a dominant fault structure with recharge to the fault from a secondary fracture system.

2.5 Conceptual Model Verification using *FracMan* and *MAFIC*

FracMan is a discrete fracture network code developed by Golder Associates (2009[b]), which enables the construction of a numerical representation of discrete fracture elements that can be used by the flow solver *MAFIC* to simulate steady state and transient flow conditions. *FracMan*/*MAFIC* was used to create numerical groundwater flow models of fractured rock aquifer geometries to test the feasibility of the conceptual model based on a comparison of simulated and observed pressure response diagnostic plots.

3.0 DERIVATIVE ANALYSIS RESULTS

3.1 2004 Constant-Rate Aquifer Test Recovery Analysis

In 2004, after drilling and construction of the City's ASR pilot test well (ASR-1), a 72-hour constant-rate aquifer test was conducted for initial hydrogeologic characterization of the site. Results from the drilling and testing of ASR-1 are documented in the Dallas ASR Hydrogeologic Feasibility Study report (Golder, 2005).

The aquifer test pressure response derivative plot shows wellbore storage and skin effects, as indicated by the initial positive unit slope of the rising limb of a "hump" in the derivative curve with apex at approximately 10 minutes elapsed time (Figure 2). The derivative curve then exhibits a brief transition with a period of near-zero slope at approximately 100 minutes, indicating a relatively small portion of the aquifer near the well that exhibits radial flow conditions. The derivative curve displays a positive slope beginning at about 200 minutes elapsed time, indicating a negative boundary condition in the aquifer (i.e.,

a decrease in transmissivity or a flow-limiting boundary). The slope of the derivative after 200 minutes is between zero and ½ (approximately ¼ over the length of the test), which is indicative of bilinear flow conditions.

Overall, the *HydroBench* simulation of the constant-rate test produces a very good match for the log-log, semi-log, and Cartesian plots of the pressure data and their respective derivatives (Figures 2 – 4). The Further, the magnitude of the decrease in transmissivity from the inner shell to the outer shell at approximately 1000 to 2000 feet from ASR-1 is generally consistent with the change in transmissivity from early- to late-time estimated using the straight-line analyses (see Table 1). Transmissivity estimates derived from derivative matches are considered more representative.

3.2 Cycle 7 Injection Recovery Analysis

The derivative plot for the Cycle 7 injection period recovery data was simulated with the same two-shell system approach used for the pumping test recovery analysis. The *HydroBench* simulation produced a good match to observed data, and the characteristics of the derivative curve and calculated parameters are consistent with the aquifer test results (Table 1, Figures 5 – 7). The characteristics of the derivative plot also show a skin effect and an infinite-acting radial flow period followed by a near-zero slope transition period and ¼-slope derivative trend indicating a small radial-flow zone and decrease in effective transmissivity away from the well (2nd shell) as bilinear fracture flow conditions become dominant.

4.0 CONCEPTUAL MODEL DEVELOPMENT

The purpose of a conceptual model is to simplify and organize available aquifer and well information into a representation of the aquifer/well system that allows for intuitive evaluation of the system as a whole. The development of a sensible conceptual model is a key element in constructing a useful numerical model. It is important that valid hydrogeologic conditions of the aquifer system are incorporated in the conceptual model, otherwise predictive simulations using the numerical model could be inaccurate or unrepresentative (Anderson and Woessner, 2002).

A conceptual model was developed for the Dallas ASR system as a basis for construction of a numerical groundwater flow model with *FEFLOW*. In addition to the results of the pressure response derivative analysis above, the conceptual model was developed using the following information:

- Observation well response to recharge and recovery at ASR-1
- Inferred geologic lineaments from topographic and landform analysis
- Field observations of geologic fault traces and spring locations in the vicinity of ASR-1
- Results of a dynamic borehole survey at ASR-1 during Cycle 3 recovery

4.1 Observation Well Response

Several years of pilot testing have shown a consistent water level response pattern in a subset of observation wells located near ASR-1. Of the twelve observation wells in the City's network, only three have exhibited hydraulic response: the Presser well (POLK 51605), the upper Lowe well (POLK 51112), and the piezometer at the Ellendale Spring (POLK 52645) (Figure 8). It appears that aquifer hydraulics are primarily controlled by fractures, joints, and/or faults in the basalt aquifer, based on the irregular spatial distribution of the wells that respond to ASR operations. This pattern of hydraulic response is used as the basis for conceptualizing the aquifer characteristics and the geometry of the ASR storage zone that control hydrogeologic conditions.

4.2 Inferred Geologic Structures

The distribution of wells that respond to ASR operations, topographic features observed in the project area, and the location of hydrologic features such as seeps and springs appear to generally align in linear patterns. Firstly, the Presser well (POLK 51605), the piezometer (POLK 52645), and ASR-1 (POLK 52155) are roughly oriented along a linear trend that coincides with mapped springs to the northwest and southeast of ASR-1 (Figure 9). Secondly, the upper Lowe Well (POLK 51112) and ASR-1 are roughly oriented along a linear trend that aligns with a linear topographic escarpment to the east-southeast of ASR-1 (south and southeast of the City of Dallas) (Figure 9). This escarpment could be associated with the same structural deformation in the Willamette Valley that has produced other similarly trending northwest-southeast faults in the areas of the Salem Hills, Lebanon, Albany, and Corvallis as mapped by Yeats and others (1991). Based on these observations, we have hypothesized that geologic structures (i.e., faults or shear-zones with associated fracturing and permeability) within the basalt aquifer are the primary hydrogeologic controls for the observed response to ASR operations.

4.3 Field Observations

A conceptual model based on a fracture-flow aquifer system is supported by the presence and location of geologic faults, springs, and linear topographic features observed in the field. A recent visit to the Valley Concrete and Gravel quarry located north of the ASR-1 site revealed several faults with orientations (strike) consistent with the more northerly-oriented lineament hypothesized to connect ASR-1 with the Ellendale Spring and the Presser Well. These faults were relatively vertical and showed significant apertures which could support the flow of groundwater (Figure 10). In addition, a seasonal spring was identified at the quarry in a location consistent with the trend of the northerly-oriented lineament (Figure 11). Other site visits to the abandoned quarry along Martin Rd. (located approximately 2,500 feet northwest of ASR-1) identified other minor fault traces in the quarry walls, although no orientation measurements are available. Finally, the Presser well (POLK 51605) is located in the bottom of a steeply incised valley which is in line with the northerly-oriented lineament and is the location of several seasonal springs.

4.4 Borehole Survey

Phase 1 of the feasibility study included a dynamic borehole survey conducted in the City's existing ASR well (ASR-1) to identify variability in flow contribution and water quality with depth in the open borehole as a function of pumping rate (Golder, 2009[a]). The results of the bore survey flow profile indicated that the most productive zone of the aquifer is found in an interval between 500 and 542 feet while pumping at 250 gpm, and between 500 and 512 feet when pumping at 200 gpm. The flow profile also indicated that no flow is contributed to the well below a depth of approximately 562 feet. Water samples taken from 505 to 825 feet indicate that specific conductance increases with depth and pH decreases with depth to a level of 560 feet, but is uniform below that depth.

4.5 Resulting Conceptual Model

Derivative analysis of pressure response data from aquifer testing and pilot testing at ASR-1 have indicated consistent hydraulic properties (see Table 1), and in conjunction with the observational data noted above suggest that three hydrogeologic zones are present in the basalt aquifer in the project area.

1. Zone 1 - A relatively high-transmissivity zone (T = 10,000 – 15,000 gallons per day per foot, gpd/ft) extending approximately 1000 to 2000 feet from the ASR-1 well (Shell 1 of the derivative analysis model). Zone 1 is interpreted to result from localized high fracture density within the Siletz River Volcanic (SRV) formation, and to hydraulically connect ASR-1 to the larger scale linear fault structures. Zone 1 is interpreted to exist as a high transmissivity zone only within a discrete horizontal plane located above 560 feet below ground surface. Below this depth fracture density is still relatively high, but fractures are closed due mineral precipitation, sediment infill, and/or structural reduction of fracture aperture (as observed in cores).

2. Zone 2 - A somewhat lower-transmissivity zone (T = 1,500 – 2,100 gpd/ft) exhibiting bilinear flow conditions interpreted to result from linear flow through permeable fault structures (Shell 2 of the derivative analysis model). The faults allow transmission of hydraulic pressure signals from recharge and recovery activity at ASR-1 to the three observations wells located within or immediately adjacent to the fault zones.

3. Zone 3 - A low-permeability and low-transmissivity zone comprising the bulk of the Siletz River Volcanic (SRV) formation. This zone includes sequences of vesicular pillow basalt flows, tuff-breccias, and massive lava flows and sills, mostly of marine origin (Snavely and others, 1968). Groundwater flow is mainly controlled by localized fracturing and characterized by low-yielding wells and non-radial flow patterns. Observation wells that do not respond to ASR-1 activity occur in this zone.

5.0 CONCEPTUAL MODEL VERIFICATION

The conceptual model was verified through both desktop and field investigation techniques. A discrete fracture network distribution and groundwater flow simulation model was used to confirm the ability to simulate observed pressure response and flow regimes in the aquifer with conceptual model parameters. A seismic survey was conducted in the vicinity of ASR-1 to verify the presence of fault structures inferred as the ASR storage zone in the conceptual model.

5.1 Preliminary Fracture Network and Groundwater Flow Model

A simple discrete fracture network model developed with *FracMan* and *MAFIC* was used to evaluate the validity of our conceptual model hypothesis. A simple block model (described in Figure 11) was constructed using the parameters defined in the conceptual model. Simulations of the 2004 pumping test were conducted to confirm whether an aquifer geometry based on two permeable, intersecting faults within a low transmissivity formation could produce a modeled pressure response derivative similar to the observed pressure response derivative at ASR-1.

The simulation of pressure response during the recovery phase of the 2004 pumping test resulted in a reasonable match between the shape of the observed and simulated pressure response derivative curves (see Figure 12). Further, the modeled pressure field during the drawdown phase of the pumping test simulation indicates flow and drawdown occurring primarily within the fault zones with only minor drawdown within the formation surrounding formation (see Figure 13), which is consistent with observation well response to ASR-1 activity.

The results of the preliminary fracture network groundwater flow model indicated that the conceptual model is sufficiently accurate to form the bases of a future detailed groundwater flow and transport model (Task 2 of the grant study).

5.2 Geophysical seismic survey

Following the development of the conceptual model, a seismic survey was conducted to verify the presence of fault structures thought to control groundwater flow. The seismic survey consisted of two 940-ft (286-m) transects: one oriented north-south along the gravel driveway to the Dallas Water Treatment Plant (Line 1), and the other oriented east-west along Ellendale Road near the intersection with Rob Mill Road (Line 2; Figure 14). A full technical description of the seismic survey is included as Attachment 1 to this memo.

Refraction results from both transects revealed the presence of significant low velocity zones, which are indicative of fault zones within the bedrock. A significant low-velocity zone indicative of a fault structure was detected about 600 feet (183 m) from the south end of Line 1. Two significant low-velocity zones were detected along Line 2: located about 220 feet (67 m) and about 800 feet (244 m) from the west end of the line (Figure 15). These two low-velocity zones may represent two distinct faults or they could be

near-surface splays associated with a single fault at greater depth (i.e., a “flower” structure). The locations of both of the low velocity zones within the bedrock are consistent with the locations of the inferred fault zones incorporated into the conceptual model. In addition, the low-velocity zones observed along both seismic transects were quite narrow (approximately 60 feet in width), which suggests that the faults have a near-vertical orientation.

The results of the seismic survey in combination with the other project observations are considered strong evidence to support the conceptual model that has been developed.

6.0 CONCLUSIONS AND FUTURE WORK

The derivative analysis of the pressure response data for the ASR-1 well and the seismic survey has successfully provided insight for the development of a reasonable conceptual model of the City’s ASR system supported by both data analysis and direct observation. The conceptual model consists of three zones of transmissivity:

- Zone 1 - a relatively localized high transmissivity zone intersected by the ASR-1 well, interpreted to be a heavily fractured shallow horizontal zone extending approximately 1000 to 2000 feet from the well and hydraulically connecting the well to a fault system.
- Zone 2 – a lower transmissivity zone compared to Zone 1, exhibiting bilinear flow conditions interpreted to result from linear flow through two intersecting permeable fault structures which form the main ASR storage zone.
- Zone 3 – the overall SRV basalt formation composed of layered marine volcanic deposits, which contributes insignificant storage volume to the ASR system and isolates most neighboring observation wells from pressure responses related to recharge and recovery activities at ASR-1.

Task 2 of the grant study will build on this work by using the conceptual model as the basis for constructing a finite-element groundwater flow and transport model to test possible scenarios for the expansion and optimization of the City’s ASR program.

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TABLES

TABLE 1

Comparison of results from traditional pumping test analysis and derivative analysis simulations

Free Parameters:	Transmissivity (gpd/ft)	Storativity (-)	Radius (ft)	Skin Factor
Constant-rate pumping response				
Straight-line early time[1]	20,200	-	-	-
Straight-line late time[1]	9,980	-	-	-
Constant-rate pumping recovery				
Straight-line early time[1]	14,000	-	-	-
Straight-line late time[1]	8,100	-	-	-
HydroBench Shell 1	9,428	2.2×10^{-4}	1,115	4.7
HydroBench Shell 2	1,591	2.2×10^{-4}	-	-
Cycle 7 Injection recovery				
HydroBench Shell 1	14,997	1.6×10^{-4}	2,007	28
HydroBench Shell 2	2,122	1.6×10^{-4}	-	28

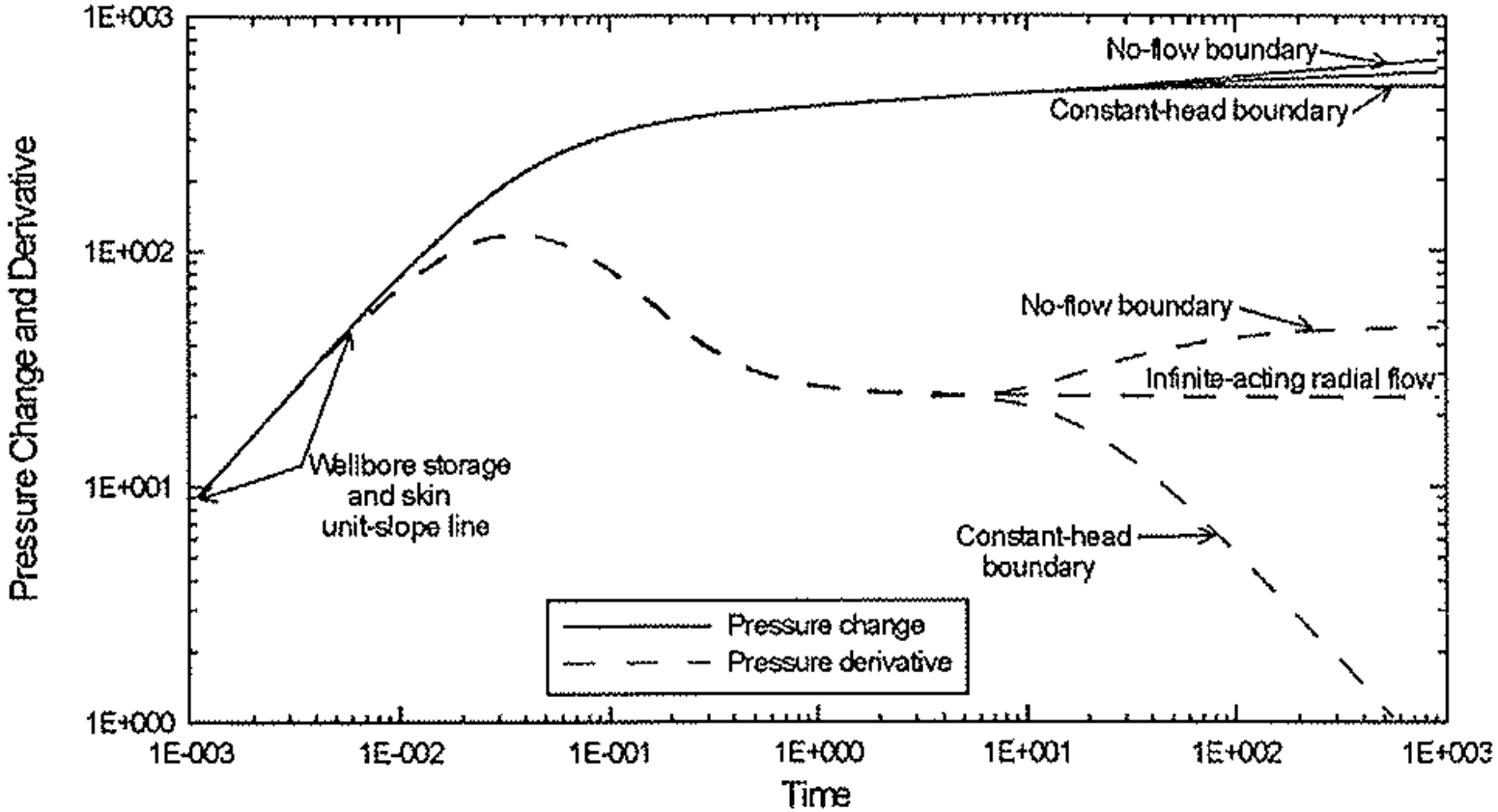
Note: 1. Aquifer transmissivity estimated using the Cooper-Jacob straight-line method (Cooper & Jacob, 1946).

TABLE 2

Parameters used in FracMan model

Object	Permeability (m/s)	Compressibility (1/psi)	Aperture (m)
Fault 1	1.0×10^{-3}	1.0×10^{-4}	1
Fault 2	1.0×10^{-3}	1.0×10^{-4}	1
Bulk aquifer matrix	1.0×10^{-5}	1.0×10^{-4}	6

FIGURES



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		Checked	MW
	Project Name: Grant Feasibility Study / Project No.: 053-9747.400	Reviewed	PB
	Client Name: City of Dallas / Date: January 5, 2011	FIGURE	1

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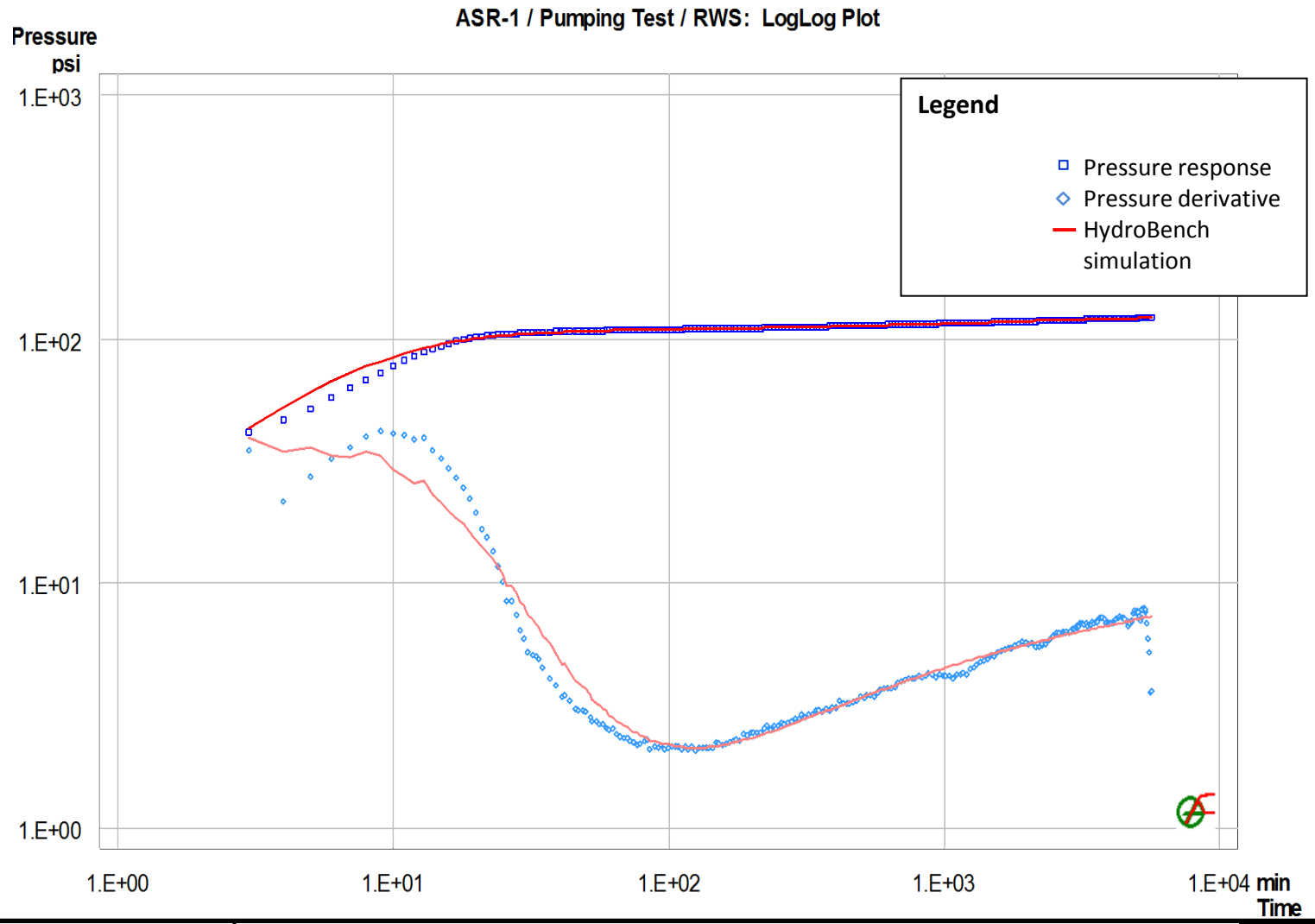

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 2

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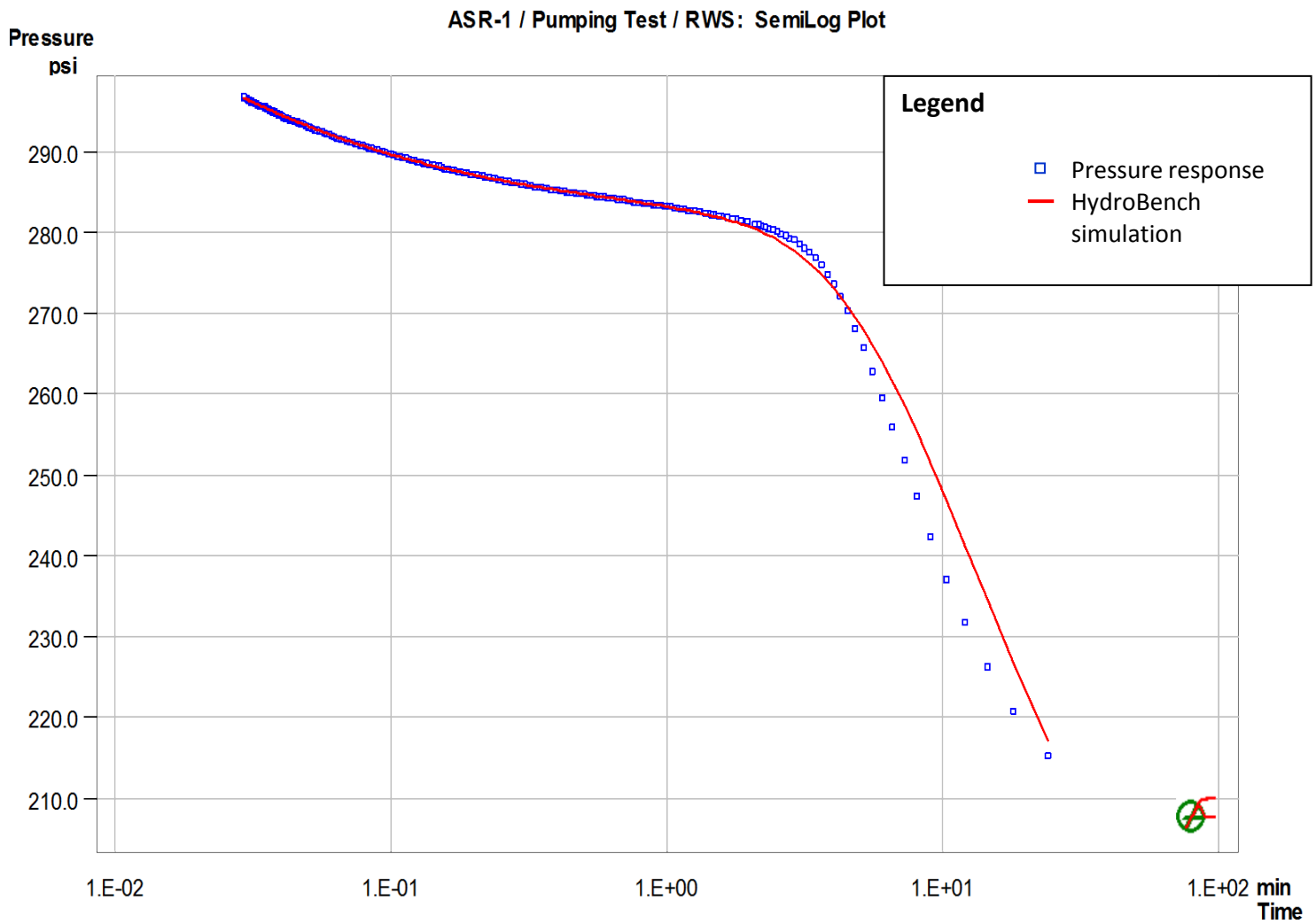

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 3

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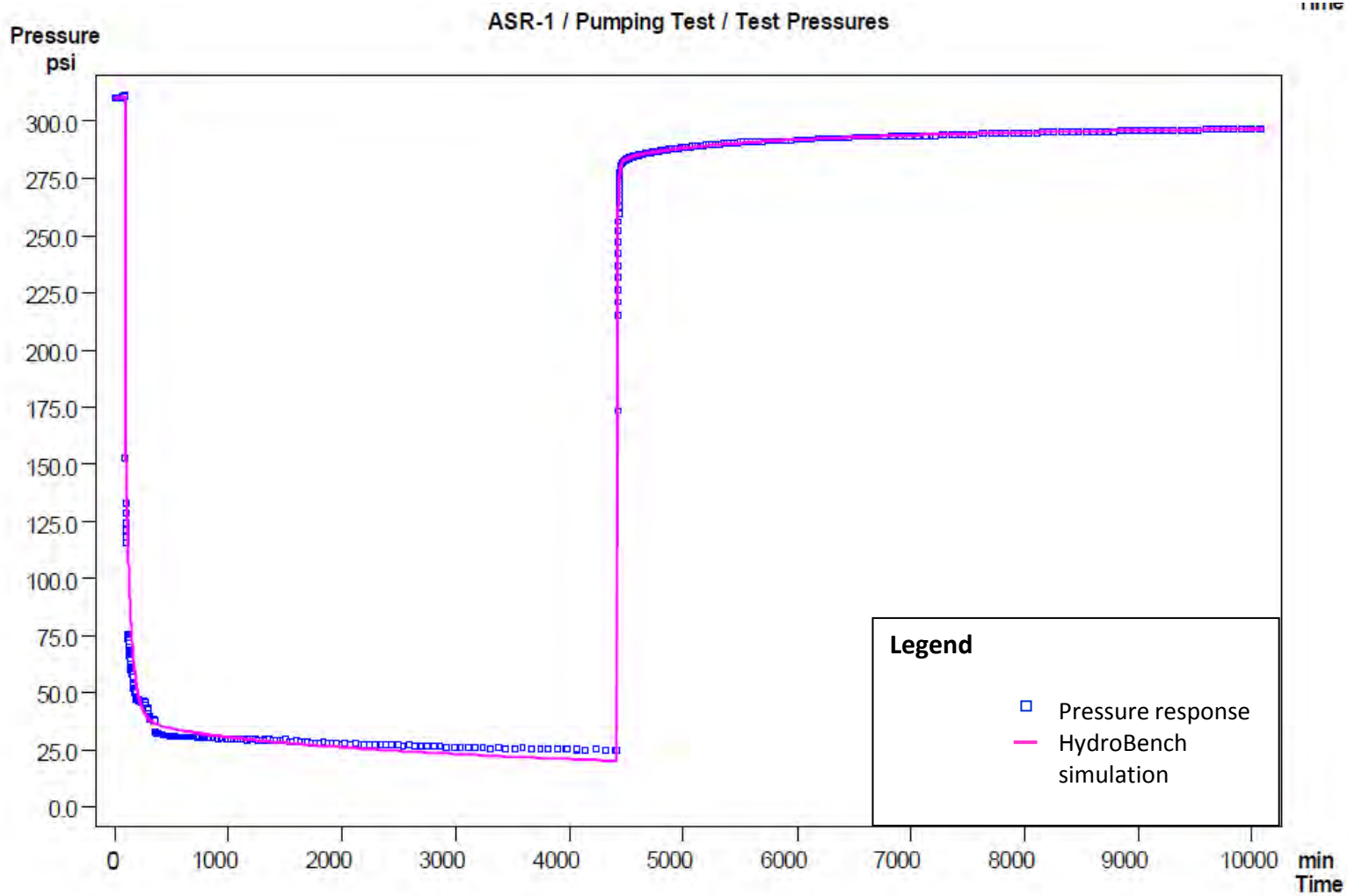

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 4

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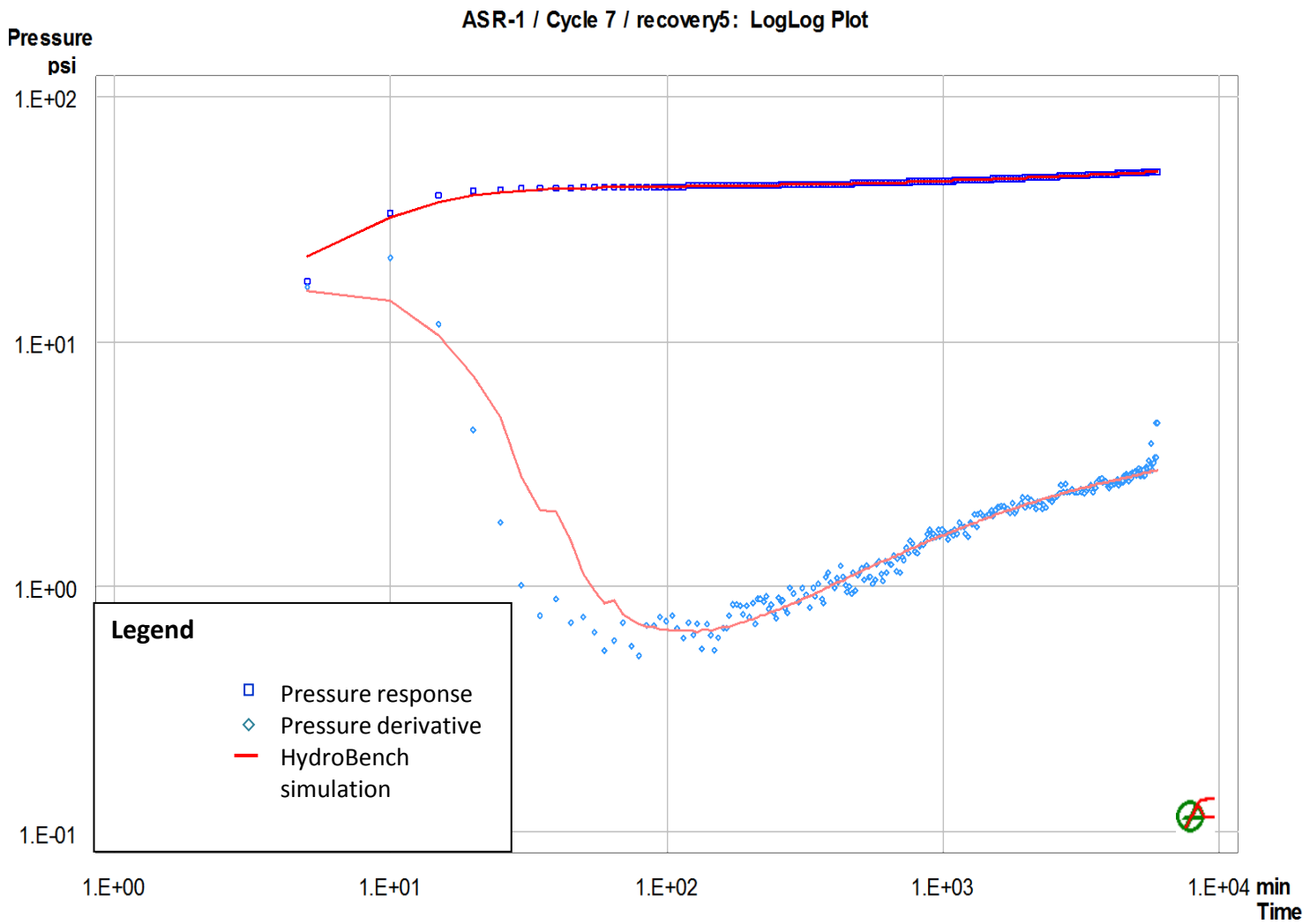

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 5

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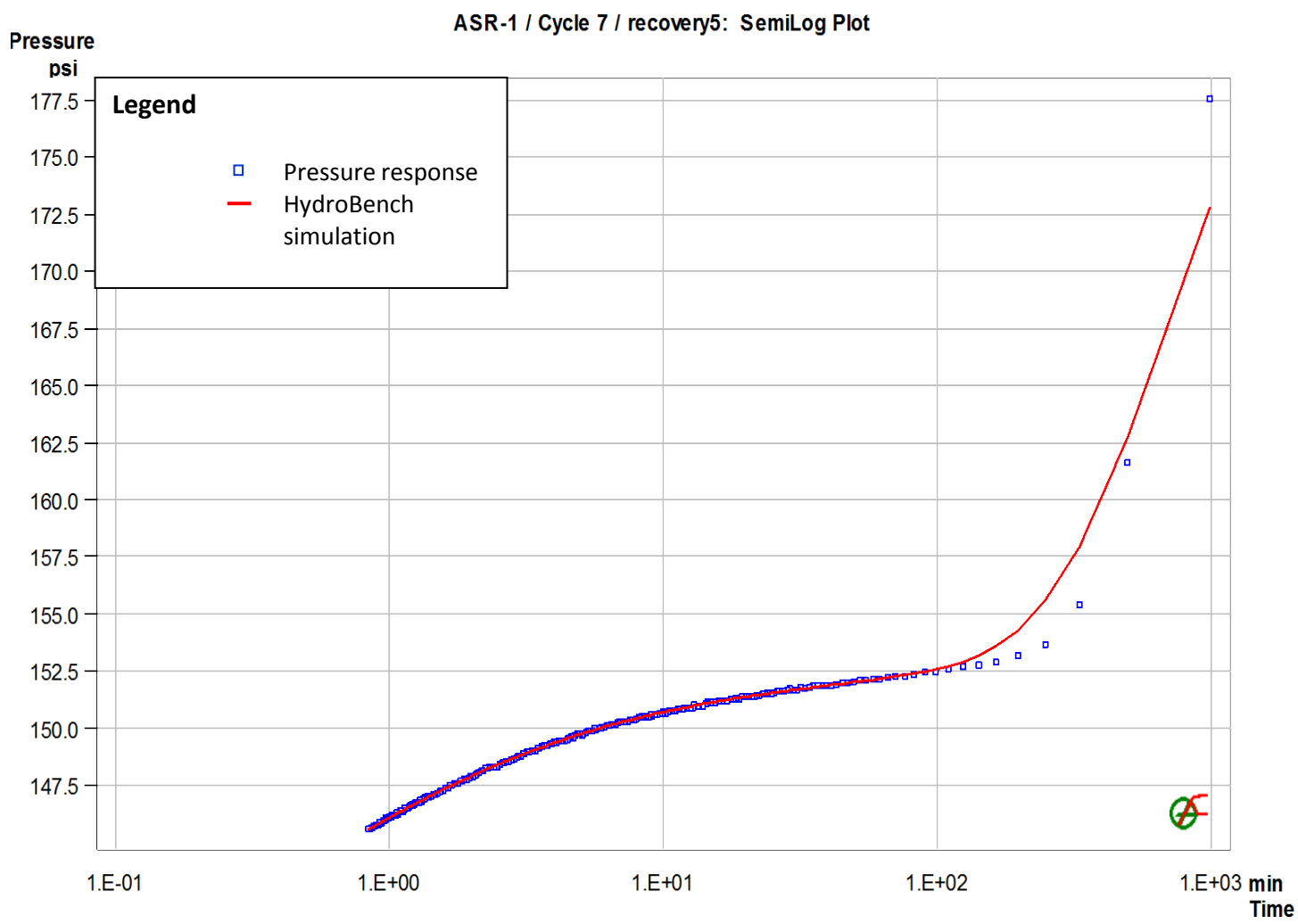

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 6

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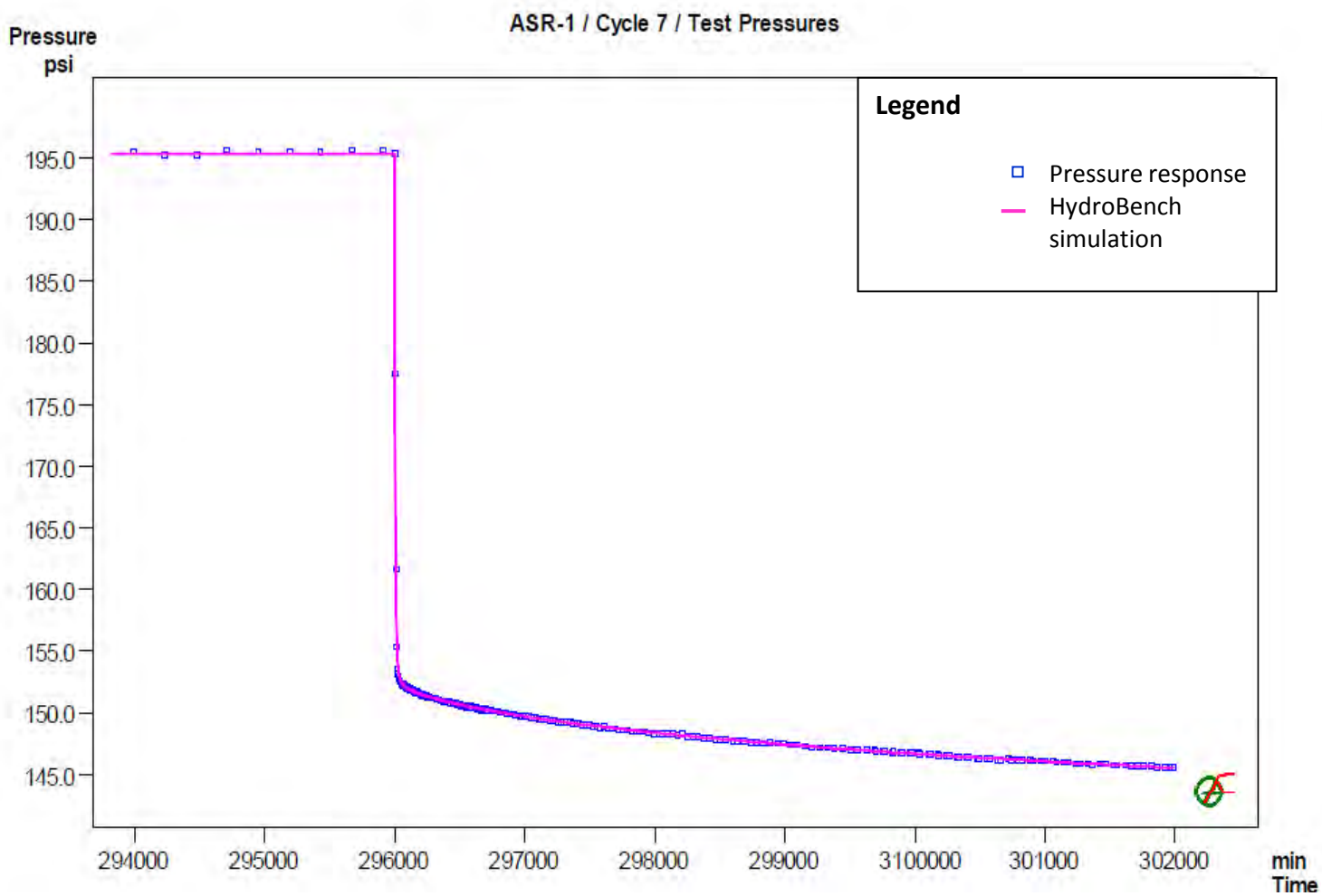

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	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 7

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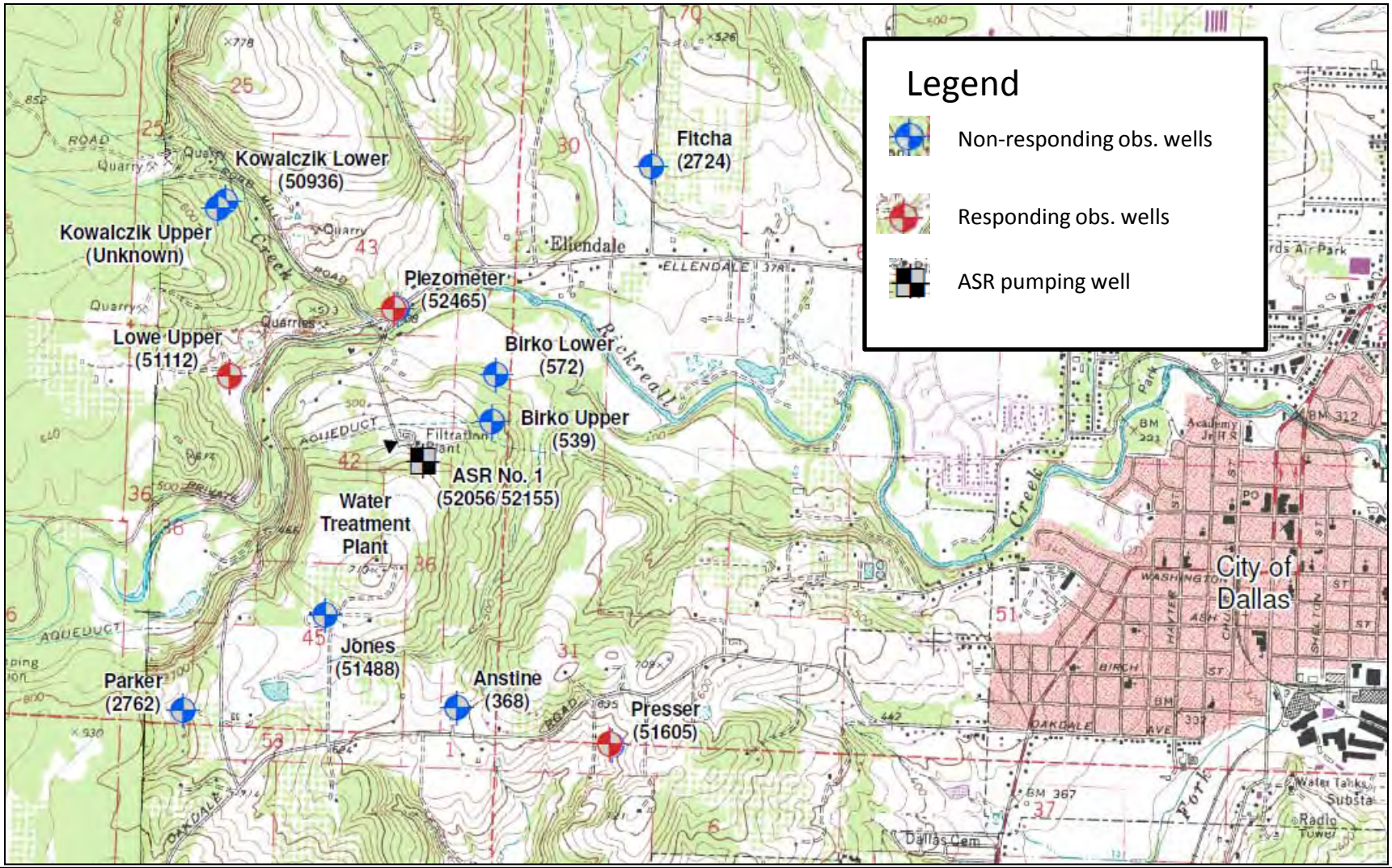

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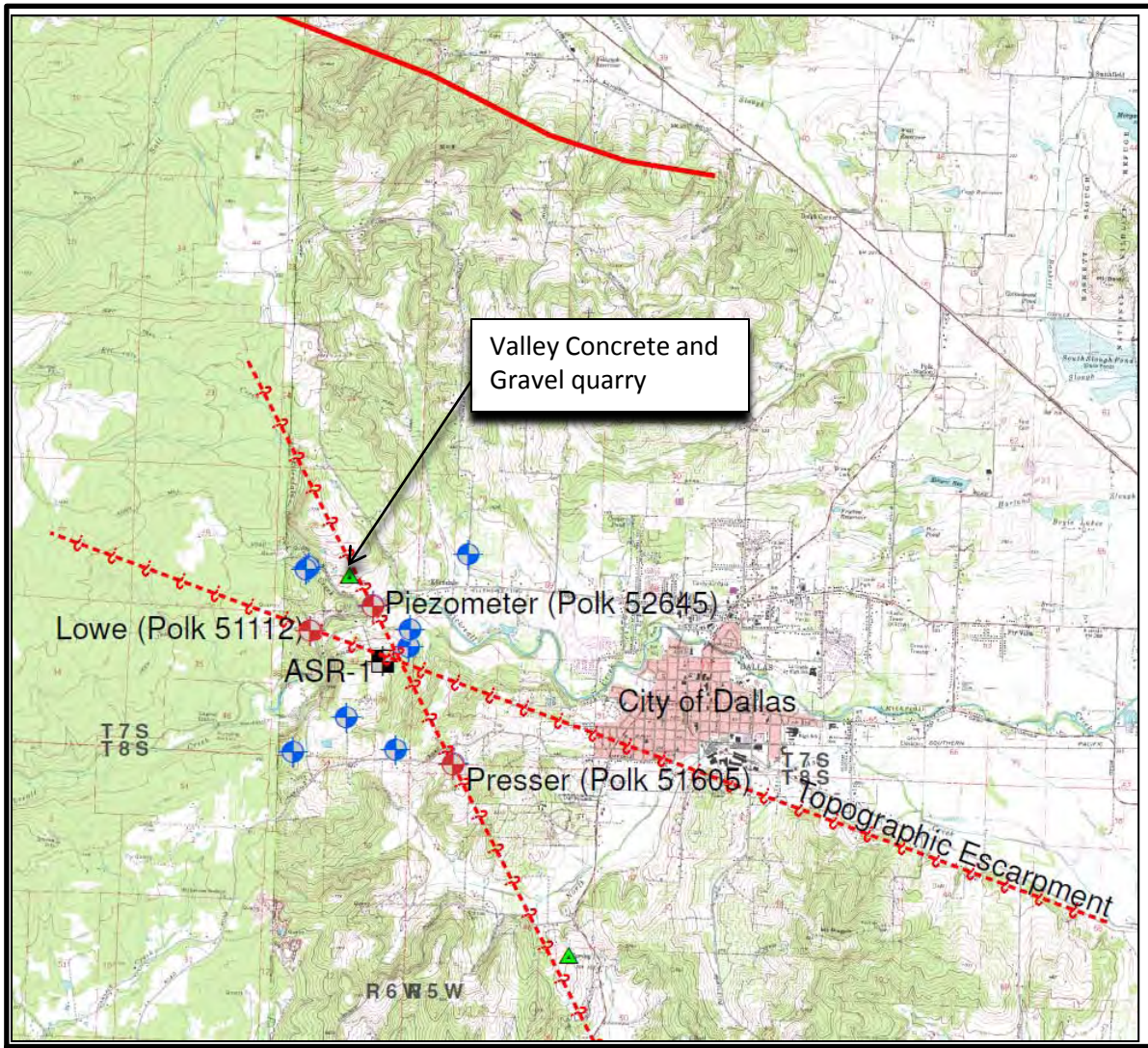
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	
	Client Name: City of Dallas	Date: July 8, 2009	FIGURE 8



Legend

- Non-responding obs. wells
- Responding obs. wells
- ASR pumping well
- Spring
- Known fault
- Inferred fault

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Title	Observation Well Network with Inferred Fault Lineaments	Drawn	SLH
		Checked	MW
Project Name	Grant Feasibility Study	Reviewed	PB
Project No.	053-9747.400	FIGURE	9
Client Name	City of Dallas		
Date	July 8, 2009		

Golder Associates	Title: Picture of fault observed within quarry		Drawn: SLH
			Checked: MW
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	Reviewed: PB
	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 10

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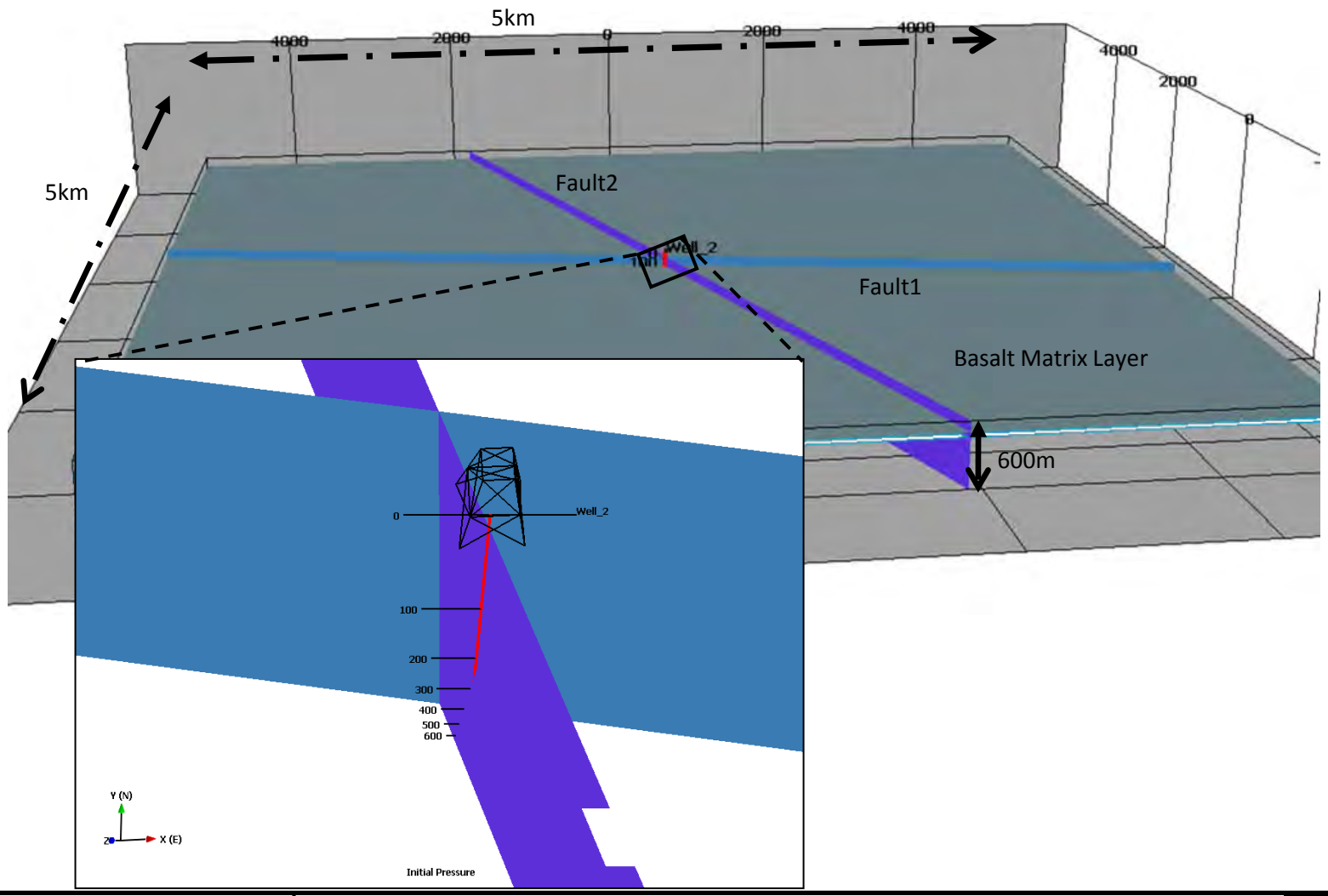
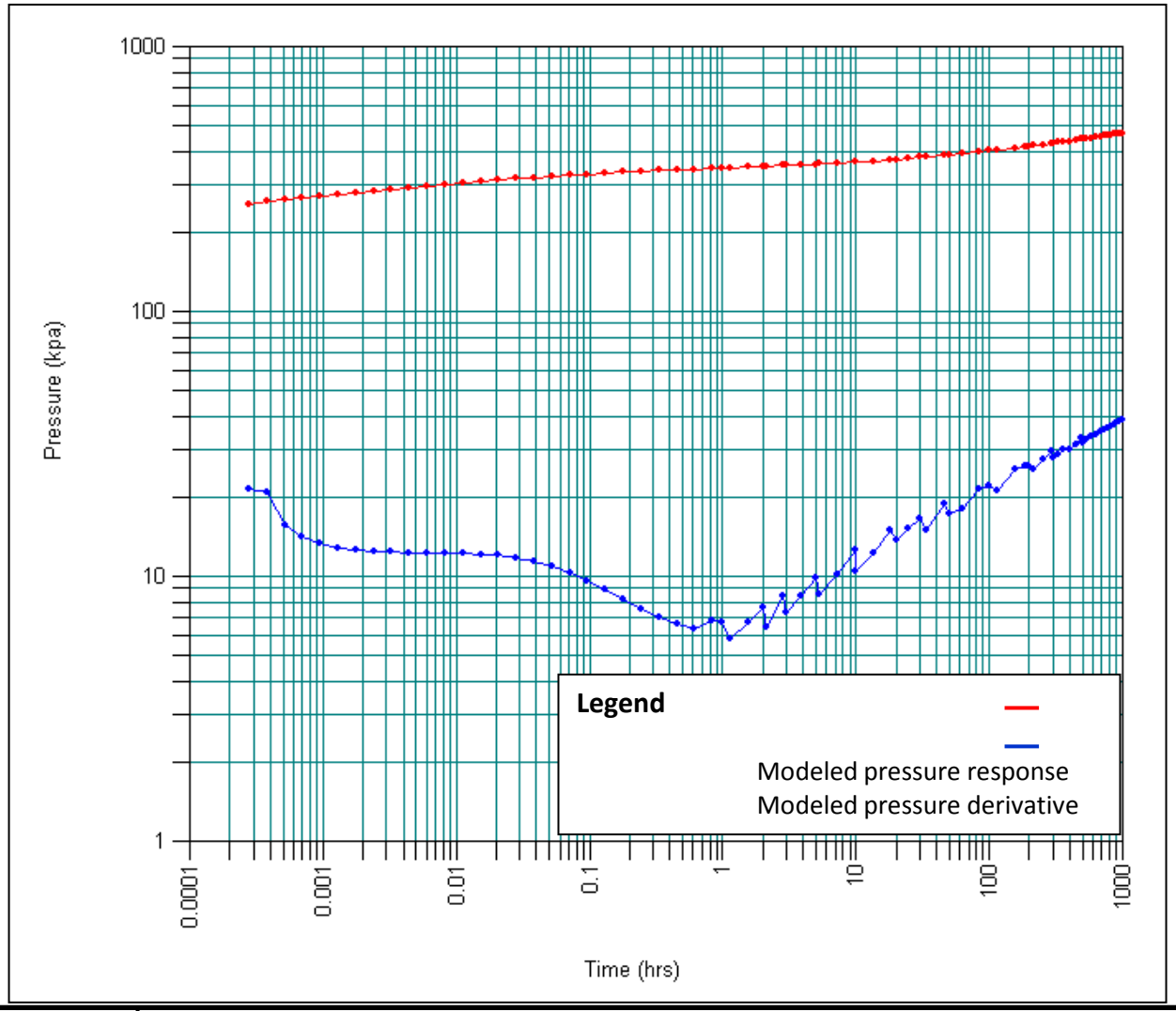


Golder Associates	Title: FracMan model description	Drawn	SLH
		Checked	MW
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	Reviewed: PB
	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 11

S:\Projects\2005\053-9747-400_DallasASR\OWRD Grant Work\0839747-400_Dallas Grant Study Reporting\Grant Study Report Apdx A - Task 1 Tech Memo\Apdx A Figures 1-7 and 10-15.xlsx



Golder Associates	Title: Log-log plot of FracMan model results	Drawn	SLH
		Checked	MW
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	Reviewed: PB
	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 12

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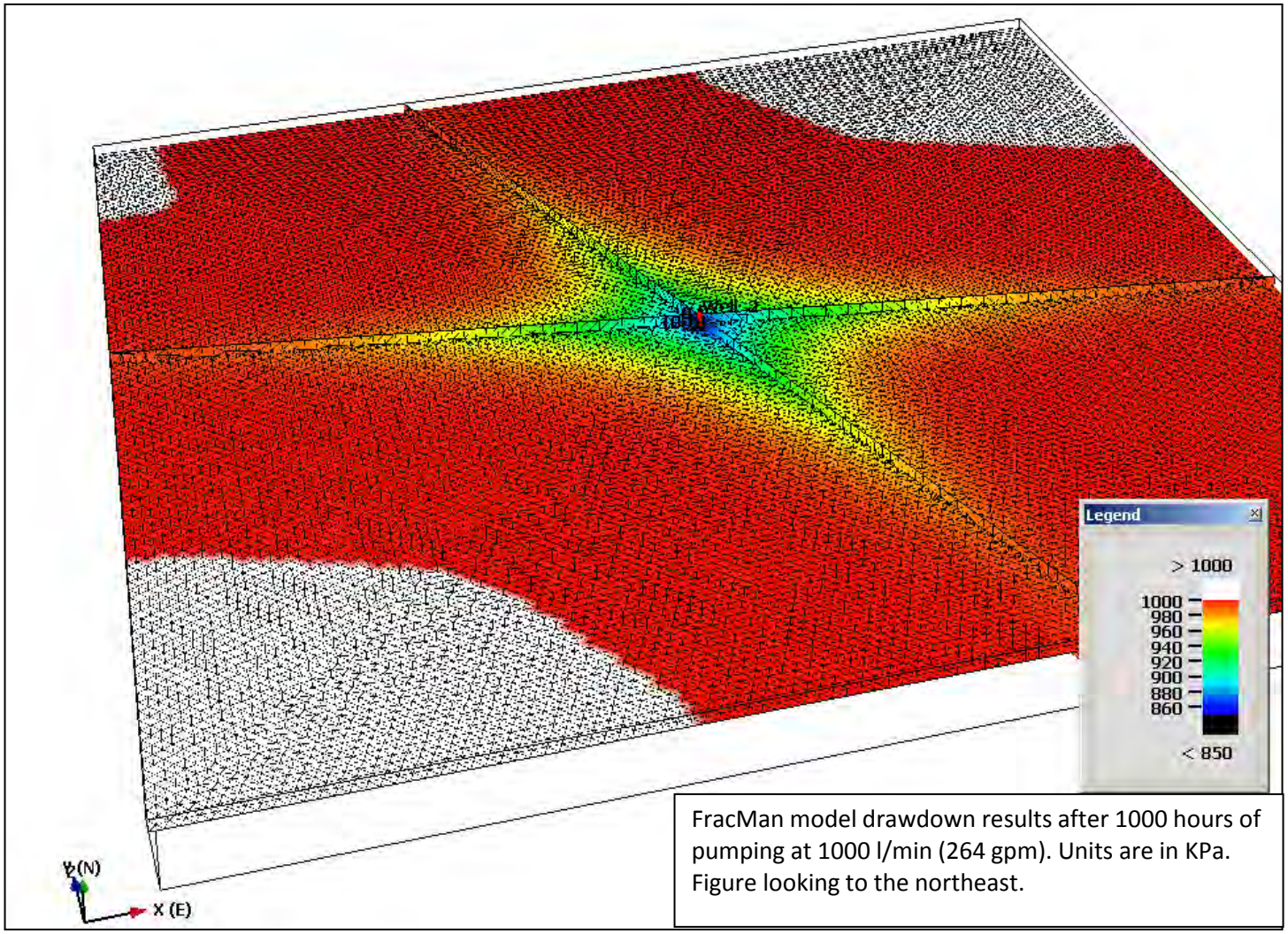

FracMan model drawdown results after 1000 hours of pumping at 1000 l/min (264 gpm). Units are in KPa. Figure looking to the northeast.

Golder Associates	Title: FracMan model results	Drawn	SLH
		Checked	MW
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	Reviewed: PB
	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 13

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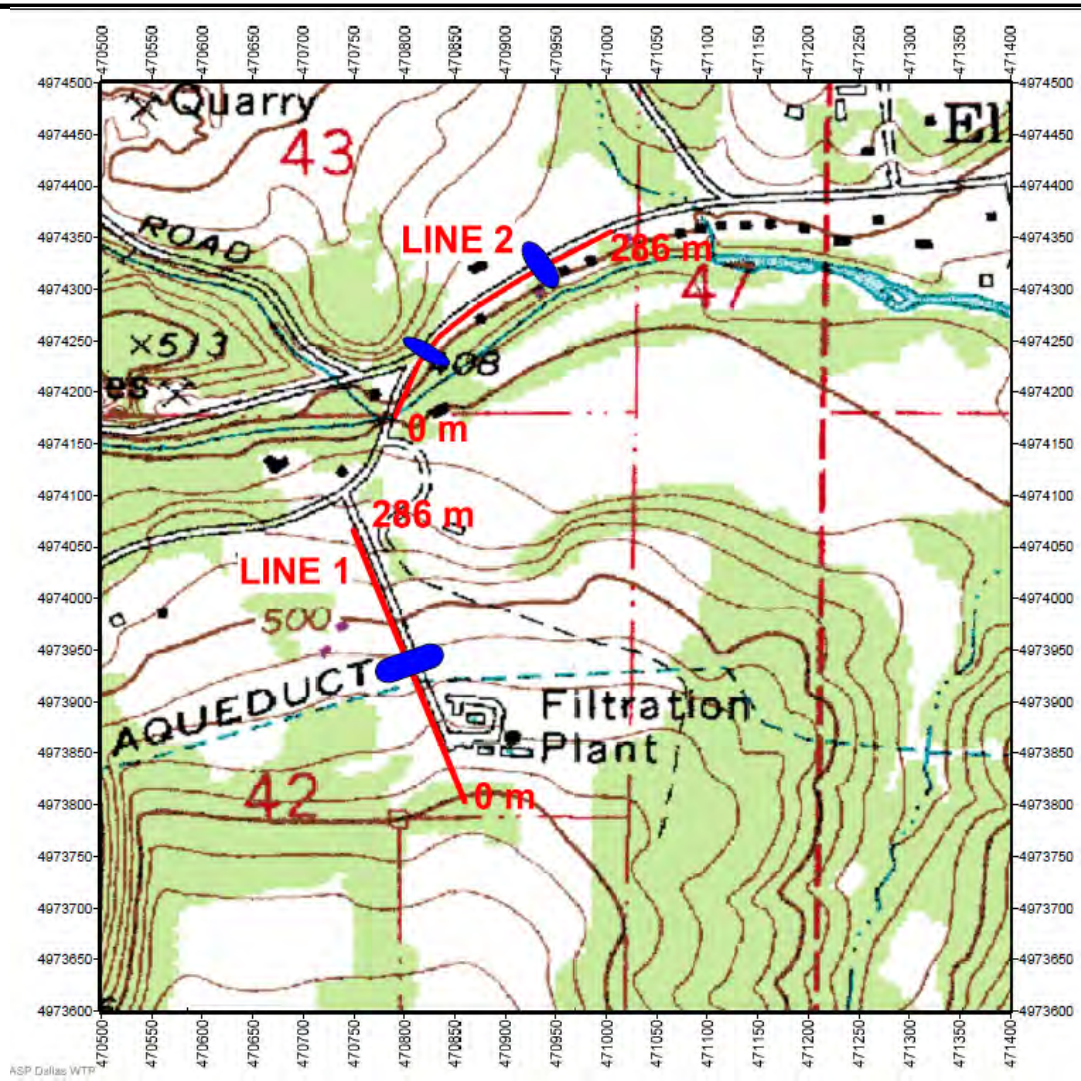

Site Map

Instrumentation

Geometrics Geode 48 Channel Seismograph

PEG-40 Seismic Source

Notes

- Project Location
- Seismic Line
- Interpreted Fault Zones

Horizontal Datum: UTM Zone 10N with NAD83
Vetical Datum: MSL
Base Map: USGS Dallas OR Quadrangle, 1986

0 100 200 meters

N

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FIGURE 2
GEOPHYSICAL RESULTS

Golder Associates	Title: Geophysical survey results		Drawn: SLH
			Checked: MW
	Project Name: Grant Feasibility Study	Project No.: 053-9747.400	Reviewed: PB
	Client Name: City of Dallas	Date: January 5, 2011	FIGURE 14

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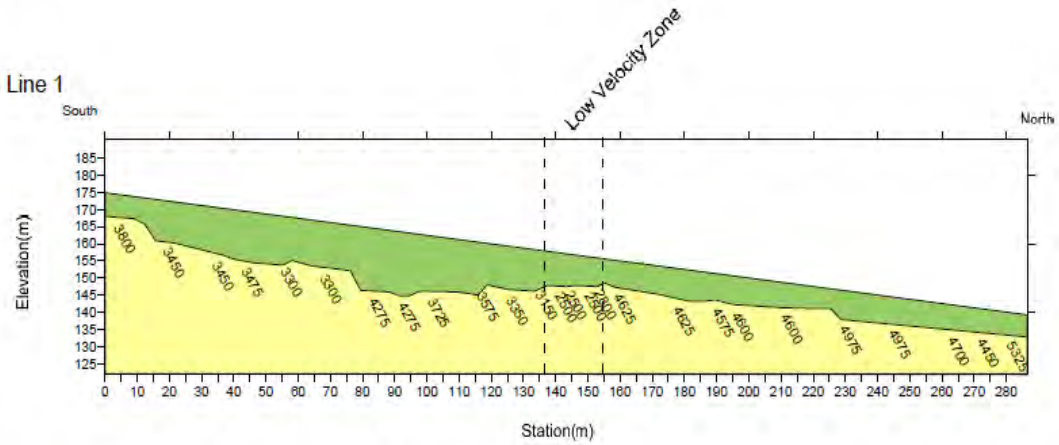

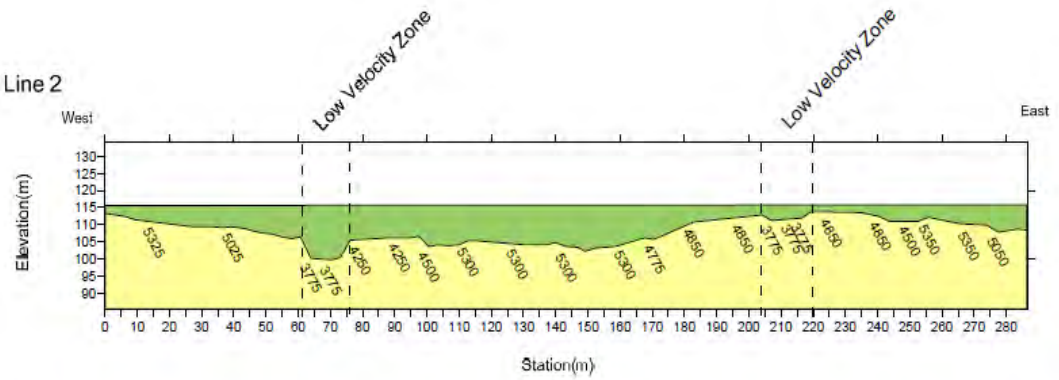

053-9747.400-06 ASR Dallas WTP

Site Map

Instrumentation

Geometrics Geode 48 Channel Seismograph

PEG-40 Seismic Source

Notes

Project Location

Interpreted Bedrock Surface

Calculated Bedrock Velocity

Vetical Datum: MSL

0 30 60

Scale: 1in:30m

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FIGURE 3
SEISMIC REFRACTION RESULTS

Golder Associates	Title: Seismic refraction results	Drawn	SLH
		Checked	MW
	Project Name: Grant Feasibility Study / Project No.: 053-9747.400	Reviewed	PB
	Client Name: City of Dallas / Date: January 5, 2011	FIGURE	15

S:\Projects\2005\053-9747-400_DallasASR\OWRD Grant Work\0839747-400_Dallas Grant Study Reporting\Grant Study Report Apdx A - Task 1 Tech Memo\Apdx A Figures 1-7 and 10-15.xlsx

8.0 ATTACHMENT 1 of Appendix A: GEOPHYSICAL SEISMIC SURVEY

TECHNICAL MEMORANDUM

Date: September 30, 2009 **Project No.:** 053-9747-400.06

To: Mark Wirganowicz **Company:** Golder Associates Inc.

From: Matthew Benson

RE: REPORT ON THE GEOPHYSICAL INVESTIGATION NEAR ELLENDALE ROAD DALLAS, OR

On September 16 and September 17, 2009 a geophysical survey was conducted near the City of Dallas Water Treatment Plant. Seismic refraction and reflection data were collected simultaneously to help determine the presence of potential fault zones in two areas. After processing seismic refraction data it was determined that processing the seismic reflection data would not yield significantly different results.

Figure 1 shows the study area in relation to the City of Dallas, Oregon. Figure 2 presents the geophysical line locations along Ellendale road and the gravel road leading to the water treatment plant. Figure 3 presents the interpreted seismic refraction profiles for each line.

1.0 PROJECT OBJECTIVE

The objective of the geophysical survey was to attempt to determine the presence of suspected fault zones. Seismic refraction was chosen as the primary method to help meet this objective. Seismic refraction is a cost effective method to locate low velocity zones often associated with fault zones. Seismic reflection was chosen as a secondary method if seismic refraction did not meet the objective.

2.0 METHODOLOGY

2.1 Seismic Refraction

Seismic refraction is a method commonly used to determine the compressional velocity and model the depth to bedrock. The method requires a seismic energy source to introduce seismic waves into the subsurface. The seismic waves penetrate the overburden and travel along interfaces where there is an increase in compressional velocity. Typically this is the water table or the top of the bedrock. While the seismic waves are traveling along this surface, they continually transmit seismic waves back to the ground surface where they are detected by geophones. The geophones convert the acoustic energy in the ground to an electric signal that is transmitted by the geophone cable to the seismograph. The seismograph detects the arriving electric signals with respect to time and stores the records digitally for future data processing. The data is processed to determine the compressional velocity of the earth material through which the energy has traveled and to model the subsurface geology. This geophysical model depicts the earth in cross-section showing the velocity and thickness of the subsurface layers below the seismic line.

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Seismic refraction and reflection data were collected using a 48-channel Geometrics GEODE seismograph. The 48 geophones were spaced at 3 meters intervals. A PEG-40 trailer hitch mounted seismic source was used. A minimum of 54 shot points were recorded for each spread, with shot locations beginning at 9 meters off one end of the spread and at consecutive 3 meter intervals to 9 meters off the other end of the spread. Refraction data were processed using the commercially available IXRefraX software.

3.0 RESULTS

3.1 Line 1 - Gravel Road to Water Treatment Plant

The upper panel in Figure 3 shows the interpreted bedrock elevation and velocity profile along the Line 1. Line 1 begins at the intersection of the gravel road and the first residential driveway at the top of the hill. This line is 286 meters long. The overburden velocities range from 675 meters per second (m/s) to 975 m/s, characteristic of unconsolidated sediments. The compressional velocities of the underlying bedrock range from 2,500 m/s to 5,325 m/s.

There is one low velocity zone between Station 136 and 154; seismic velocity values mapped in this area range between 2,500 m/s and 2,800 m/s. This low velocity zone is interpreted as the location of a potential fault zone. Compressional velocities greater than 2,775 m/s are interpreted as representing bedrock, belonging to the Siletz River Volcanics.

3.2 Line 2 - Ellendale Road

Figure 3 shows the interpreted bedrock elevation and velocity profile along the line which began 9 meters from the east side of the bridge along Ellendale Road and continues east along the south edge of the road for 286 meters. The depth to bedrock along this line ranges from 6 to 21 meters below the ground surface. This is deeper than expected based on field observations of a bedrock outcrop located beneath the bridge (approximately 9 meters west of the transect) that is 3 meters below the ground surface. The compressional velocities of the bedrock in this area range from 3,775 m/s to 5,350 m/s.

There are two zones of relatively low seismic velocity on Line 2, between Stations 62 and 76 and between Stations 204 and 220. Seismic velocity values mapped in this area are approximately 3,775 m/s. These low velocity zones are interpreted as the location of potential fault zones. Compressional velocity values greater than 3775 m/s are interpreted as representing bedrock belonging to the Siletz River Volcanics.

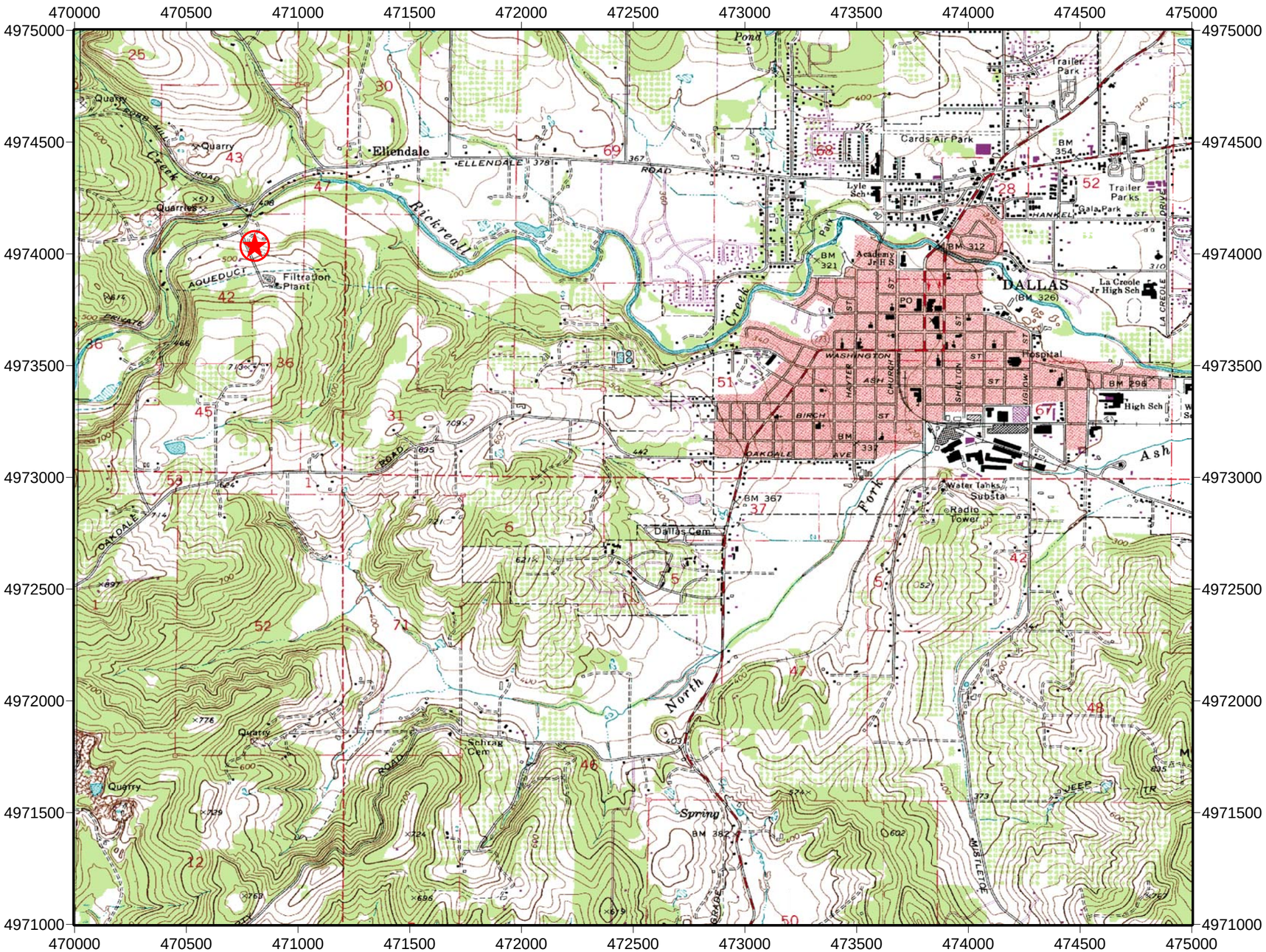
4.0 LIMITATIONS

Golder services are conducted in a manner consistent with the level of care and skill ordinarily exercised by other members of the geophysical community currently practicing under similar conditions subject to the time limits and financial and physical constraints applicable to the services. Seismic refraction is a remote sensing geophysical method that may not detect all changes in stratigraphy, such as zones of low

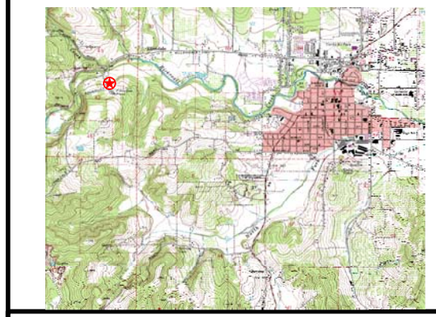
compressional velocities, because of site conditions. Furthermore, it is possible that low compressional velocity anomalies that are interpreted to be fault zones may upon intrusive sampling prove to be misinterpreted.

Attachments: Figures

FIGURES



Site Map



Instrumentation

Geometrics Geode 48 Channel Seismograph

PEG-40 Seismic Source

Notes

⊛ Project Location

Horizontal Datum: UTM Zone 10N with NAD83
Vetical Datum: MSL
Base Map: USGS Dallas OR Quadrangle, 1986

0 500 1000
meters

N

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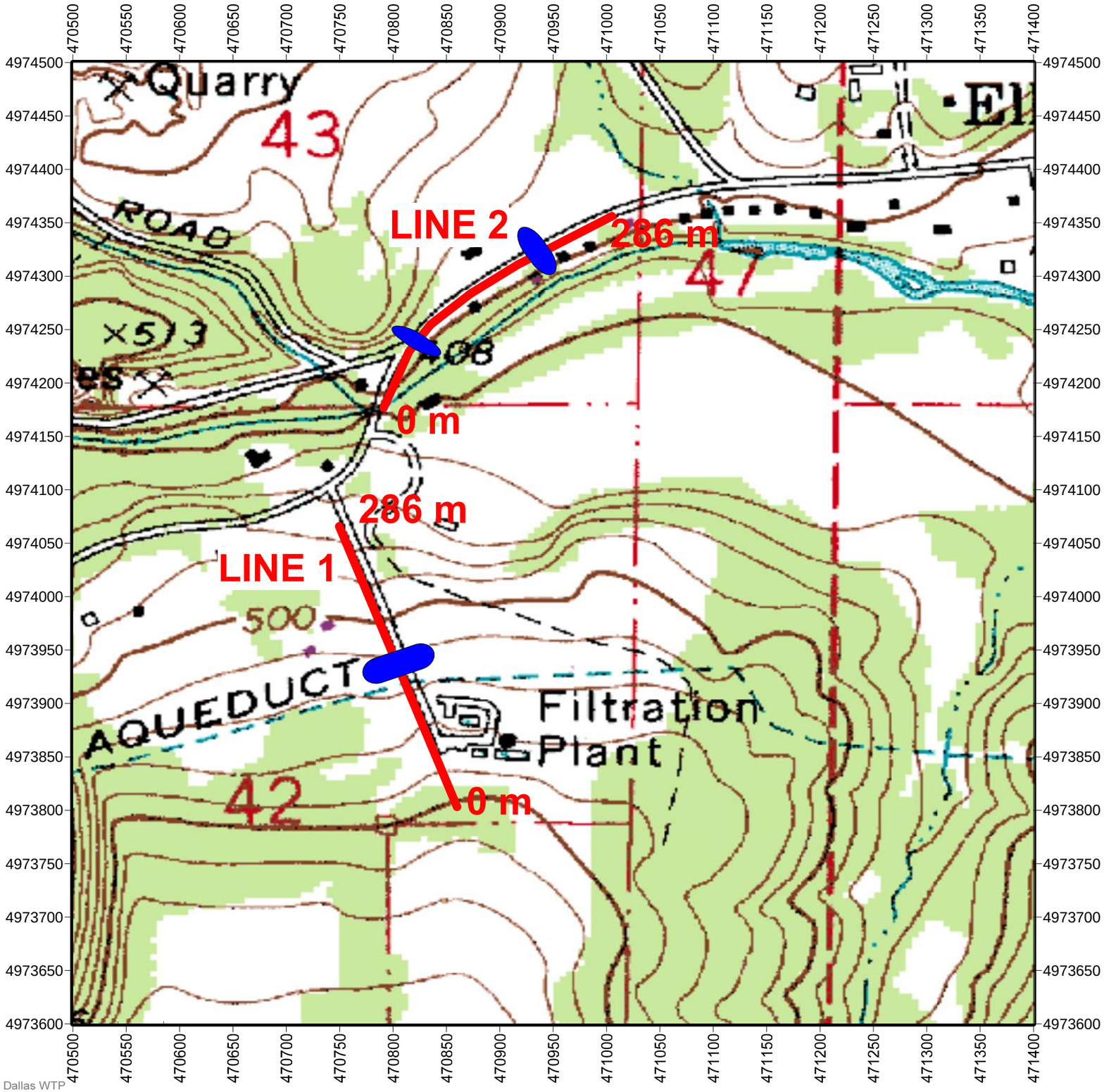
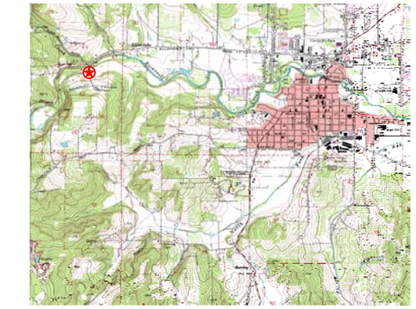
FIGURE 1
PROJECT LOCATION MAP



Site Map



Instrumentation

Geometrics Geode 48 Channel Seismograph

PEG-40 Seismic Source

Notes

Project Location

Seismic Line

Interpreted Fault Zones

Horizontal Datum: UTM Zone 10N with NAD83
Vetical Datum: MSL
Base Map: USGS Dallas OR Quadrangle, 1986

0 100 200
meters

N

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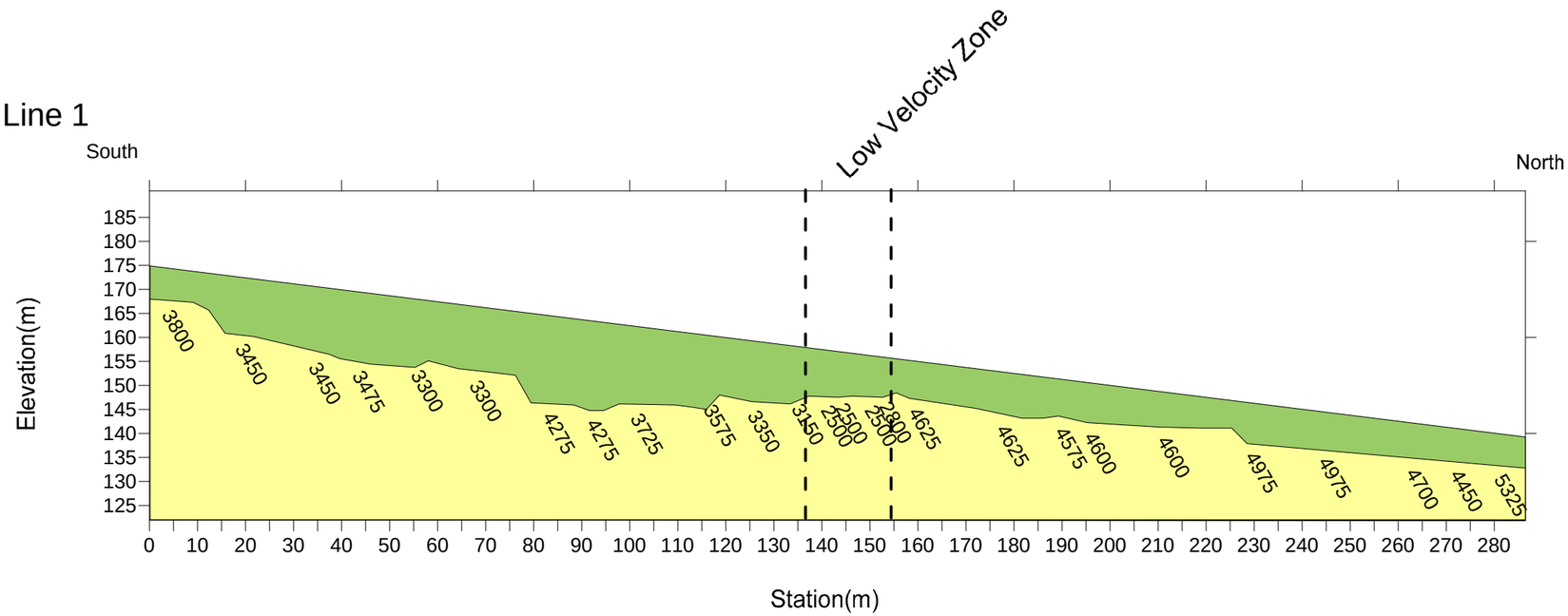
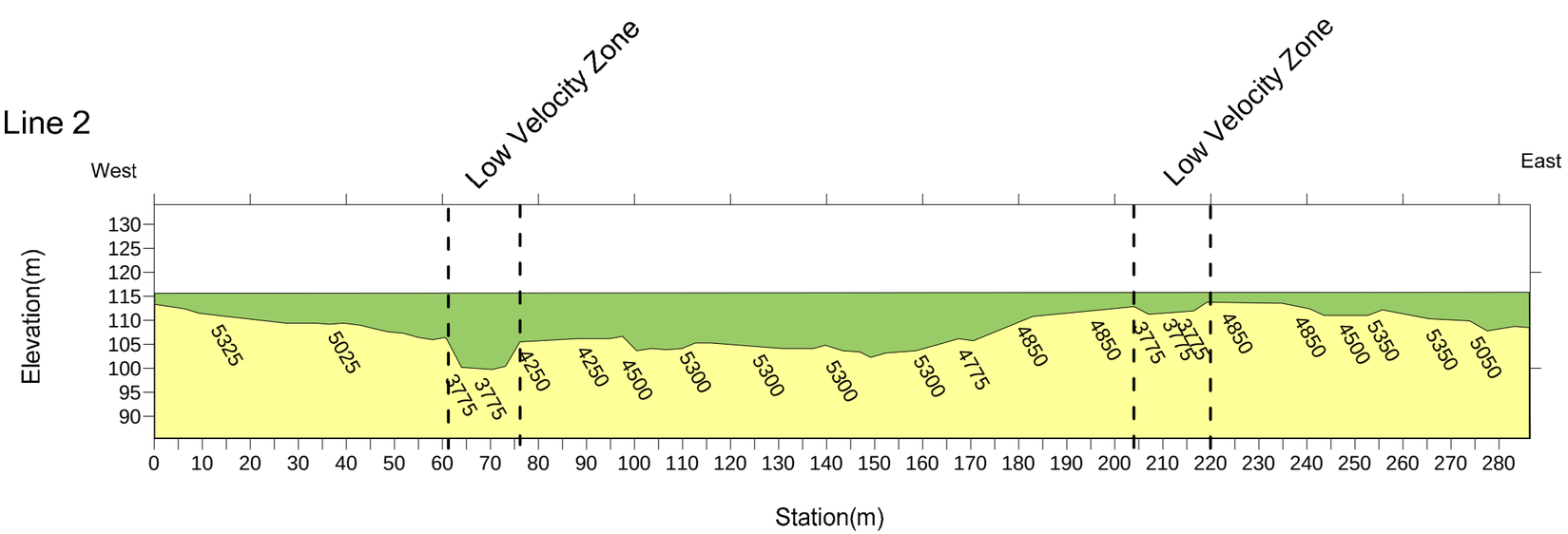
FIGURE 2
GEOPHYSICAL RESULTS

053-9747.400-06 ASP Dallas WTP

Line 1

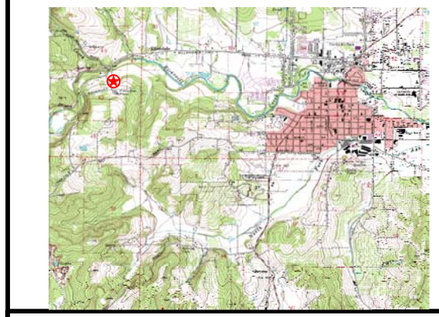


Line 2



053-9747.400-06 ASP Dallas WTP

Site Map



Instrumentation

Geometrics Geode 48 Channel Seismograph

PEG-40 Seismic Source

Notes

Project Location

Interpreted Bedrock Surface

12375 Calculated Bedrock Velocity

Vetical Datum: MSL

0 30 60

Scale: 1in:30m

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Grant Feasibility Study

FIGURE 3
SEISMIC REFRACTION RESULTS

APPENDIX B

TECHNICAL MEMORANDUM
DALLAS ASR OPTIMIZATION AND EXPANSION STUDY
TASK 2 – NUMERICAL MODELING

Technical Memorandum

CITY OF DALLAS

Appendix B

ASR Optimization/Expansion Study: Task 2

Numerical Groundwater Flow and Transport Modeling

Submitted To: Oregon Water Resources Department
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Salem, Oregon 97301

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Distribution: Bob Rice – OWRD
Fred Braun – City of Dallas
Kenn Carter – City of Dallas

September 2010
0539747-400.04

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1.0 INTRODUCTION

This technical memorandum presents the results of numerical groundwater flow and transport modeling performed as Task 2 of the "City of Dallas ASR Optimization/Expansion Study" (the grant study). The grant study was performed in conjunction with the Oregon Water Resources Department (OWRD) Conservation, Reuse, and Storage Grant Program, jointly funded by the City of Dallas (City) and OWRD under state grant number GB0008-09. The overall objectives of the grant study are to gain an improved understanding of the hydrogeologic conditions of the aquifer system at the City's Aquifer Storage and Recovery (ASR) facility, identify candidate locations for additional ASR wells, and assess alternative operational management strategies to optimize recovered water quality and quantity from the City's existing ASR well (named "ASR-1").

Task 2 work focused on meeting the second and third goals of the grant study using a numerical groundwater flow and transport model of the Siletz River Volcanics (SRV) aquifer system in the vicinity of ASR-1. The calibrated model was used to perform forward simulations of various ASR system expansion and optimization scenarios to gain a qualitative understanding of potential improvements to recovered water quality and quantity.

1.1 Numerical Modeling Overview

A groundwater flow and transport model was constructed using the finite-element numerical modeling software, FEFLOW® (Diersh, 1994), and was based on the conceptual model developed in Task 1 of the grant study (see Appendix A). The numerical model was calibrated so that model parameters such as hydraulic conductivity, storage compressibility (specific storage), porosity, dispersivity, and system geometry remained consistent with the conceptual model. Model calibration focused on representing water levels and recovered water quality in the vicinity of ASR-1, and water levels at observation wells. The calibrated model was used as a forecasting tool to qualitatively assess the potential benefits to ASR recovered water quality and quantity that may be realized through addition of a new well to the ASR system and/or changes in operational practices at ASR-1. Task 2 work was conducted in 4 stages:

1. Construct a steady-state groundwater flow model and calibrate the model to match simulated water levels with observed water levels measured at ASR-1 and responding wells in the observation well network. The steady state model output was used to define initial water level conditions for future transient model simulations.

2. Construct a transient groundwater flow model to simulate drawdown and recovery at ASR-1 during the 72-hour pumping test and during the recovery stages of ASR pilot testing Cycles 5 and 7. Refine model calibration to match transient simulation results to observed water level drawdown and recovery at ASR-1 and observation wells during these events.

3. Construct a transient mass transport model to simulate recovered water total dissolved solids (TDS) concentrations at ASR-1 during the recovery stages of Cycles 5 and 7. Refine model calibration to match transient simulation results to observed recovered water TDS concentrations at ASR-1 during these events.

4. Forecast transient recovered water TDS concentrations for several model scenarios incorporating a second ASR well located at three potential sites and alternative ASR operational practices.

1.2 Conceptual Model Background

The conceptual model developed in Task 1 included the following three zones of transmissivity that formed the geometric basis for model construction:

- Zone 1 - a relatively localized high transmissivity zone intersected by the ASR-1 well, interpreted to be a shallow horizontal zone with open fractures extending approximately 1000 to 2000 feet from the well and hydraulically connecting the well to a fault system. Zone 1 is referred to as the "connective layer" within this report.
- Zone 2 – a lower transmissivity zone compared to Zone 1, exhibiting bilinear flow conditions interpreted to result from linear flow through intersecting permeable fault structures which form the main ASR storage zone and many smaller intersecting fracture/fault structures. Zone 2 is referred to as the "fault zone" within this report.
- Zone 3 – the overall SRV basalt formation composed of layered marine volcanic deposits that contribute insignificant storage volume to the ASR system and isolate most neighboring observation wells from pressure responses related to recharge and recovery activities at ASR-1. Zone 3 is referred to as "massive basalt" within this report.

2.0 MODEL CONSTRUCTION

Model construction consisted of the following components, which are described in more detail in the subsections below.

- Geometry and mesh generation and discretization
- Material property delineation and assignment
- Boundary condition delineation
- Initial condition delineation (for transient models)
- Observation point establishment
- Calibration of steady state and transient simulations

2.1 Model Geometry and Finite-Element Mesh Generation

The finite-element numerical model was constructed to represent local hydraulic conditions in the SRV confined aquifer in the vicinity of ASR-1, rather than the surrounding regional groundwater flow system (Figure 1). The model was constructed as a rectangular box-shaped confined aquifer with a flat surface elevation profile. The full model geometry is approximately 60,000 x 40,000 x 568 feet in volume (Figures 2 and 3) to minimize boundary effects on transient simulations, though the practical focus of the model is on a relatively small area in the vicinity of ASR-1.

The numerical model was divided into multiple layers to optimally simulate three dimensional groundwater flow and mass transport related to injection and recovery of municipal source water during ASR operations (Figure 3). The model was initially constructed to represent the aquifer matrix existing from the ground surface to the depth of the productive zone as defined by the dynamic borehole survey

conducted during Cycle 7 recovery (BESST Inc, 2008). However, the model framework was vertically refined to represent the material approximately 150 feet above and below the productive zone of the aquifer to minimize numerical transverse dispersion after mass transport components were added to the model (discussed in further detail in Section 3.3).

A 3-dimensional finite-element mesh (planer series of interconnected triangles) was constructed with mesh nodes located at the corners of each triangle-shaped element. The numerical model solves groundwater flow and mass transport equations at each node and interpolates results across the volume of each element. It is desirable to discretize a mesh to create greater node density in areas of the model that experience relatively large changes in groundwater flow and mass transport processes to improve numerical calculation stability and reduce the distance over which solutions are interpolated. Mesh discretization is accomplished by splitting the triangular elements to increase the number of nodes. The mesh was discretized horizontally at the fault zones and in the vicinity of the ASR-1 pumping well by a factor of 20 (Figure 2). Additional mesh refinement was implemented immediately adjacent to ASR-1 to minimize numerical dispersion using the Peclet number criterion recommended by Anderson and Woessner (2002) and Zheng and Bennett (2002).

2.2 Material Properties

Modeled material properties represent the physical characteristics of the simulated porous medium. Material properties are attributed to the elements and nodes within the model as a series of parameters that allow groundwater flow and mass transport equations to be solved during model simulations. The primary groundwater flow parameters are hydraulic conductivity (K) and specific storage (Ss). The primary mass transport parameters are porosity (n) and dispersivity (D) in the longitudinal and transverse directions with respect to flow. The groundwater flow model was constructed with three hydraulic conductivity zones as defined in the conceptual model developed in Task 1:

- A thin horizontal layer with relatively high conductivity connecting ASR-1 with the fault zones (Zone 1 of the conceptual model)
- Two intersecting fault zones with relatively high conductivity (Zone 2 of the conceptual model)
- A surrounding basalt matrix with relatively low conductivity (Zone 3 of the conceptual model)

The thin zone (10 feet) of high hydraulic conductivity was constructed to represent the ASR-1 production zone identified with the dynamic flow profile conducted in July 2008 (BESST Inc., 2008). This connective layer is conceptualized as a permeable zone within the basalt formation characterized by a series of open interconnected fractures that hydraulically connect ASR-1 with the adjacent fault zones and responding observation wells located along those fault zones. The fault zones were modeled as high hydraulic conductivity zones with a width of approximately 40 feet that propagate throughout the full model thickness of 568 feet. The surrounding basalt matrix was modeled with relatively low hydraulic

conductivity values compared to the fault zones and the connective layer. Figure 4 depicts the geometry of modeled hydraulic conductivity zones.

2.3 Boundary Conditions

Specified (fixed) head and/or flux boundary conditions are necessary to solve the groundwater flow components of a numerical model, while specified concentration boundary conditions are necessary to solve the mass transport components of a numerical model.

2.3.1 Groundwater Flow Boundary Conditions

Fixed head boundary conditions were prescribed along the SW and NE edges of the model to create a groundwater gradient of approximately 0.001 ft/ft to the northeast (Figure 5), consistent with the assumed regional groundwater flow direction and gradient from the Coast Range toward the Willamette Valley. Elevation values for the fixed head boundaries were determined during the calibration process to match simulated and observed heads in responding observation wells in the steady state solution (Section3.1.1).

In addition to the fixed head boundary conditions, a well (prescribed flow) boundary condition was used to simulate pumping and injection at ASR wells during transient simulations (Figure 5). A time-varying step function was used to describe the flow rates at ASR wells according to the time period being simulated or forecast.

2.3.2 Mass Transport Boundary Conditions

A fixed concentration boundary condition was applied to the southwest edge of the model to represent a background total dissolved solids (TDS) concentration of 4190 mg/L based on the initial groundwater sample collected from ASR-1 in 2004 (Golder, 2005). A constant concentration of 83 mg/L based on the average source water TDS concentration was prescribed at ASR wells during simulated injection periods (Figure 5).

2.4 Initial Conditions

Initial parameter conditions based on the conceptual model were assigned throughout the numerical model as a starting point for model calibration. An initial head value of 400 feet was designated for the entire model to generally match observed static water levels in the ASR aquifer. An initial hydraulic conductivity value of 283 ft/day (10^{-3} m/s) was assigned to the modeled fault zones and a value of 57 ft/day (2×10^{-4} m/s) was assigned to the modeled connective layer. The low conductivity matrix was assigned a hydraulic conductivity value of approximately 0.3 ft/day (10^{-6} m/s). A specific storage value of 10^{-4} was assigned for the entire modeled area based on published values for non-compressive fractured rock aquifers (Anderson and Woessner, 2002).

2.5 Observation Points

The Dallas ASR pilot testing observation network is composed of ten observation wells and one piezometer. Two observation wells and the piezometer exhibit water level buildup and drawdown coincident with the injection and pumping phases of ASR operations. The responding observation wells (Lowe, POLK51112 and Presser, POLK56697) and the piezometer are located coincident with two intersecting fault zones defined in the conceptual model developed during Task 1 (Figure 6).

All ten observation wells were incorporated in the model as reference points used for the groundwater flow calibration. The observation points are included in layer 2 of the model, located approximately 100 feet above the ASR-1 production zone and 50 feet below the top of the modeled SRV aquifer (Figure 3) to represent the difference in elevation between the average depth of the responding observation wells and the depth of ASR-1. The piezometer was not used as an observation point for the model because it is screened at a very shallow depth (0.7 to 1.7 ft bgs) and head in the piezometer represents near-surface water levels that were outside the geometric scope of the final model. Therefore, the majority of model calibration focused on the three responsive observation points in the model, which included ASR-1, POLK68036; Lowe, POLK51112; and Presser, POLK56697.

2.6 Steady State and Transient Model Simulations

A steady state numerical groundwater model solution represents an equilibrated groundwater flow system in which water inflow to and outflow from the model are equivalent and there is no change in storage. For this study, the steady state was groundwater flow model was calibrated to match simulated head values with observed head values at ASR-1 and responding observation wells during static water level conditions in the ASR aquifer. The steady state solution was used as the initial model conditions when performing transient model simulations.

Transient numerical groundwater models are run for a defined period of time during which modeled groundwater flow and mass concentration input, output, and storage may vary. For this study, transient models were created to simulate the following discrete events:

- 2004 pumping test – pumping over a 72-hr time period (Golder, 2005)
- Cycle 5 ASR pilot test – injection (recharge), storage, and pumping (recovery) over approximately 3 months (Golder, 2007)
- Cycle 6 ASR pilot test – injection (recharge), storage, and pumping (recovery) over approximately 11 months (Golder, 2008)
- Cycle 7 ASR pilot test – injection (recharge), storage, and pumping (recovery) over approximately 8 months (Golder, 2009)
- ASR forecasting simulations

Once the initial steady state model and transient simulations of pumping and pilot testing events produced an acceptably calibrated model, ASR forecasting simulations were run to evaluate several scenarios

involving the addition of new wells to the ASR system and alternative single well ASR recharge-storage-recovery programs.

3.0 MODEL CALIBRATION

Calibration of the numerical model was conducted using several steady state and transient groundwater flow and mass transport simulations. Model calibration was iterative: parameter inputs were first roughly calibrated to simulate simple scenarios involving short time periods with a single model perturbation (e.g., only pumping at ASR-1 for 72 hours) and then were further refined until more complex scenarios involving successively longer time periods and/or several perturbations (e.g., injection, storage, and recovery at ASR-1 over an 8 month pilot testing cycle) could be accurately simulated. A manual calibration method was used in order to ensure parameters assigned to the conductive layer, fault zones, and basalt matrix were within previously measured and/or published parameter value ranges.

3.1 Groundwater Flow Model Calibration

The original groundwater flow model included seven layers designed to represent subsurface basalt material from the top of the SRV to the depth of the productive zone intersected by the ASR-1 well (Figure 3). The following parameters were manually adjusted during calibration to match simulated head values with observed head values at the three responsive observation points (ASR-1, POLK68036; Lowe, POLK51112; and Presser, POLK56697):

- Fixed head boundary condition values
- Hydraulic conductivity of the three defined zones (conductive layer, fault zones, and basalt matrix)
- Thickness of the conductive layer
- Specific storage of the three defined zones

3.1.1 Steady State Model Calibration Results

The fixed head boundary conditions were adjusted during calibration of the steady state model to match simulated with observed static water level values at the three responsive observation points. Calibration was conducted using pre-pilot testing static water level measurements collected during the spring of 2006. The final specified head values of 430 feet along the southwest edge of the model and 390 feet along the northeast edge of the model resulted in an appropriate hydraulic gradient across the model domain of approximately 0.001 ft/ft to the NE (Table 1 and Figure 7).

The initial hydraulic conductivity parameter inputs resulted in an average unit flux across the steady state model of approximately 3.94 in/yr (0.105 m/yr). There was not sufficient field data to estimate average Darcy flux through the SRV in the vicinity of Dallas and therefore to calibrate hydraulic conductivity values in the steady state model. However, the modeled unit flux resulting from the initial hydraulic conductivity parameters represents a realistic condition that may occur if 7% of the average annual rainfall in the adjacent coast range (60 in/yr as measured at the Rockhouse station, located in the coast range

approximately 5 miles SW of the site) were to infiltrate to this depth in the SRV aquifer system and drive flow through the study area toward the regional discharge zone at the Willamette River. Given the low vertical permeability away from fault zones, this seems a reasonable parameter estimation.

3.1.2 Transient Groundwater Flow Model Calibration

The equilibrated hydraulic head field defined by the calibrated steady state groundwater flow model was used as the initial head condition for the transient model. Two transient flow simulations were conducted during which hydraulic parameters were adjusted to match simulated with observed drawdown and buildup water levels at the three responding observation points, as well as the lack of water level response in the remaining observation wells.

3.1.2.1 2004 Constant-Rate Pumping Test Calibration Results

The first transient groundwater flow model was constructed to simulate the September 2004 pumping test conducted at a constant rate of 291 gpm (1586 m^3/day) for 72 hours. The hydraulic conductivity of the three defined zones and the thickness of the connective layer were adjusted to roughly match simulated drawdown to observed drawdown at the end of the 72-hour pumping test at the three responding observation points (ASR-1, Lowe, and Presser wells). Model parameters used for a subset of the calibration simulations are presented in Table 2.

The observed drawdown in ASR-1 was adjusted to represent head conditions in the aquifer near the ASR assuming a theoretical well efficiency of 25%. The theoretical well efficiency was calculated using two methods presented by Driscoll (1986) to estimate otherwise un-modeled head loss that occurs during pumping and injection at the well-aquifer interface.

Initial calibration of the model resulted in a reasonable match between simulated and observed drawdown at ASR-1 (2.86% difference), but drawdown at the Lowe and Presser wells was under-predicted by the model (differences of 56.7% and 76%, respectively). The under-prediction of drawdown response at relatively large distance from ASR-1 may be due to the simplified fractured aquifer geometry used in the model and/or un-modeled aquifer heterogeneity. It is possible to calibrate the model to better represent observation well response at the expense of accuracy near the ASR well. Because the primary objective is to evaluate system expansion alternatives and effects, the near-field response was prioritized during calibration.

The final calibrated hydraulic conductivity values for the connective layer, fault zones, and basalt matrix were 142 ft/day (5 X 10^{-4} m/s), 283 ft/day (10^{-3} m/s), and 2.83 X 10^{-4} ft/day (10^{-9} m/s), respectively. Final hydraulic conductivity values for the highly fractured zone and the fault zones were similar to initial values. The hydraulic conductivity of the basalt matrix was reduced to eliminate significant drawdown in the non-responding observation wells, and remains consistent with published values for unfractured igneous rocks (Freeze and Cherry, 1979). The calibrated thickness of the connective layer was increased to 12 feet,

remaining consistent with the thickness of the productive zone identified during the dynamic borehole survey (BESST Inc., 2008).

3.1.2.2 Cycle 5 Pilot Test Calibration Results

The Cycle 5 ASR pilot test simulation was used to refine the model calibration given longer stress periods and the hydraulic effects of buildup during the injection period. The Cycle 5 pilot test was the first large scale ASR cycle, consisting of injection for 70 days at an average rate of 168 gpm (916 m^3/day), storage for 45 minutes, and recovery for 11 days at an average rate of 242 gpm (1319 m^3/day). Model calibration focused on adjusting hydraulic conductivity and specific storage parameters to match buildup water levels at the end of the recharge period, though the model simulated the full cycle to confirm that the final model solution after the recovery period reasonably approximated observed conditions. Model parameters used for a subset of the calibration simulations are presented in Table 3.

The hydraulic conductivity, thickness of the connective layer, and specific storage model parameters were refined to match simulated to observed buildup data at the end of the injection period for the three responding observation sites. Observed buildup values for the ASR-1 well were adjusted based on a theoretical well efficiency of 25%. An average buildup value corresponding to the average injection rate was referenced for calibration of the model due to the variability of injection rates and observed water levels during the Cycle 5 injection period.

Refined calibration of the model resulted in simulated buildup values matching the observed buildup at ASR-1 at the end of the simulated Cycle 5 recharge period and in general over the course of the full simulation (Figure 8). The difference between simulated and observed water level buildup at the Lowe and Presser observation points did not improve, with buildup under-predicted by 10.2 and 9.2 feet at the two wells, respectively. Although the magnitude of the response observed relatively far from ASR-1 at the Lowe and Presser wells was not precisely matched in magnitude, the model does simulate the general water level response pattern observed at those wells due to ASR operations (Figures 9 and 10). The fracture system complexity over prevents discrete representation of connectivity and penetration over significant distance from the tested well.

The final calibrated hydraulic conductivity value for the fault zones and connective layer was 142 ft/day (4.5×10^{-4} m/s). The calibrated hydraulic conductivity of the basalt matrix and the thickness of the connective layer remained unchanged from the results of the 72-hr pumping test calibration. Decreasing modeled specific storage resulted in an improved match between simulated and observed buildup values at the Lowe and Presser observation points, but also resulted in buildup at the non-responding observation points and increased buildup at ASR-1, so the specific storage also remained unchanged.

3.2 Mass Transport Model Calibration

Three transient mass transport model scenarios were developed to simulate the fate and transport of fresh water recharged to the SRV aquifer during ASR pilot testing cycles 5, 6, and 7. Model calibration focused on matching simulated total dissolved solids (TDS) concentrations in recovered water at ASR-1 to observed concentrations during ASR pilot testing cycles. The Cycle 5 simulation was used to determine the sensitivity of recovered water TDS to several model parameters and to develop an initial calibrated mass transport model. The Cycle 7 simulation was used to refine the mass transport model calibration with a focus on adjusting the highly sensitive dispersivity parameter.

3.2.1 Mass Transport Model Parameters

The following additional parameters were added to the calibrated groundwater flow model to simulate mass transport:

- Initial TDS concentrations throughout the model
- TDS concentration boundary conditions at model inflow zones, including a constant concentration boundary along the upgradient side of the model and concentration step-functions at ASR wells to simulate injection of low-TDS treated drinking water during recharge
- Dispersivity and porosity parameters associated with each conductivity zone

The TDS concentration of native groundwater (4190 mg/L) was assigned to all model nodes as initial conditions and designated at the fixed head boundary along the up-gradient side (southwest edge) of the model. The native groundwater TDS concentration was obtained from lab analysis of groundwater samples collected during the initial ASR-1 pumping test conducted in 2004. The TDS concentration of ASR source water (83 mg/L) was designated at the ASR-1 well node during injection periods. The source water TDS concentration was obtained from lab analysis of injected treated water during Cycle 5. All source water TDS concentrations have been reported to be generally between 60 and 100 mg/L during ASR pilot testing operations and the value of 83 mg/L was considered representative for all recharge phases.

Additional model parameters governing mass transport included effective porosity and dispersivity (longitudinal and transverse). The fractured connective layer and fault zones were assigned a porosity value of 0.15, while the massive basalt matrix was assigned a porosity value of 0.025 (Domenico and Schwartz, 1990). Initial dispersivity values were assigned model default values of 16.4 feet (5 meters) for the longitudinal dispersivity and 1.64 feet (0.5 meters) for the transverse dispersivity to serve as a starting point for calibration.

3.2.2 Model Framework Design Evolution

During the transient mass transport model calibration process, the original model framework (described in Section 2.1, above) was modified to limit vertical numerical dispersion in mass transport simulations. The

revised model framework included definition of additional model layers below the connective layer and further vertical discretization of layers centered on the connective layer (Figure 11). The addition of model layers to the bottom of the model domain and further vertical discretization did not impact groundwater flow solutions (simulated head values) as the boundary conditions, material properties, and geometry of the connective layer and the fault zones remained unchanged.

3.2.3 Cycle 5 Pilot Test Model Calibration Results

The Cycle 5 simulation was used to perform a sensitivity analysis of several parameters to determine their effect on simulated values of recovered water TDS concentrations. Final recovered water TDS proved to be sensitive to dispersivity, and insensitive to the remaining parameters, including hydraulic conductivity, thickness of the connective layer, specific storage, modeled gradient, and porosity. Table 4 and Figure 12 show a subset of the sensitivity analysis simulation results. Simulated water levels at the three responding observation wells remained sensitive to changes in groundwater flow parameters (hydraulic conductivity, thickness of the connective layer, and specific storage), so these parameters remained fixed throughout the remainder of the mass transport simulation calibration process.

Adjustments to model dispersivity resulted in a match between simulated and observed final TDS concentrations at only one point in time during the Cycle 5 simulation. The remainder of the simulated TDS concentration time series curve did not match corresponding observed TDS concentrations (Figure 12). Spatial discritization of dispersivity was found to be necessary to match simulated TDS concentration time series curves with observed time series curves.

To allow better predictions of water quality response, two zones of dispersivity were created in the horizontal connective layer of the Cycle 5 model. A low dispersivity area was designated near the pumping well to represent the high conductivity zone existing in the vicinity of ASR-1 as a region with low hydrodynamic dispersion potential. A higher dispersivity zone was established in the remainder of the layer to represent greater hydrodynamic dispersion as injected fresh water encountered larger areas of the aquifer. Adjustment of the two dispersivity values and the radius of the low dispersivity zone produced a good match between simulated and observed TDS concentrations over the full time series (Table 5 and Figure 13). The calibrated longitudinal dispersivity for the low-dispersivity zone around the well is 33 feet (10 meters) with a radius of approximately 197 feet (60 meters) (Figure 14). The calibrated longitudinal dispersivity for the surrounding conductive zones (faults and connective layer) is 656 feet (200 meters). The distribution of the freshwater plume within the connective layer at the end of the simulated Cycle 5 recovery period is shown in Figure 15.

3.2.4 Cycle 7 Pilot Test Model Calibration Results

The final solution of the calibrated Cycle 5 pilot test model was used as the initial conditions for the Cycle 6 pilot test simulation. Because of the erratic recovery schedule during the Cycle 6 pilot test, further calibration was not conducted with the Cycle 6 simulation. Cycle 6 pilot test simulation results were used

as the initial conditions for the Cycle 7 pilot test simulation to maintain a consistent representation of water quality within the aquifer as the City's ASR program progressed.

The Cycle 7 ASR pilot test schedule consisted of aquifer recharge at a rate of 165 gpm for 203 days, storage for three days, and recovery at a rate of 250 gpm for 20 days followed by further recovery at a lower rate of 200 gpm for 20 days. Observed water level buildup in ASR-1 during Cycle 7 was 17% less than that observed in Cycle 5 given the same injection rates. This improvement in well specific capacity is hypothesized to result from near-well conditioning of the system over successive ASR cycles (Golder, 2008). In order to simulate this change in near-well aquifer conditions with successive ASR cycles, the modeled well efficiency was assumed to increase from 25% during Cycle 5 to 32% during Cycle 7.

Further calibration during the Cycle 7 pilot test simulation was conducted to refine the values and spatial distribution of the dispersivity zones to simulate recovered water TDS concentrations as closely as possible over a full-scale ASR cycle. An additional zone of moderate dispersivity was added to the model in order to match simulated and observed recovered water TDS concentrations over the longer recovery period experienced during Cycle 7. Table 6 and Figure 16 show a subset of the dispersivity calibration simulation results. The best fit simulated TDS recovery values were obtained by increasing the radius of the low dispersivity zone to approximately 105 meters, assigning a moderate dispersivity value of 590 feet (180 meters) in an intermediate zone with an external radius of 140 meters, and increasing the background dispersivity to 1,312 feet (400 meters) throughout the remainder of the connective layer (Figure 17). The final simulated recovered water TDS concentrations (Run 5, Figure 16) match observed values for the first 30 days of pumping, but underestimate observed TDS concentrations at later times.

Further calibration efforts did not narrow the gap between simulated and observed recovered water TDS concentrations at late times and model calibration was terminated at this point. The final calibrated Cycle 7 model simulates groundwater flow and mass transport processes in the SRV aquifer near ASR-1 during full-scale ASR pilot testing activities through approximately 2/3 of the final recovery phase, after which it under-predicts recovered water TDS concentrations. The model is sufficiently representative that comparisons of additional well locations and operations changes are suitable for planning purposes. Sufficient uncertainty and complexity in fracture network geometry is obviously present, and the model should not be used to predict a specific concentration at a specific time at any location. The simulated distribution of the freshwater plume within the connective layer at the end of the simulated Cycle 7 recovery period is shown in Figure 18.

4.0 MODEL FORECASTING ANALYSIS

The final conditions of the calibrated Cycle 7 numerical model were used as initial conditions in a series of forecasting models developed to qualitatively evaluate potential improvements in ASR system recovery (increased quantity and/or improved quality) that may be realized if a second ASR well was added to the system and/or potentially resulting from alternative ASR cycle rate and duration management strategies.

Forecasting simulation results were evaluated with respect to relative improvements in combined (two-well) system recovered water quality and quantity as compared to that obtained from a baseline single-well ASR system operated under typical conditions. The forecasting results are intended to aid in the selection of an appropriate location for installation of an additional ASR well and/or implementing alternative management strategies by providing a general representation of possible improvements to the ASR program. Forecasting model results are not meant to determine the exact location or operational characteristics of a new well.

4.1 Additional ASR Well Locations

Three new well locations were selected for forecasting analysis with input from the City. New wells were located within or near the Water Treatment Plant site to maintain proximity to existing ASR infrastructure, near the conceptualized locations of the permeable fault zones to increase potential aquifer storage capacity, and at least 100 feet from property lines to satisfy Department of Health (DOH) setback requirements. The three new well locations are described below and shown in Figure 19.

- **ASR-2** is located near the intersection of the two conceptualized fault zones west of the Water Treatment Plant site boundary
- **ASR-3** is located within the Water Treatment Plant site boundary on the northern side of the property
- **ASR-4** is located near the fault trending along northern boundary of the Water Treatment Plant site

New ASR wells were assumed to have the same physical properties and engineering components as ASR-1. Additional well boundary conditions (specified flow) were applied at a mesh node for each of the three new well location scenarios at the same depth as the ASR-1 well (Figure 19). The model mesh was discretized for each new well using the same methods that were applied to the ASR-1 well. A constant concentration boundary was specified during injection at each new well and the same calibrated dispersivity zones developed during the Cycle 7 simulation for ASR-1 were applied around each new well scenario to maintain consistency in simulated recovered water TDS concentrations.

Available water level buildup and drawdown were calculated at each new ASR well location assuming a static water level elevation of 410 feet based on average measured static water levels in ASR-1. Available drawdown was based on the distance between the static water level elevation and the pump intake elevation. Available buildup was based on the distance between the static water level elevation and the land surface elevation at the location of each new well. Because the model simulates water level buildup and drawdown within the aquifer adjacent to the well, as opposed to within the well itself, a well efficiency factor of 32% was applied to available drawdown values based on the calibrated Cycle 7 model results. The well efficiency correction factor limits the available drawdown at each ASR well, but does not limit available buildup as injection can be performed under pressurized conditions in the well bore as long as the piezometric surface in the aquifer remains safely below the land surface elevation.

4.2 ASR Operational Management Scenarios

Forecasting model simulations were performed to evaluate the potential improvements to recovered water quality and quantity (or tradeoffs between the two) given four ASR operational management scenarios that were applied to both wells in the model.

- **Scenario 1** (the baseline scenario) simulates a typical ASR cycle consisting of injection at a rate of 165 gpm (900 m^3/day) for 200 days, storage for 3 days, and recovery at a rate of 250 gpm (1360 m^3/day) for 50 days at each well. Scenario 1 results in a recharge volume of 47.5 million gallons and a recovered volume of 18 million gallons, recovering approximately 38% of the water injected annually at the well.
- **Scenario 2** simulates an alternative ASR management time schedule intended to maximize recovered water quality by simulating recharge for two years with a single recovery period at the end of the second year. Injection during the two recharge periods occurs at a rate of 165 gpm (900 m^3/day) for 200 days separated by a 165 day storage period. The second recharge period is followed by a 3 day storage period and recovery at a rate of 250 gpm (1360 m^3/day) for 50 days. Scenario 2 results in a recharge volume of 190 million gallons and a recovered volume of 36 million gallons, recovering approximately 19% of the water injected annually at the well.
- **Scenario 3** simulates an alternative ASR management rate schedule intended to maximize system efficiency with respect to the volume of water recovered as a percentage of the volume injected, while also maximizing the total volume of water injected and recovered. The ASR cycle recharge, storage, and recovery periods occur over the same time scales specified in Scenario 1, but injection rates were maximized within the limits of available buildup and recovery rates were adjusted within the limits of available drawdown during each simulation to obtain a 50% recovery efficiency and the maximum volume of recovered water at the well.
- **Scenario 4** simulates the potential for long term improvement in recovered water quality over five successive typical ASR cycles. Each cycle is conducted according to the Scenario 1 rate and time schedule, with a 165 day rest period between each recovery and injection cycle.

Forecasting simulation results were evaluated with respect to relative improvements in combined (two-well) system recovered water quality and quantity as compared to that obtained from a baseline single-well ASR system operated under typical conditions (Scenario 1). Model parameters used in the baseline and forecasting scenarios and qualitative comparisons of simulation results are presented in Table 7.

4.3 Baseline Single-Well Forecasting Simulations

Baseline forecasting simulations were conducted to determine the background performance of a single-well ASR system operated under typical conditions (Scenario 1), as well as under an alternative operational management condition intended to maximize recovered water quality (Scenario 2). The two operational scenarios are described in Section 4.2 and detailed in Table 7. The results for each baseline single-well forecasting simulation are presented in Table 8 and described in the following subsections.

4.3.1 Scenario #1

The ASR-1 baseline simulation results formed the reference against which all subsequent simulations were compared (this scenario is termed “the baseline simulation” in the following sections). Recovered

water quality modeled during the baseline simulation indicates a modest improvement in recovered water quality (slightly lower TDS concentration) compared to that modeled during the Cycle 7 simulation (Figure 20), as may be expected with continued conditioning of the SRV aquifer due to freshwater recharge.

Single-well baseline simulations were also conducted for each new ASR well location to evaluate potential water level buildup and drawdown resulting from injection and pumping cycles at those wells in the absence of hydraulic interference from ASR-1. Buildup and drawdown values resulting from these simulations (Table 8) were used to comparatively evaluate the potential hydraulic interference between two ASR wells operating simultaneously during dual-well simulations.

4.3.2 Scenario #2

An ASR-1 single-well scenario #2 simulation was conducted to evaluate potential improvements in recovered water quality based on the development of a larger freshwater storage zone in the SRV aquifer. Forecasting simulation results for two consecutive recharge phases followed by a single recovery phase indicated a 15% improvement in TDS concentration compared to the baseline results (Figure 20). These results suggest that freshwater recharged during the previous year can be recovered the following year to improved recovered water quality, at the expense of recovering only 18% of the recharged volume (Table 8).

4.4 ASR-2 Forecasting Simulations

Forecasting simulations were conducted with a two-well ASR system composed of ASR-1 and ASR-2 using all four operational management scenarios described in Section 4.2 and detailed in Table 7. ASR-2 is located east of the Water Treatment Plant property boundary near the intersection of the two hypothesized fault zones (Figure 19).

The quality and quantity of water recovered from the combined system were evaluated for all scenarios, while hydraulic interference between the two ASR wells was evaluated for scenario #1 only. Results for each forecasting simulation are presented in Table 8 and described in the following subsections. Improvements in recovered water quality during all simulations occur due to an assumed increase in the rate of aquifer conditioning in the connective layer between the ASR-1 and ASR-2, as well as due to the proximity of ASR-2 to the fault structures hypothesized to be the main source of storage for the system.

4.4.1 Scenario #1

Scenario #1 simulates two ASR wells each injecting and pumping at baseline rates and durations, effectively doubling the injected and pumped volume of the ASR system for a total recovered volume of 36 MG, equal to a recovery rate of 0.72 MGD (see Table 7 for scenario parameters). Operating ASR-1 and ASR-2 simultaneously in a two-well ASR system resulted in a 21% improvement (decrease) in final recovered water TDS concentrations as compared to the baseline simulation (Figure 21, Table 8). Operating two wells simultaneously resulted in less than 10 feet of additional buildup and drawdown in the

two wells due to hydraulic interference, and did not result in excessive drawdown (below the pump intake).

4.4.2 Scenario #2

Scenario #2 simulates potential improvements in recovered water quality based on the development of a larger freshwater storage zone in the SRV aquifer (see Table 7 for scenario parameters). Senario #2 forecast results indicate a 43% improvement in final recovered water TDS concentration as compared to the single-well baseline simulation (Figure 21, Table 8), and a 32% improvement compared to the single-well scenario #2 simulation. This improvement in recovered water quality is balanced by a reduced percent recovery of injected water (19%) and the restriction of recovering water every other year.

4.4.3 Scenario #3

Scenario #3 simulates potential improvements in recovered water quantity obtained by adjusting injection and pumping rates at both ASR wells to recover 50% of recharged water at the end of an ASR cycle (see Table 7 for scenario parameters). ASR injection rates were maximized at 174 gpm and 137 gpm for ASR-1 and ASR-2, respectively, assuming an injection specific capacity of 1 gpm/ft and available buildup in the wells keeping water levels 5 feet below ground surface.

Recovered water TDS concentrations resulting from the scenario #3 simulation indicate a modest improvement over baseline conditions (Figure 21, Table 8) with a 10% improvement in final recovered water quality. However, the recovered volume of water from scenario #3 is increased to 45 MG , equivalent to a daily recovery rate of 0.90 MGD over the simulated 50 day recovery period, a 25% improvement over scenario 1.

4.4.4 Scenario #4

Scenario #4 simulates the potential for long term improvement in recovered water quality over five successive typical ASR cycles with a two-well system utilizing ASR-1 and ASR-2 (see Table 7 for scenario parameters). The magnitude of annual improvements in recovered water quality are forecasted to decrease with successive years, as experienced for the existing single-well system over the first three years of full-scale pilot testing (Table 8 and Figure 22). Relatively large year to year improvements in recovered water quality during scenario #4, as compared to observed improvements in the single well system, may occur due to an increase in the rate of aquifer conditioning in the connective layer between the ASR-1 and ASR-2, in addition to the benefit of placing ASR-2 closer to the fault structures hypothesized to be the main source of storage for the system.

4.5 ASR-3 Forecasting Simulations

Forecasting simulations were conducted with a two-well ASR system composed of ASR-1 and ASR-3 using operational management scenarios 1 through 3 as described in Section 4.2 and detailed in Table 7.

ASR-3 is located within the Water Treatment Plant property boundary to the northwest of the existing ASR-1 well (Figure 23).

The quality and quantity of water recovered from the combined system were evaluated for all modeled scenarios, while hydraulic interference between the two ASR wells was evaluated for scenario #1 only. Results for each forecasting simulation are presented in Table 8 and described in the following subsections. Improvements in recovered water quality during all simulations are occur due to an assumed increase in the rate of aquifer conditioning in the connective layer between the ASR-1 and ASR-3, as well as due to the proximity of ASR-3 to the fault structures hypothesized to be the main source of storage for the system.

4.5.1 Scenario #1

Operating ASR-1 and ASR-3 simultaneously in a two-well ASR system resulted in a modeled 13% improvement in final recovered water TDS concentrations as compared to the baseline simulation (Figure 23, Table 8). The magnitude of recovered water quality improvement was less than that obtained from a two-well system utilizing ASR-2, likely because of the greater distance between ASR-3 and the two fault zones. Operating two wells simultaneously resulted in less than 10 feet of additional buildup and drawdown in the two wells due to hydraulic interference, and did not result in excessive drawdown (below the pump intake).

4.5.2 Scenario #2

Operating ASR-1 and ASR-3 simultaneously with the scenario #2 forecasting model (see Table 7 for scenario parameters) resulted in a 36% improvement in final recovered water TDS concentration as compared to the single-well baseline simulation (Figure 23, Table 8), and a 25% improvement compared to the single-well scenario #2 simulation. This improvement in recovered water quality is balanced by a reduced percent recovery of injected water (19%) and the restriction of recovering water every other year.

4.5.3 Scenario #3

Operating ASR-1 and ASR-3 simultaneously with the scenario #3 forecasting model (see Table 7 for scenario parameters) resulted in injection rates maximized at 174 gpm and 135 gpm for ASR-1 and ASR-3, respectively, assuming an injection specific capacity of 1 gpm/ft and available buildup in the wells keeping water levels 5 feet below ground surface. Recovered water TDS concentrations resulting from the scenario #3 simulation indicate a nominal improvement compared to baseline conditions (Figure 23, Table 8) with a 1% improvement in final recovered water quality. However, the recovered volume of water from scenario #3 is increased to 44 MG, equivalent to a daily recovery rate of 0.87 MGD over the simulated 50 day recovery period, a 21% improvement over scenario 1 results.

4.6 ASR-4 Forecasting Simulations

Forecasting simulations were conducted with a two-well ASR system composed of ASR-1 and ASR-4 using operational management scenarios 1 and 3 as described in Section 4.2 and detailed in Table 7. ASR-4 is located outside the Water Treatment Plant property boundary to the northwest of the existing ASR-1 well (Figure 24).

The quality and quantity of water recovered from the combined system were evaluated for both modeled scenarios, while hydraulic interference between the two ASR wells was evaluated for scenario #1 only. Results for each forecasting simulation are presented in Table 8 and described in the following subsections. Improvements in recovered water quality during all simulations are occur due to an assumed increase in the rate of aquifer conditioning in the connective layer between the ASR-1 and ASR-4, as well as due to the location of ASR-4 along a fault structure hypothesized to be the main source of storage for the system.

4.6.1 Scenario #1

Operating ASR-1 and ASR-4 simultaneously in a two-well ASR system resulted in a modeled 12% improvement in final recovered water TDS concentrations as compared to the baseline simulation (Figure 24, Table 8). The magnitude of recovered water quality improvement was less than that obtained from a two-well system utilizing ASR-2, likely because ASR-4 intersects only one fault zone whereas ASR-2 intersects both. Operating two wells simultaneously resulted in less than 9 feet of additional buildup and drawdown in the two wells due to hydraulic interference.

4.6.2 Scenario #3

Operating ASR-1 and ASR-4 simultaneously with the scenario #3 forecasting model (see Table 7 for scenario parameters) resulted in injection rates maximized at 174 gpm and 119 gpm for ASR-1 and ASR-4, respectively, assuming an injection specific capacity of 1 gpm/ft and available buildup in the wells assuming maximum water levels 5 feet below ground surface. Recovered water TDS concentrations resulting from the scenario #3 simulation indicate a nominal improvement compared to baseline conditions (Figure 24, Table 8) with a 1% improvement in final recovered water quality. However, the recovered volume of water from scenario #3 is increased to 42 MG, equivalent to a daily recovery rate of 0.85 MGD over the simulated 50 day recovery period, a 17% improvement over scenario 1 results.

5.0 RESULTS AND CONCLUSIONS

A finite-element groundwater flow and transport model was constructed based on the Dallas ASR site conceptual model, calibrated such that parameters remained consistent with the conceptual model, then used as a forecasting tool to qualitatively assess the potential benefits to ASR recovered water quality and quantity that may be realized through addition of a new well to the ASR system and/or changes in operational practices at ASR-1. The capacity of the City's ASR system may be doubled to approximately 0.66 MG/day by adding a second well to the City's ASR system. Additionally, a dual well system is

forecasted to condition the saline SRV aquifer more rapidly than a single well system, thereby decreasing recovered water TDS concentrations and increasing the potential recovery efficiency of a dual-well ASR system as compared to a single well system baseline scenario.

A summary of forecasting simulation results is presented graphically in Figure 25, which compares gains in water quality and volumetric recovery given the various new well locations and management scenarios. The x-axis of Figure 25 is the change in percent recovery (as a fraction of recharge volume) for a simulated two-well system compared to the percent recovery of a baseline single well system. The y-axis of Figure 25 is the percent improvement in final water quality for a dual well system compared to the final water quality a baseline single well system. The forecasting results indicate that both recovered water quality and quantity are sensitive to the simulated management scenarios (described in Section 4.2), while only water quality is sensitive to the simulated location of a second ASR well (locations shown in Figure 19). All three proposed locations are suitable for system expansion based on recovered water quantity, as model forecasting results indicate that the volume of water recovered as a percent of injected volume is not sensitive to the location of a second ASR well.

Scenario 1 simulation results predict that a two-well ASR system will result in a 12% to 21% improvement in recovered water quality as compared to a baseline single-well simulation. Nominal improvement in percent recovered water volume will occur, though 2 to 2.5 times as much water is recharged and recovered as compared to the baseline single well system in all forecasting simulations. So overall water quality increases, though it does not appear as if recovery efficiency would increase based on these simulations.

Scenario 2 simulations predict improved recovered water quality (36% to 43% increase) at the expense of percent recovered water quantity (an 18% decrease). Conversely, scenario 3 simulations predict an improvement in recovered water quantity (12% to 13% increase) with limited improvement in recovered water quality (0 to 10% improvement over background scenarios). These results suggest that the Dallas ASR system can be managed to provide greater recovered water quantity as a percent of injected volume or better recovered water quality as compared to a base-case operational practices to meet the future needs of the City's water supply system, depending on priorities. .

Forecasti simulation results indicate that the location of an additional well will have a small effect on the magnitude of improvement in water quality, though will have insignificant impact on improvement in recovered water quantity as a fraction of injected water volume. A second well placed at the intersection of the two hypothesized fault zones (PW-2 location, see Figure 19) is forecasted to result in recovered water quality that is 7% to 9% better than is forecasted to be realized from a second well placed at the other two modeled locations (PW-3 and PW-4 locations, see Figure 19, given the same management scenario). There is little difference between the forecasted recovery results for a second well placed at either PW-3 or PW-4. While PW-2 is forecast to provide slightly better improvement in recovered water

quality than site PW-3, the 7% improvement will likely be offset by the cost and permitting requirements required to develop a second well outside the current property footprint of the water treatment plant. Therefore site PW-3 is recommended as the preferred location for initial expansion to a two-well ASR system.

6.0 MODEL LIMITATIONS

It is important to recognize the limitations of the available data set and this numerical groundwater model when evaluating the predictions of the modeling results. The model serves as a tool to understanding potential impacts for stresses on groundwater systems. Limitations in the available data may limit the model's ability to accurately represent the physical conditions of the aquifer. For all numerical models, the reliability is proportional to the amount of data collected within the modeled area used to verify the results. There is significant uncertainty remaining regarding the geometry and connectivity of the fracture network in the SRV. An additional operation well with substantial pressure response data may improve the model accuracy for long term or at large distances, though it may not. The model is intended for use in comparing locations and operations relative to each other for planning purposes. It is not (nor can it be) sufficiently representative to predict a specific result at a specific location, depth, or time.

Hydrogeologic investigations and groundwater modelling are dynamic and inexact sciences. They are dynamic in the sense that the state of any hydrological system is changing with time, and in the sense that the science is continually developing new techniques to evaluate these systems. They are inexact in the sense that groundwater systems are complicated beyond human capability to evaluate them comprehensively in detail, and we invariably do not have sufficient data to do so. While the model itself obviously lacks the detailed reality of the existing hydrogeological system, the behaviour of a valid groundwater model reasonably approximates that of the real system. The validity and accuracy of the model depends on the amount of data available relative to the degree of complexity of the geologic formations, the site geochemistry, the fate and transport of the dissolved compounds, and on the quality and degree of accuracy of the data entered. Therefore, every groundwater model is a simplification of a reality and the model described in this report is not an exception.

The professional groundwater modelling services performed as described in this report were conducted in a manner consistent with that level of care and skill normally exercised by other members of the engineering and science professions currently practising under similar conditions, subject to the quality and quality of available data, the time limits and financial and physical constraints applicable to the services. Unless otherwise specified, the results of previous or simultaneous work provided by sources other than Golder and quoted and/or used herein are considered as having been obtained according to recognised and accepted professional rules and practices, and therefore deemed valid. This model provides a predictive scientific tool to evaluate the impacts on a real groundwater system of specified hydrological stresses and/or to compare various scenarios in a decision-making process. However and despite the professional care taken during the construction of the model and in conducting the

simulations, its accuracy is bound to the normal uncertainty associated to groundwater modelling and no warranty, express or implied, is made.

6.1 Use of This Report

This report has been prepared for the exclusive use of the Client or his agents. The factual information, descriptions, interpretations, comments, recommendations and electronic files contained herein are specific to the project described in this report and do not apply to any other project or site. Under no circumstances may this information be used for any other purposes than those specified in the scope of work unless explicitly stipulated in the text of this report. This report must be read in its entirety as some sections could be falsely interpreted when taken individually or out-of-context. In addition, the final version of this report and its content supersedes any other text, opinion or preliminary version produced by Golder.

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TABLES

Table 1

Comarison of Steady State Simulated and Observed Static Water Levels

City of Dallas ASR Optimization/Expansion Grant Study

Observation point	Observed Head (ft)*	Simulated Head (ft)	% difference
ASR-1	409	410	-0.24%
Lowe	407	410.5	-0.86%
Presser	412.3	410.7	0.39%
Specified head boundaries			
southwest edge of model		430	
northeast edge of model		390	

*From measured static water levels (spring '06 - pre-pilot testing)

Table 2

Transient Calibration Results for the 72-hour Pumping Test Simulation

City of Dallas ASR Optimization/Expansion Grant Study

PUMPING TEST		Pumping 291 gpm (1586 L/min) for 3 days										
	OBSERVED	SIMULATION RUNS										
	Drawdown (ft)	Drawdown (ft), at t = 72 hours										best fit
Observation Point		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
ASR-1*	70	56	45.3	56.3	300	64	64	123	125	45	58	68
Lowe	4.5	0.7	0.7	0.7	0.9	0.9	0.7	0.9	2.6	1.6	1.8	1.95
Presser	2.5	0.05	0.1	0.1	0.25	0.2	0.1	0.2	0.9	0.5	0.6	0.6
Calibrated parameter values												
K faults (10^{-4} m/s)		10	5	5	10	10	50	10	10	10	10	10
K layer 6 (10^{-4} m/s)		2	5	5	0.1	5	5	5	5	5	5	5
K matrix (10^{-4} m/s)		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00001	0.00001	0.00001	0.00001
Layer 6 thickness (ft)		10	20	15	12	12	12	5	10	20	15	12
Comparison of Simulated and Observed Drawdown, % Difference												
% diff ASR-1		20.00%	35.29%	19.57%	328.57%	8.57%	8.57%	75.71%	78.57%	35.71%	17.14%	2.86%
% diff Lowe		84.44%	84.44%	84.44%	80.00%	80.00%	84.44%	80.00%	42.22%	64.44%	60.00%	56.67%
% diff Presser		98.00%	96.00%	96.00%	90.00%	92.00%	96.00%	92.00%	64.00%	80.00%	76.00%	76.00%
avg % diff		67.48%	71.91%	66.67%	166.19%	60.19%	63.01%	82.57%	61.60%	60.05%	51.05%	45.17%

* observed drawdown value based on a well efficiency of 25%

Table 3

Transient Calibration Results for the Simulated Cycle 5 Pilot Test

City of Dallas ASR Optimization/Expansion Grant Study

CYCLE 5 PILOT TEST Injecting 168 gpm (916 m^3/d) for 70 days; storage for 45 min; Pumping 242 gpm (1319 m3/d) for 11 days

	OBSERVED Buildup (ft)	SIMULATED RUNS Buildup (ft)			specific storage adjustiments									best fit
Observation point		**1**	**2**	**3**	**4****	**5****	**6****	**7**	**8**	**9**	**10**	**11**	**12**	**13**
ASR-1*	42	41.7	42.9	209	214	198	209	23.29	47.56	38	58.38	31.2	47.23	42
Lowe	15	3	3.97	12.1	12.8	11.8	12.1	2.62	4.92	4.4	5.25	3.5	5.1	4.8
Presser	12	1.8	2.49	5.25	7.5	6.9	5.25	1.7	2.95	2.6	3.3	2.1	3	2.8
Calibration Parameters														
K faults (10^{-4} m/s)		10	7	1	1	1	1	1	1	5	5	5	4	4.5
K layer 6 (10^{-4} m/s)		5	5	1	1	1	1	10	5	5	5	5	4	4.5
K matrix (10^{-4} m/s)		0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Layer 6 thickness (ft)		12	12	12	12	12	12	12	12	12	8	30	12	12
SS matrix		0.0001	0.0001	0.0001	0.00005	0.0001	0.00008	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
SS connective layer/faults		0.0001	0.0001	0.0001	0.00005	0.00005	0.00008	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Comparison of Simulated and Observed Buildup, % Difference														
% diff ASR-1		0.71%	2.14%	397.62%	409.52%	371.43%	397.62%	44.55%	13.24%	9.52%	39.00%	25.71%	12.45%	0.00%
% diff Lowe		80.00%	73.53%	19.33%	14.67%	21.33%	19.33%	82.53%	67.20%	70.67%	65.00%	76.67%	66.00%	68.00%
% diff Presser		85.00%	79.25%	56.25%	37.50%	42.50%	56.25%	85.83%	75.42%	78.33%	72.50%	82.50%	75.00%	76.67%
avg % diff		55.24%	51.64%	157.73%	153.90%	145.09%	157.73%	70.97%	51.95%	52.84%	58.83%	61.63%	51.15%	48.22%

* observed buildup value based on a well efficiency of 25%

** imapacting water levels at non-responding observation points

Table 4

Initial Calibration of the Simulated Cycle 5 Pilot Test (Sensitivity Analysis)

Modified Model Framework: Calibrating Groundwater Flow and Mass Transport Parameters

City of Dallas ASR Optimization/Expansion Grant Study

CYCLE 5 PILOT TEST Injecting 168 gpm (916 m^3/d) for 70 days; storage for 45 min; Pumping 242 gpm (1319 m3/d) for 11 days

	SIMULATION RUNS (Adjusting K and Ss)				adjust porosity		adjust dispersivity	
Parameter	**basecase***	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Calibrated Groundwater Flow Parameters								
K Lowe fault (10^{-4} m/s)	4.5	10	0.1	4.5	4.5	4.5	4.5	4.5
K layer 6 (10^{-4} m/s)	4.5	10	0.1	4.5	4.5	4.5	4.5	4.5
K matrix (10^{-4} m/s)	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
specific storage Faults & Slice	0.0001	0.0001	0.0001	0.00005	0.0001	0.0001	0.0001	0.0001
specific storage Matrix	0.0001	0.0001	0.0001	0.00005	0.0001	0.0001	0.0001	0.0001
Calibrated Mass Transport Parameters								
porosity for high K zones	0.15	0.15	0.15	0.15	0.1	0.15	0.15	0.15
porosity for low K matrix	0.025	0.025	0.025	0.025	0.025	0.1	0.025	0.025
longitudinal dispersivity (m)	5	5	5	5	5	5	10	100
longitudinal-transverse ratio	10:1	10:1	10:1	10:1	10:1	10:1	10:1	10:1

* parameters from final calibration results of groundwater flow model (Table 4)

Table 5

Final Calibration Results for the Simulated Cycle 5 Pilot Test

Modified Model Framework: Calibrating Dispersivity Zone Parameters

City of Dallas ASR Optimization/Expansion Grant Study

CYCLE 5 PILOT TEST Injecting 168 gpm (916 m^3/d) for 70 days; storage for 45 min; Pumping 242 gpm (1319 m3/d) for 11 days

	SIMULATED RUNS								best fit		
Parameter	**basecase***	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Calibrated Dispersivity Zones											
matrix dispersivity (m)	10	10	10	10	10	10	10	10	10	10	10
dispersivity for connective layer/faults (m)	10	10	100	500	100	100	100	100	200	200	200
zone dispersivity (m)	10	1	10	10	10	10	10	10	10	10	10
zone radius (ft)	none	50	50	50	150	300	200	250	250	250	250
gradient	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.01

* parameters from calibration results of groundwater flow model parameters (#7 in Table 4)

Table 6

Calibration Results for the Simulated Cycle 7 Pilot Test

Modified Model Framework: Calibrating Dispersivity Zone Parameters

City of Dallas ASR Optimization/Expansion Grant Study

CYCLE 7 PILOT TEST Injecting 165 gpm (899 m^3/d) for 215 days; storage for 3 days; Pumping 250 gpm (1319 m3/d) for 11 days

	SIMULATION RUNS				best fit
Parameter	**1**	**2**	**3**	**4**	**5**
Calibrated Dispersivity Zones					
connective layer/fault dispersivity (m)	200	400	200	400	400
Zone 1 (inner) dispersivity (m)	10	10	0.5	10	10
Zone 2 (outer) dispersivity (m)	none	none	none	200	180
Zone 1 radius (m)	250	250	250	250	350
Zone 2 radius (m)	none	none	none	350	450

* parameters from calibration results of groundwater flow model parameters (#7 in Table 4)

Table 7

Forecasting Simulation Parameters

City of Dallas ASR Optimization/Expansion Grant Study

Parameters for various forecasting simulations conducted to assess potential improvement in recovered wtaer quality and quantity

Forecast	Well	Scenario #	Injection			Storage	Recovery				
			Rate (gpm)	Duration (days)	Total Volun (MG)	Duration (days)	Rate (gpm)	Duration (days)	Total Volume (MG)	Total Volume (% Inj. Vol.)	Combined TDS (% improvement*)
Baseline (Single Well Operations)	ASR-1	1	165	200	47.5	3	250	50	18	38%	-
	ASR-2		165	200	47.5	3	250	50	18	38%	-
	ASR-3		165	200	47.5	3	250	50	18	38%	-
	ASR-4		165	200	47.5	3	250	50	18	38%	-
	ASR-1	2	165	400	95.0	168	250	50	18	19%	15%
ASR-1 + ASR-2	ASR-1	1	165	200	95.0	3	250	50	36	38%	21%
	ASR-2		165				250				
	ASR-1	2	165	400	190.1	168	250	50	36	19%	43%
	ASR-2		165				250				
	ASR-1	3	174.3	200	89.8	3	312	50	45	50%	10%
	ASR-2		137.6				312				
	ASR-1	4	165	1000	237.6	15	250	250	90	38%	48%
	ASR-2		165				250				
ASR-1 + ASR-3	ASR-1	1	165	200	95.0	3	250	50	36	38%	13%
	ASR-3		165				250				
	ASR-1	2	165	400	190.1	168	250	50	36	19%	36%
	ASR-3		165				250				
	ASR-1	3	174.3	200	89.0	3	302.7	50	44	49%	1%
	ASR-3		134.8				302.7				
ASR-1 + ASR-4	ASR-1	1	165	200	95.0	3	250	50	36	38%	12%
	ASR-4		165				250				
	ASR-1	3	174.3	200	84.5	3	293.5	50	42	50%	1%
	ASR-4		119.2				293.5				

Notes: * compared to baseline 1-well scenario

Scenario #	Short Scenario Description
1	Typical ASR Cycle
2	Annual Recharge, Bi-annual Recovery
3	Rates adjusted to attain maximum injection volume and 50% recovery
4	5 consecutive annual ASR cycles (Sim.1 x 5)

Table 8

Forecasting Simulation Results

City of Dallas ASR Optimization/Expansion Grant Study

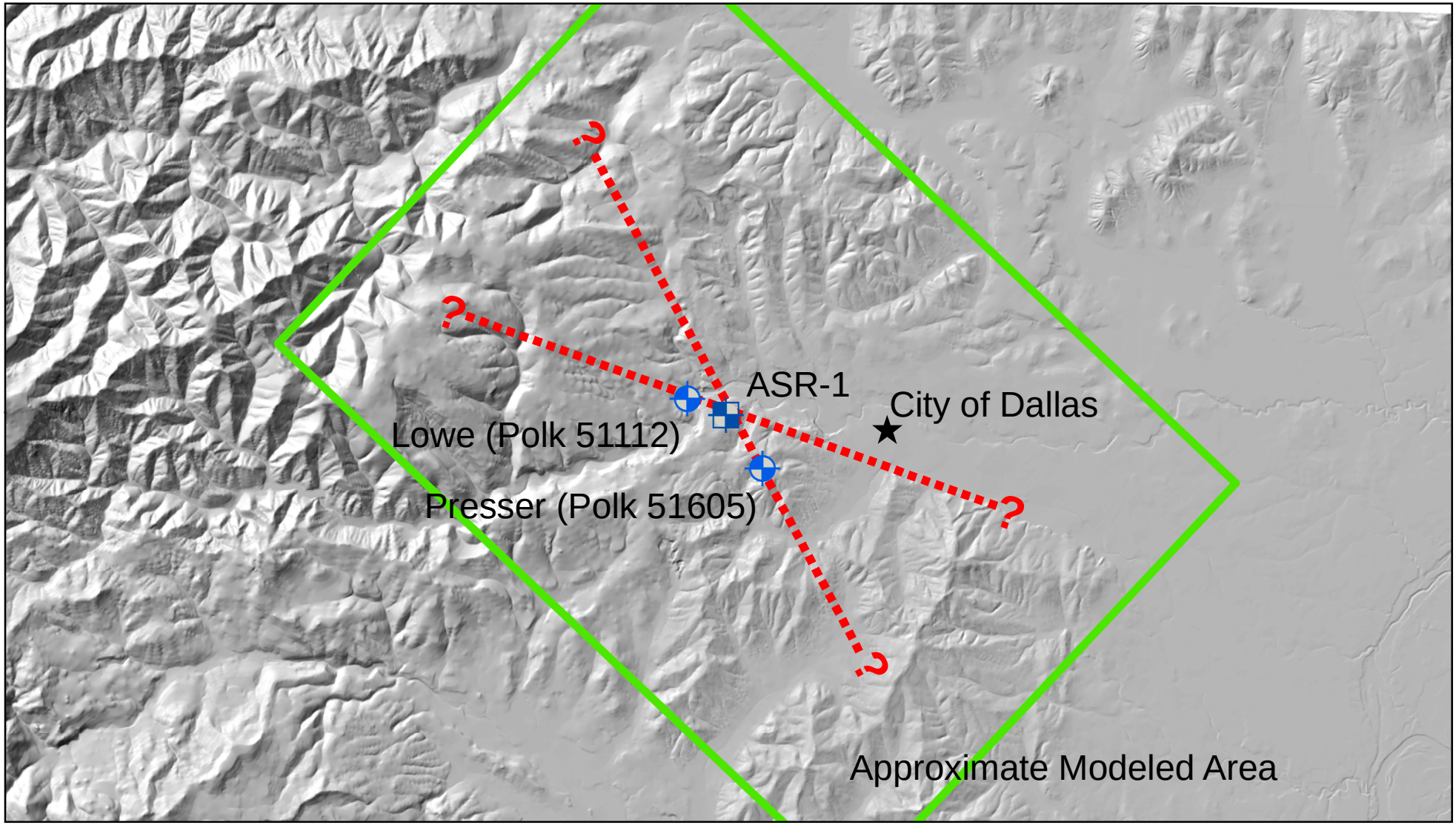
Parameters for various forecasting simulations conducted to assess potential improvement in recovered wtaer quality and quantity

Forecast	Well	Scenario #	Buildup	Drawdown	Additional Interference		Recovery		
					Buildup	Drawdown	Total Volume		Combined TDS
			ft	ft	ft	ft	(MG)	(% Inj. Vol.)	(% improvement*)
Baseline (Single Well Operations)	ASR-1	1	44.6	63.8			18	38%	-
	ASR-2		42	60.7			18	38%	-
	ASR-3		41.8	60.4			18	38%	-
	ASR-4		35.4	50.5			18	38%	-
	ASR-1	2	-	-	-	-	18	19%	15%
ASR-1 + ASR-2	ASR-1	1	52.1	73	7.5	9.2	36	38%	21%
	ASR-2		49.8	69.2	7.8	8.5			
	ASR-1	2	52.1	73		-	36	19%	43%
	ASR-2		49.8	69.2	-	-			
	ASR-1	3	53.3	92	-	-	45	50%	10%
	ASR-2		43.6	87.6	-	-			
	ASR-1	4	52.1	73	-	-	90	38%	48%
	ASR-2		49.8	69.2	-	-			
ASR-1 + ASR-3	ASR-1	1	52.6	72.5	8	8.7	36	38%	13%
	ASR-3		50.2	69.7	8.4	9.3			
	ASR-1	2	52.6	72.5	-	-	36	19%	36%
	ASR-3		50.2	69.7	-	-			
	ASR-1	3	53.6	89.5	-	-	44	49%	1%
	ASR-3		41.7	85.6	-	-			
ASR-1 + ASR-4	ASR-1	1	48.4	72.3	3.8	8.5	36	38%	12%
	ASR-4		42.9	58.9	7.5	8.4			
	ASR-1	3	52	82.8	-	-	42	50%	1%
	ASR-4		33.8	67.6	-	-			

Notes: * compared to baseline 1-well scenario

Scenario #	Short Scenario Description
1	Typical ASR Cycle
2	Annual Recharge, Bi-annual Recovery
3	Rates adjusted to attain 50% recovery
4	5 consecutive annual ASR cycles (Sim.1 x 5)

FIGURES



LEGEND

- Pumping Well
- Responding Observation Well
- Conceptualized Fault Zone

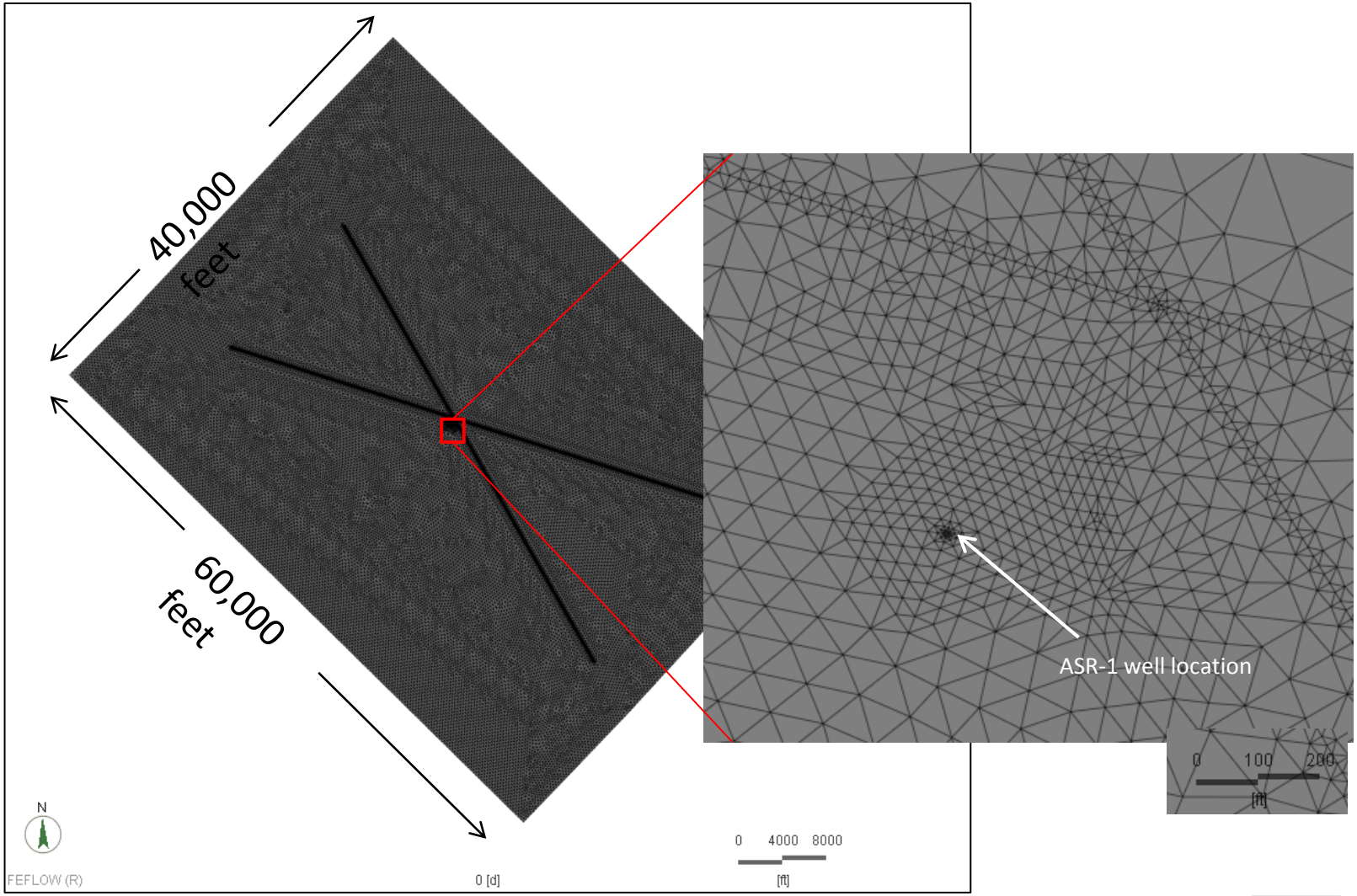
0 10,000'

N

Source: USGS

FIGURE 1
SITE MAP
CITY OF DALLAS GRANT FEASIBILITY STUDY - NUMERICAL MODELING TASK

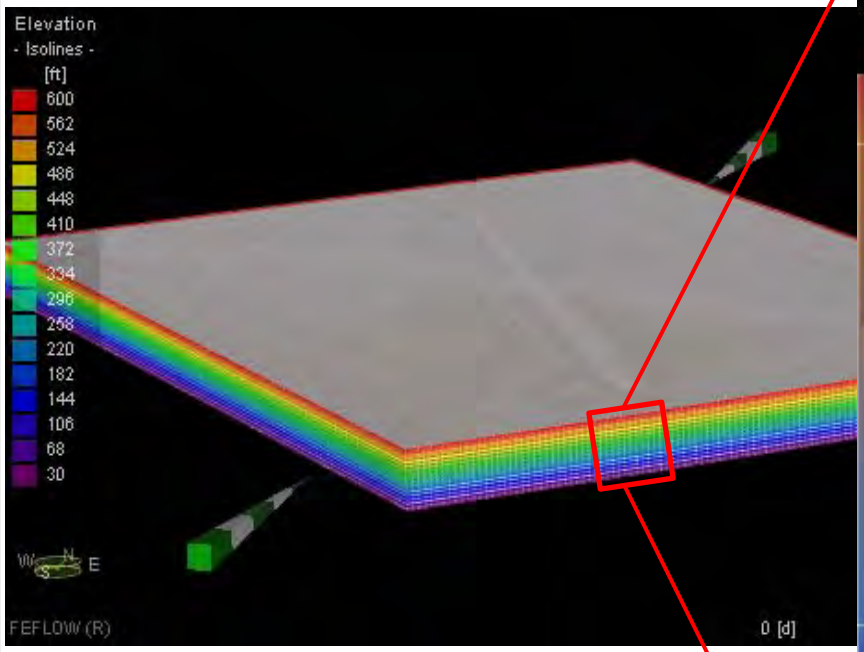
Golder Associates

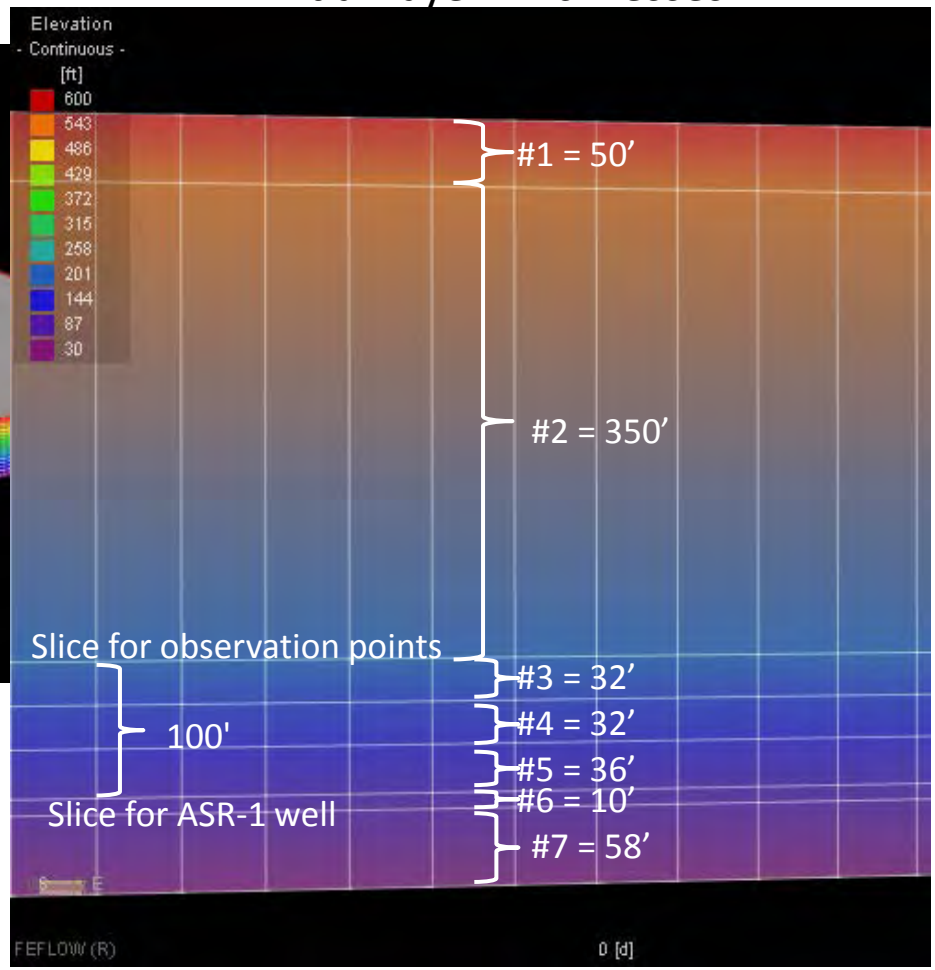


Golder Associates	Title: Model size and mesh design	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 2

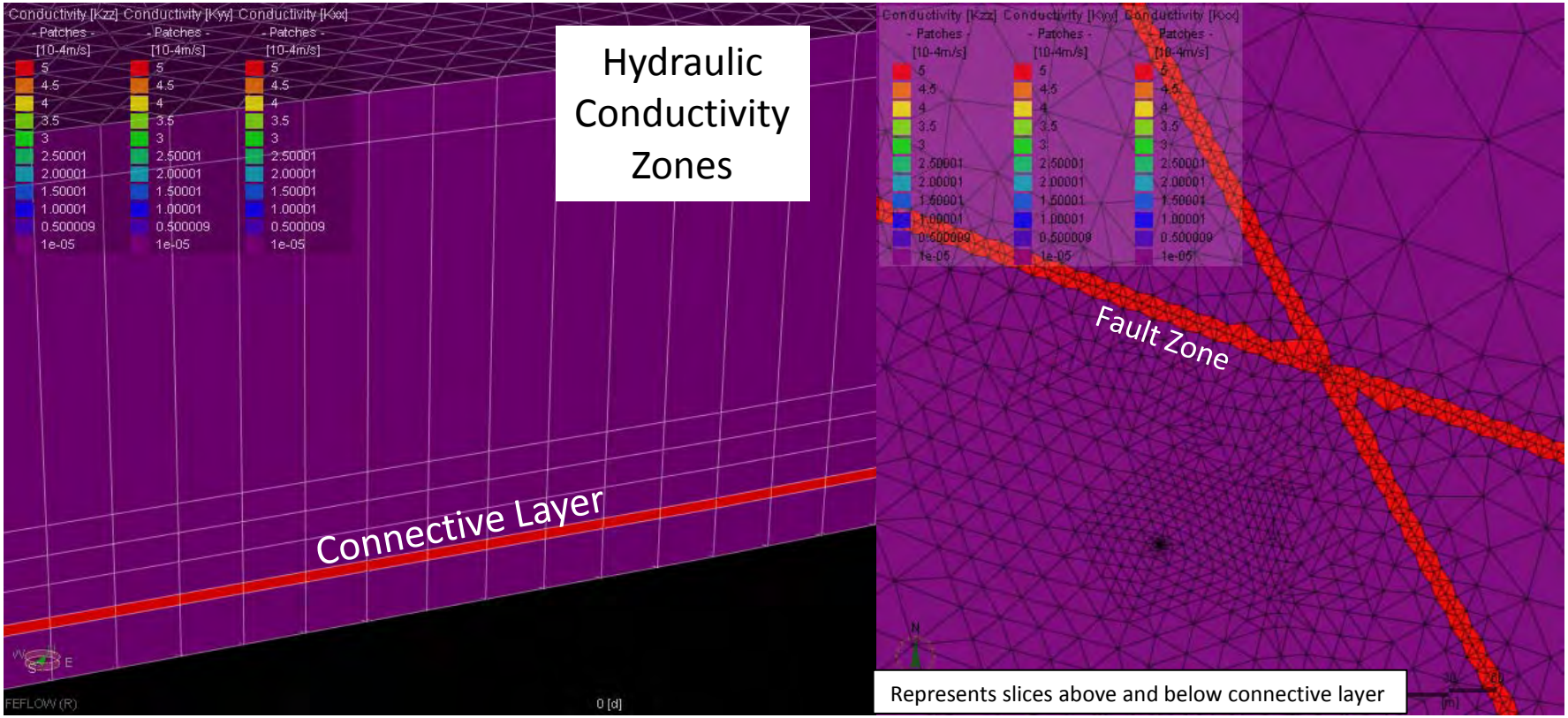
Initial Layer Thicknesses

3-D view of numerical model mesh



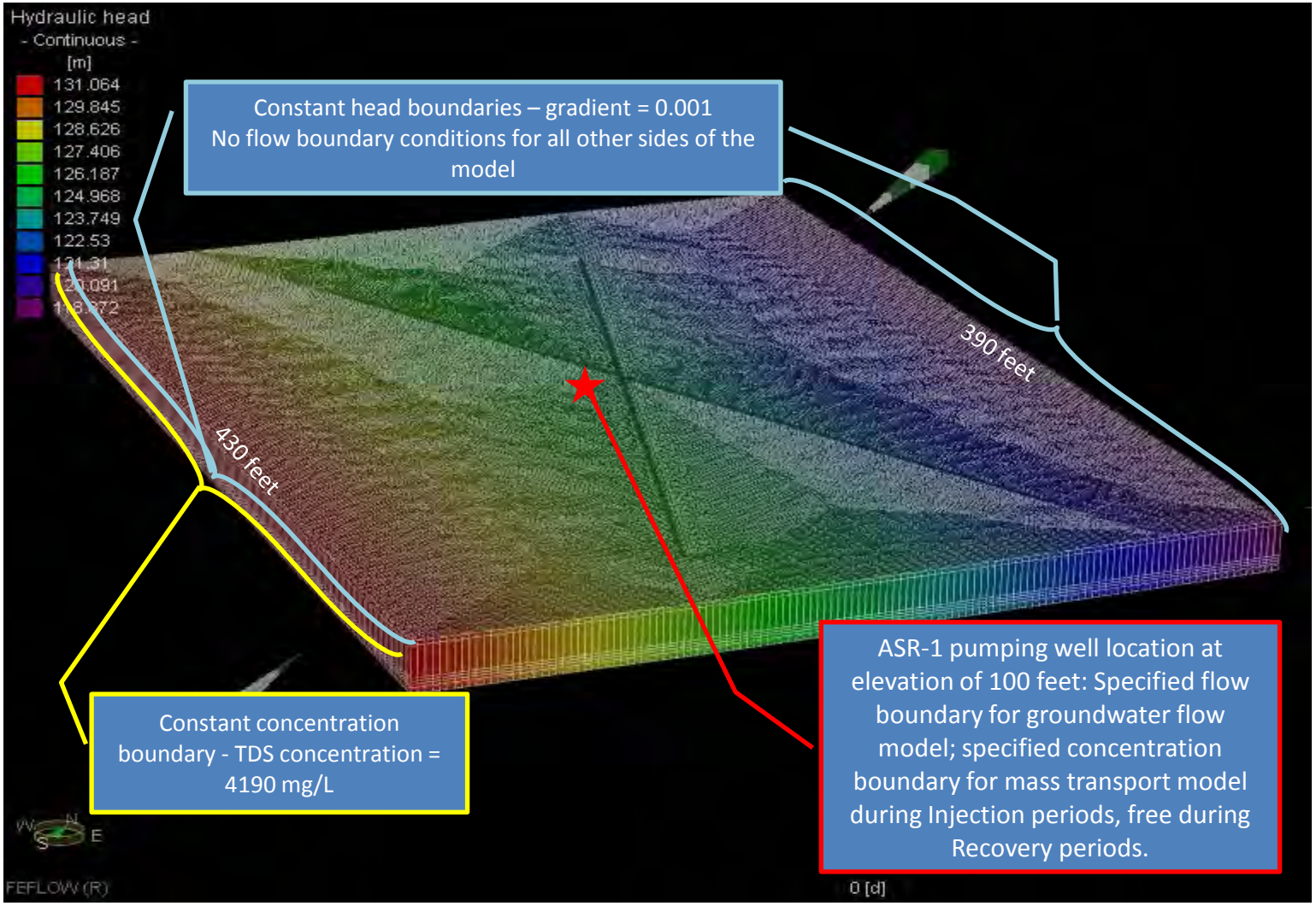


Golder Associates		Title	3-Dimensional View of Model Mesh	Drawn	SLH
				Checked	JTI
		Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed	PAB
		Client Name: City of Dallas	Date: September 2010	FIGURE	3

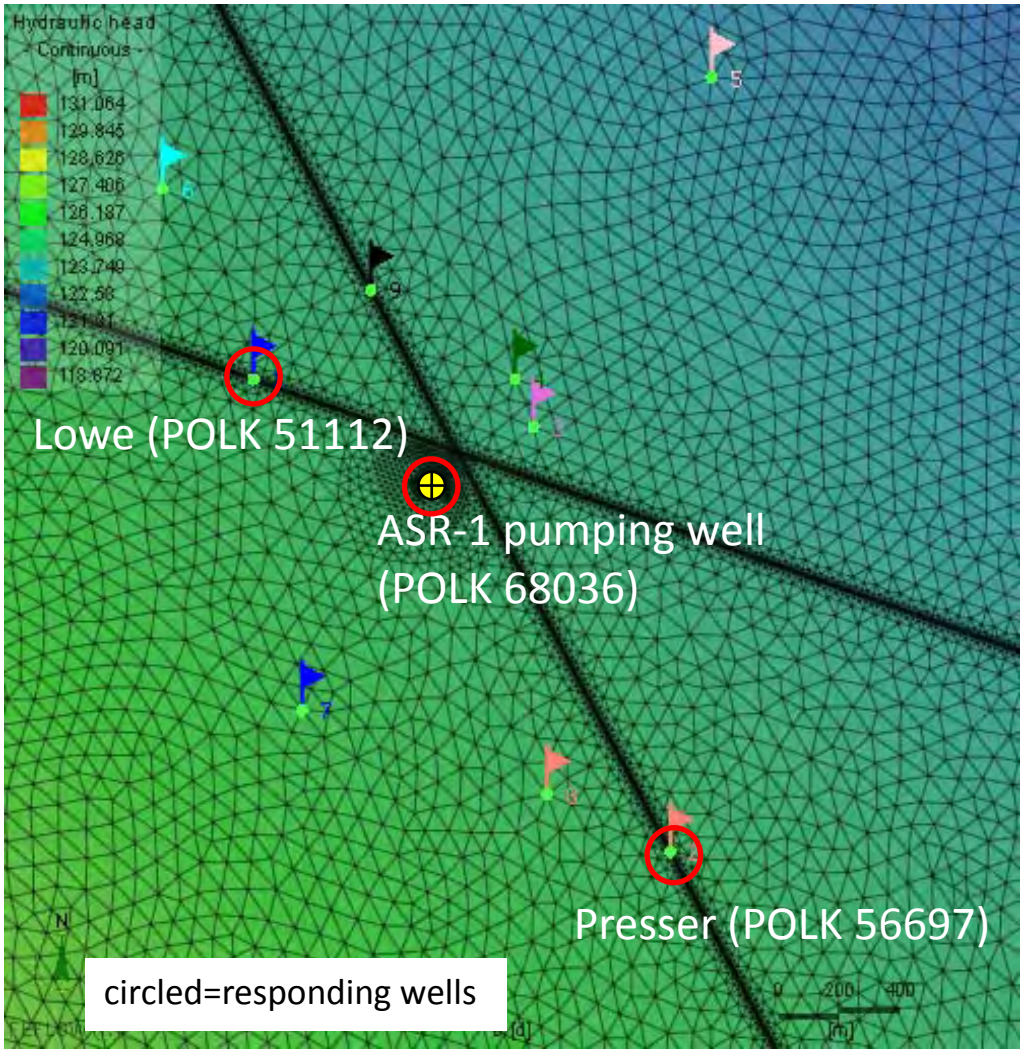


Golder Associates	Title: Contrasting Zones of Hydraulic Conductivity	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 4

S:\Projects\2005\053-9747-400_DallasASR\OWRD Grant Work\0839747-400_Dallas Grant Study Reporting\Grant Study Report Apdx B - Task 2 Tech Memo\Apdx B Figures 2-25.xlsx



Golder Associates	Title: Model Boundary Conditions		Drawn: SLH
			Checked: JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 5



Golder Associates	Title: Model Observation Points	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 6

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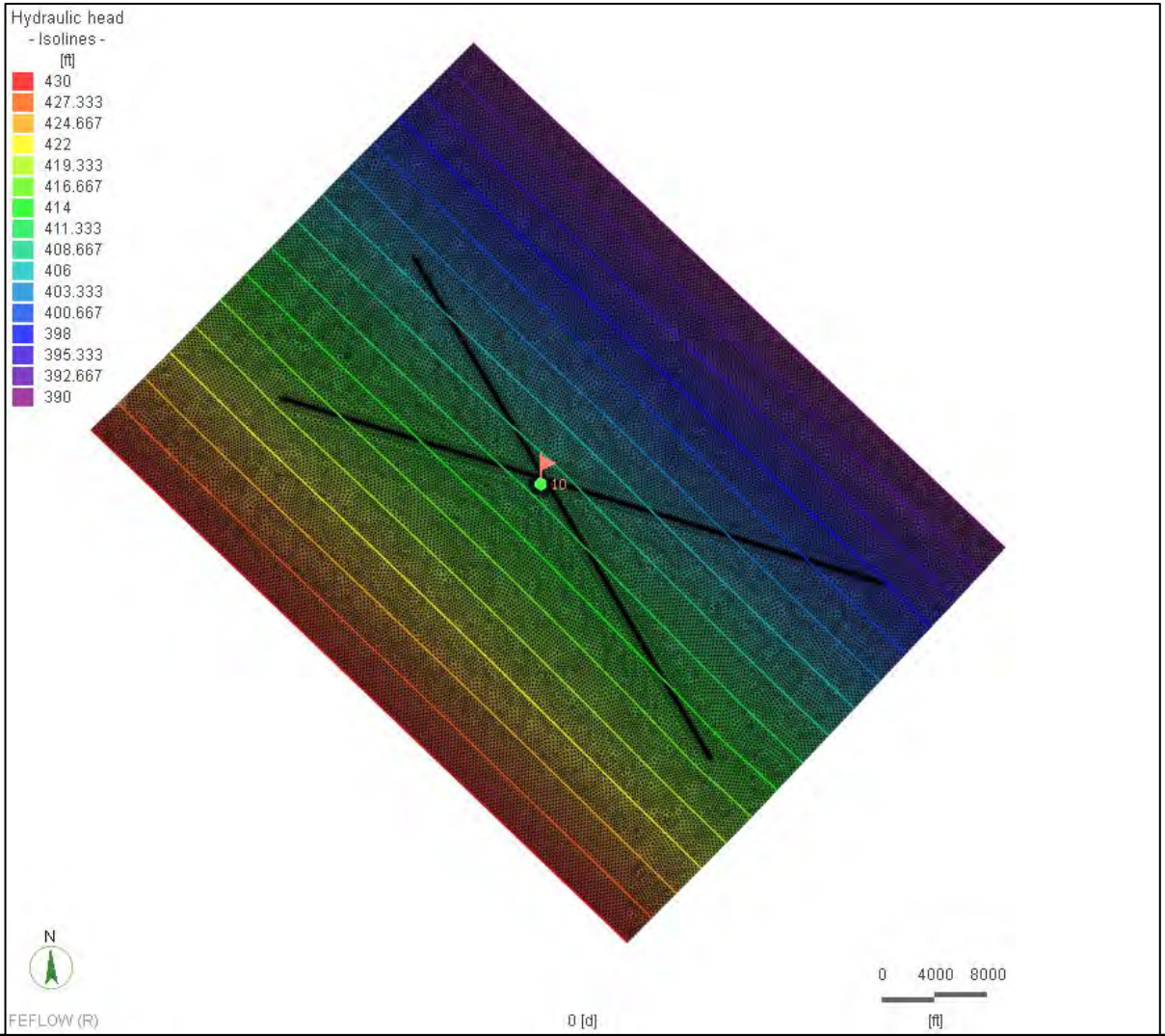

Golder Associates	Title: Steady State Groundwater Flow Solution		Drawn: SLH
			Checked: JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 7

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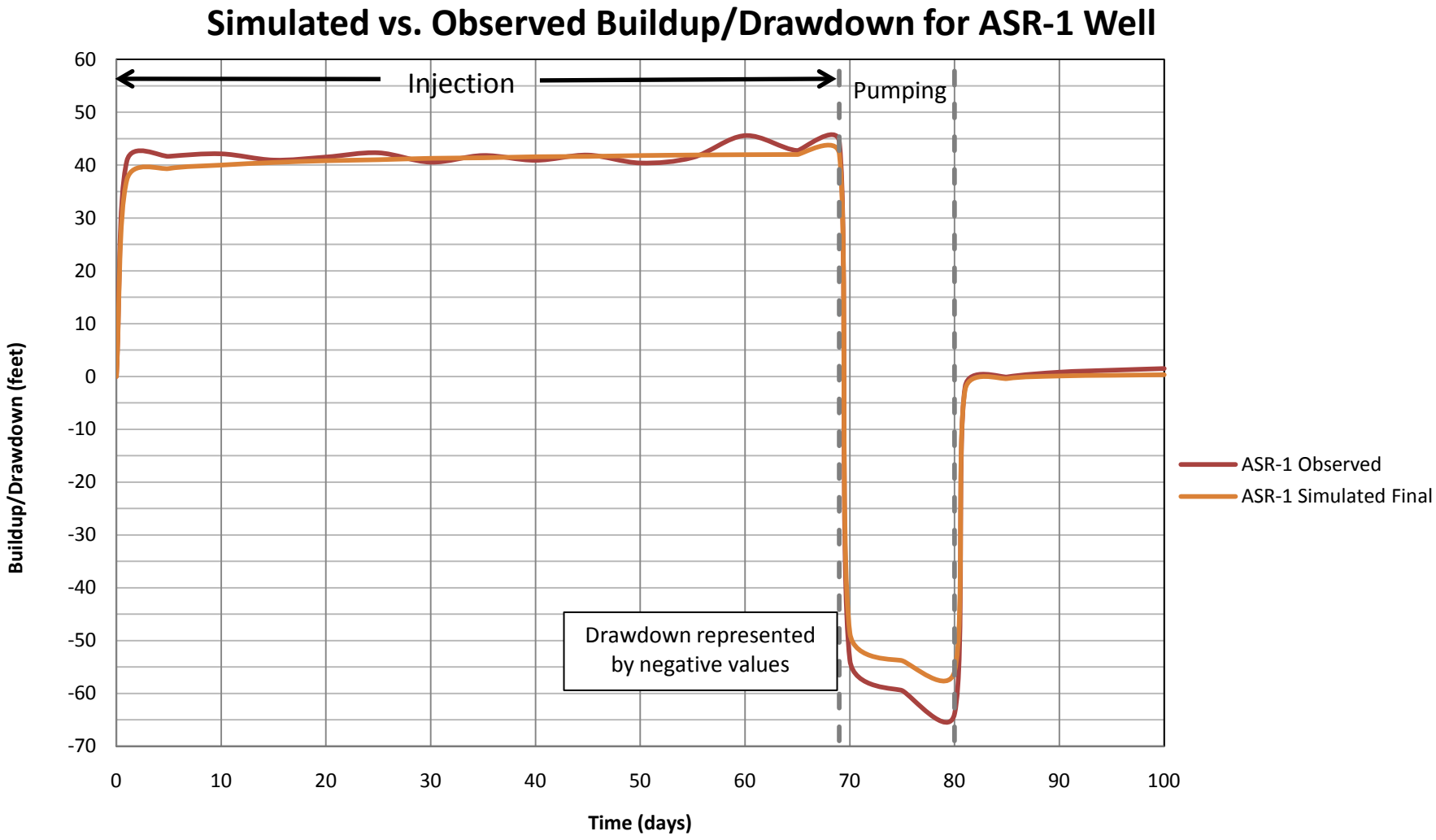
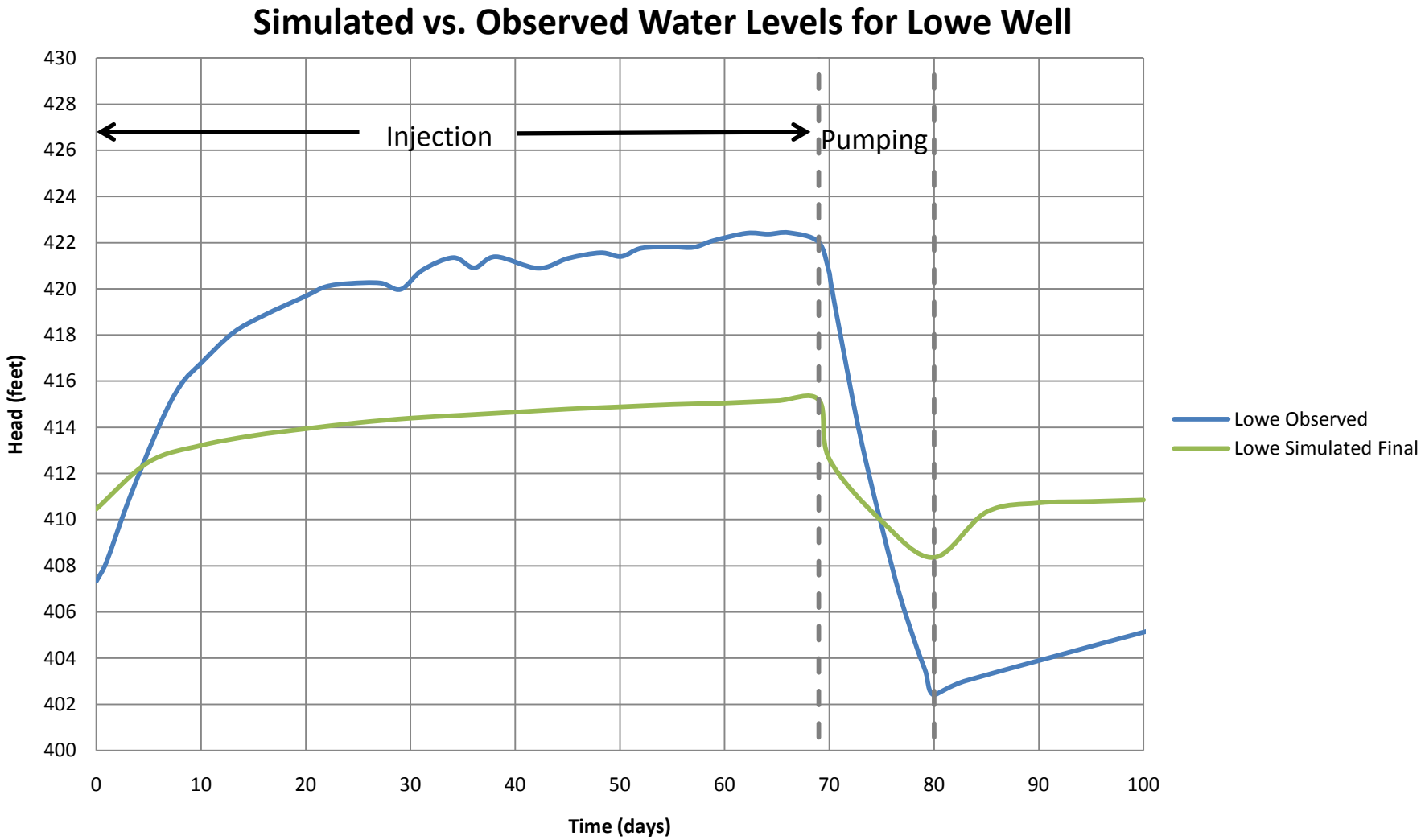
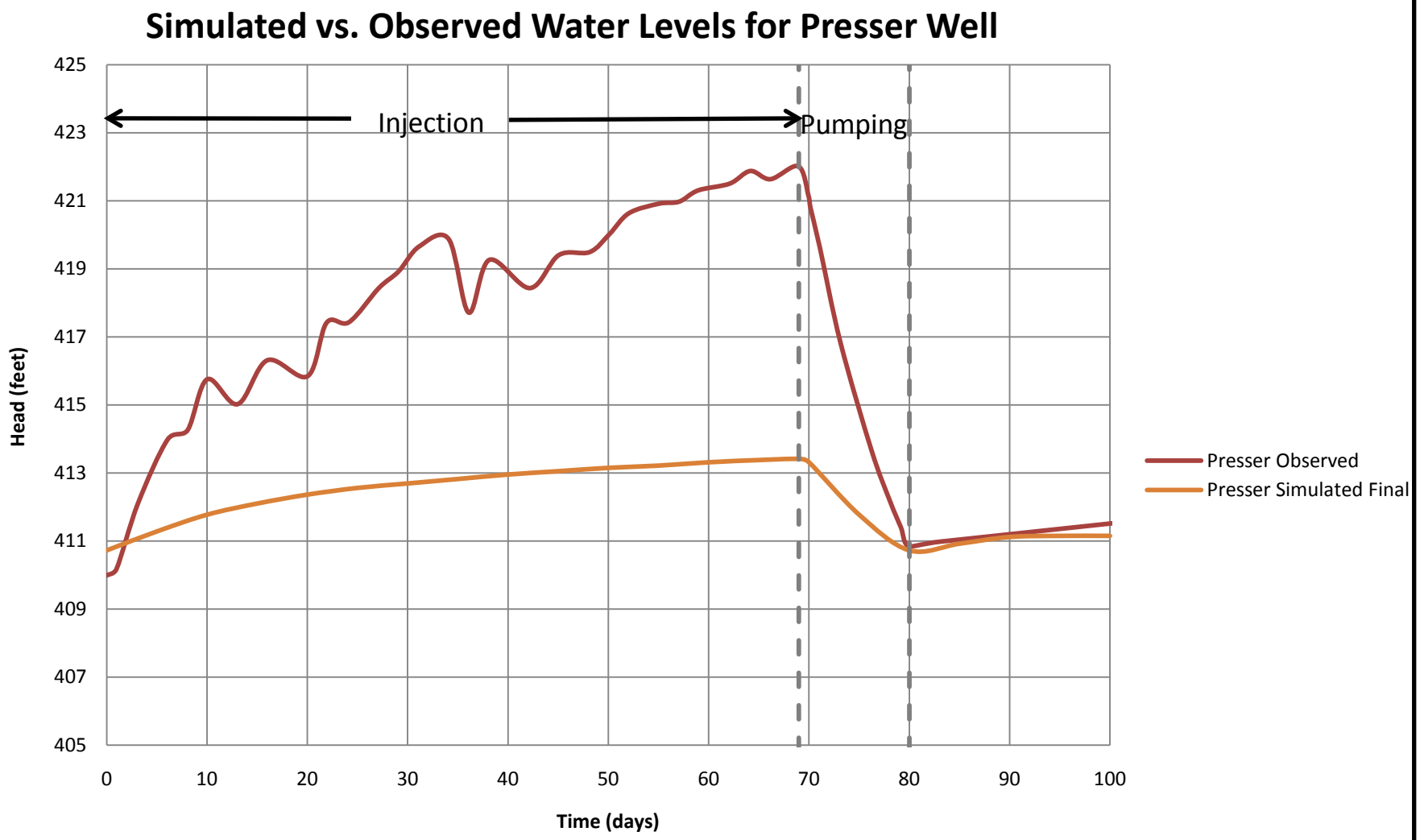


Golder Associates	Title: Final Cycle 5 Simulated and Observed Head at ASR-1 well	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 8



Golder Associates	Title: Final Cycle 5 Simulated and Observed Head at Lowe Well	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	9



Golder Associates	Title: Final Cycle 5 Simulated and Observed Head at Presser Well	Drawn	SLH
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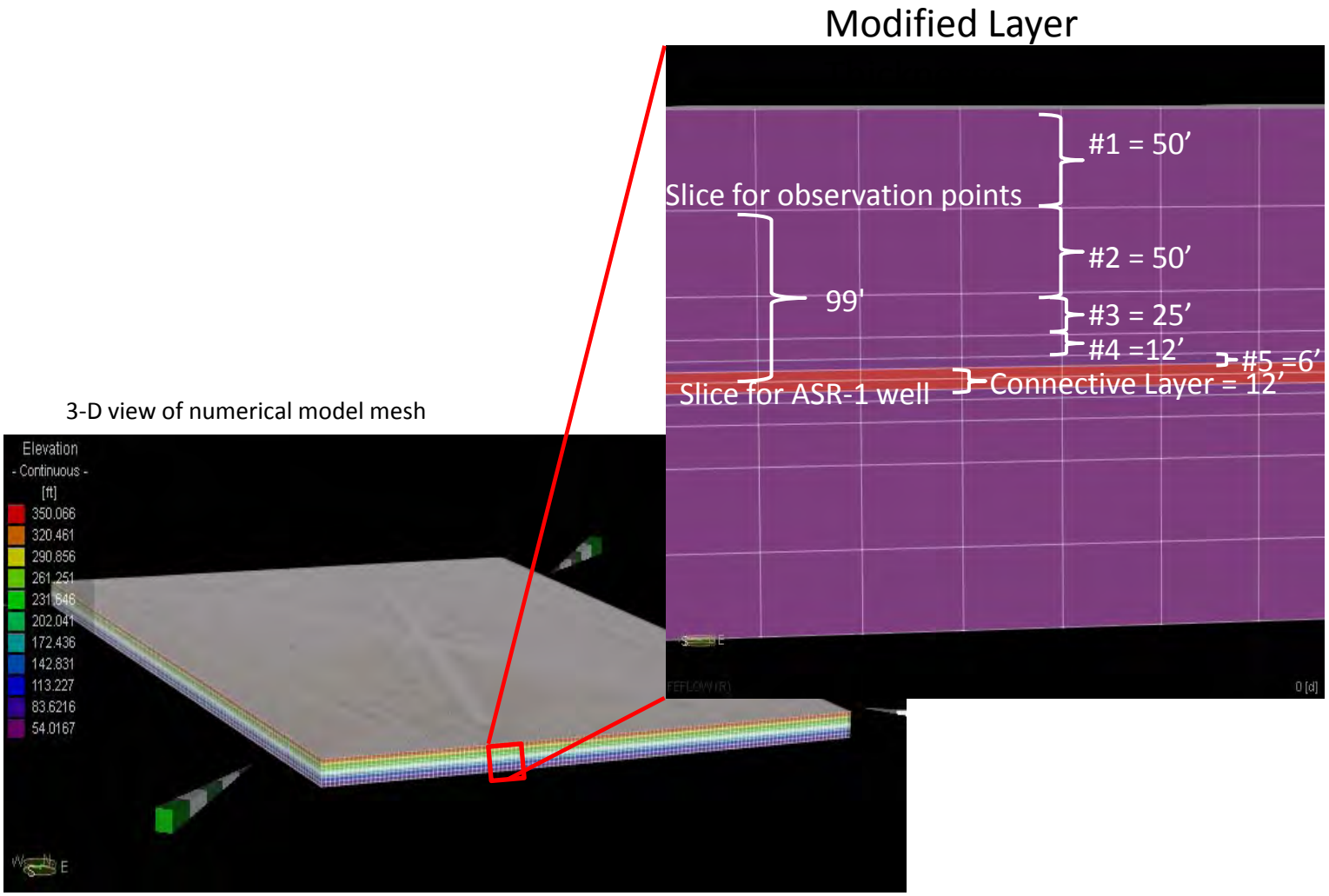
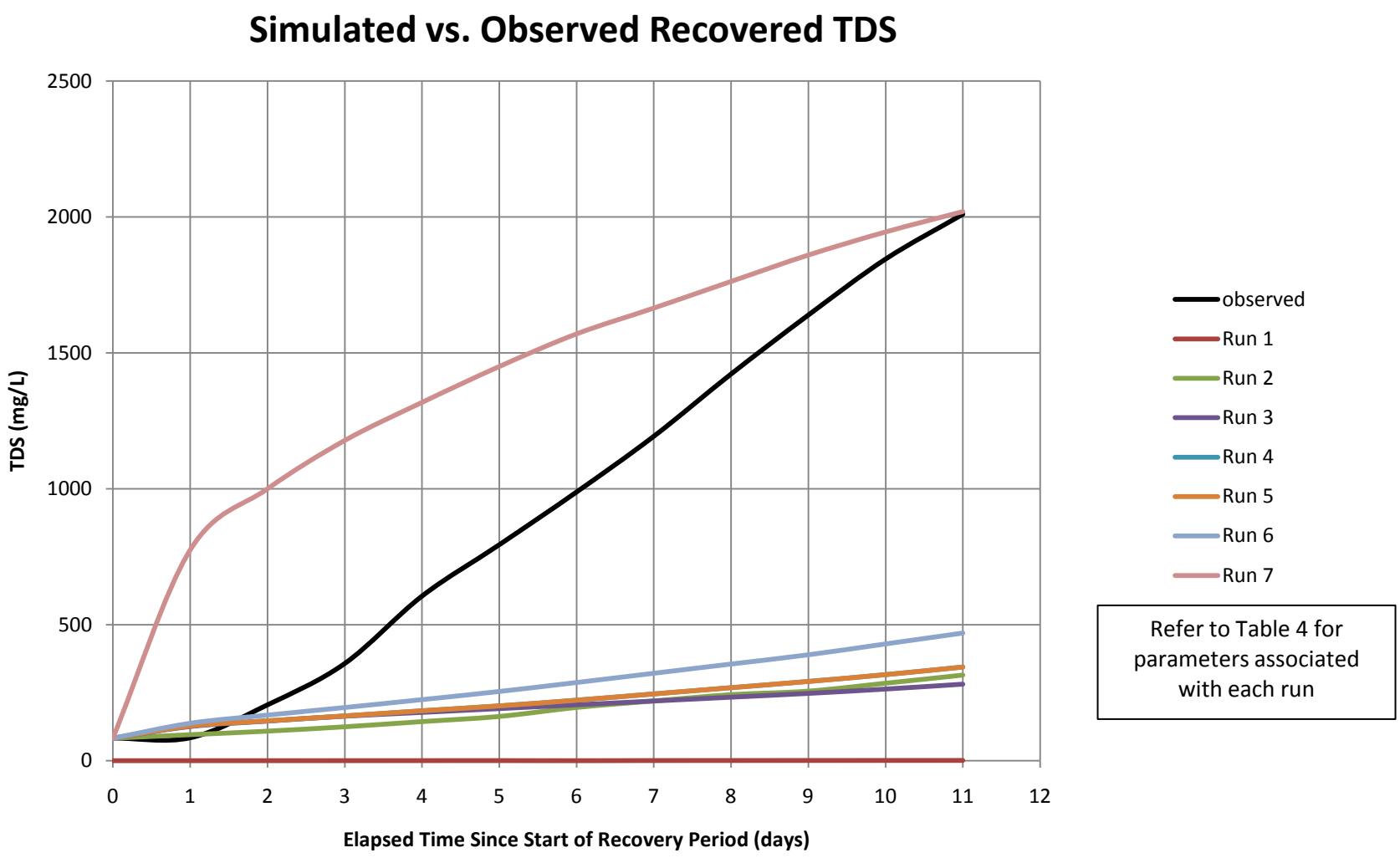
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 10

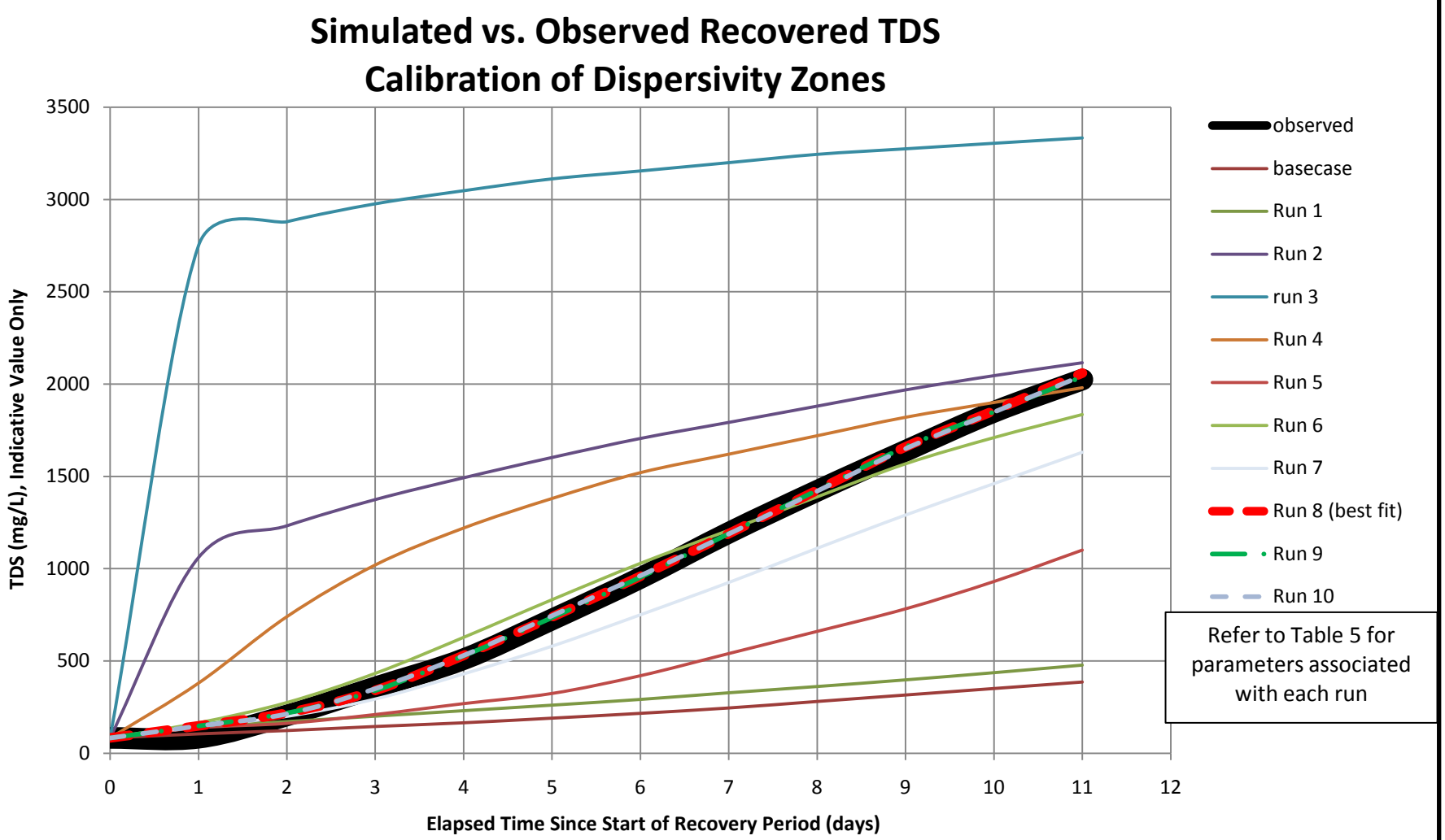


Golder Associates	Title: 3-Dimensional View of Revised Model Framework	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 11

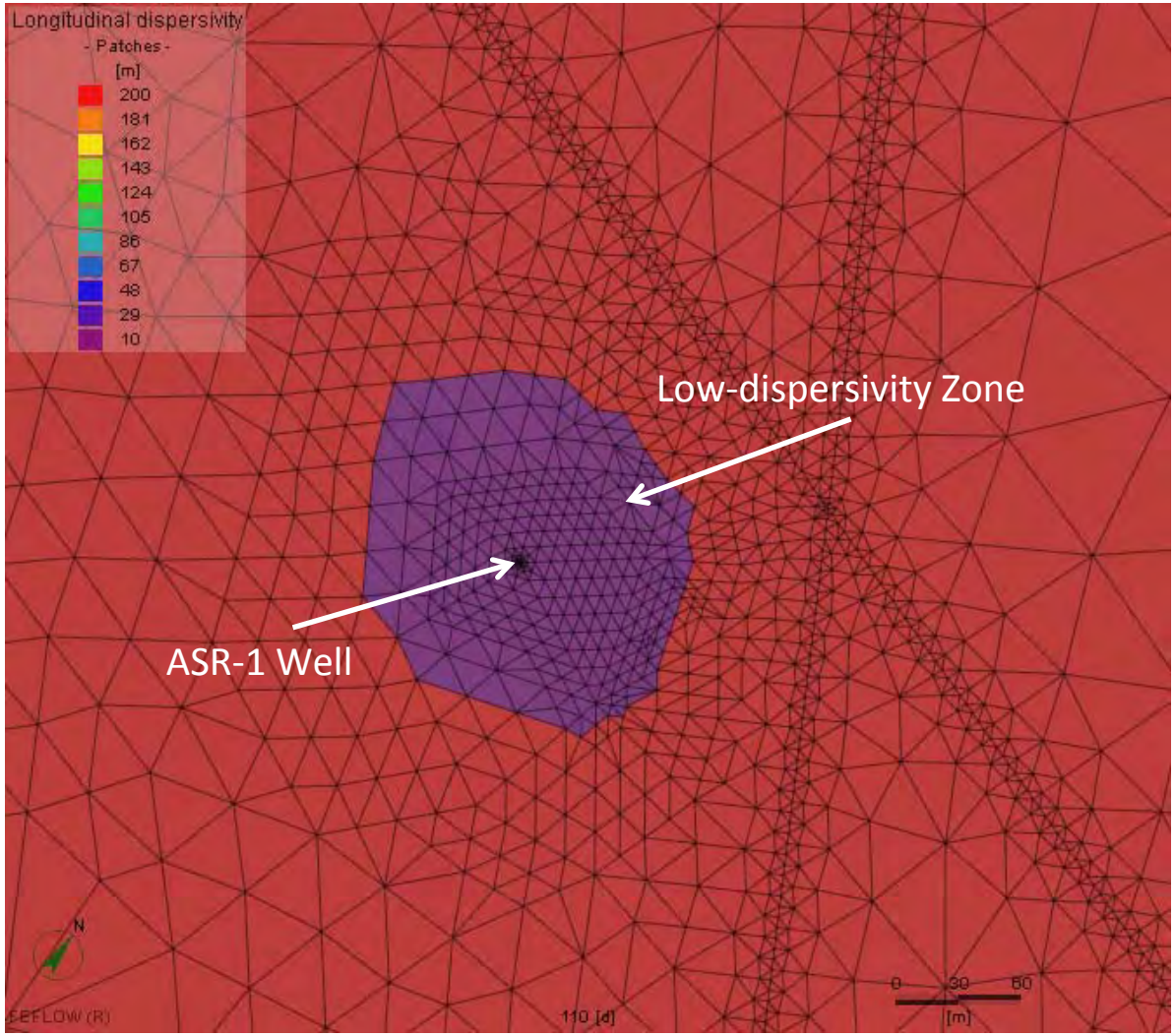


Title	Mass Transport Calibration Results for Cycle 5	Drawn	SLH
		Checked	JTI
Project Name	ASR Feasibility Grant Study	Reviewed	PAB
Project No.	0539747-400.04	FIGURE	12
Client Name	City of Dallas		
Date	September 2010		

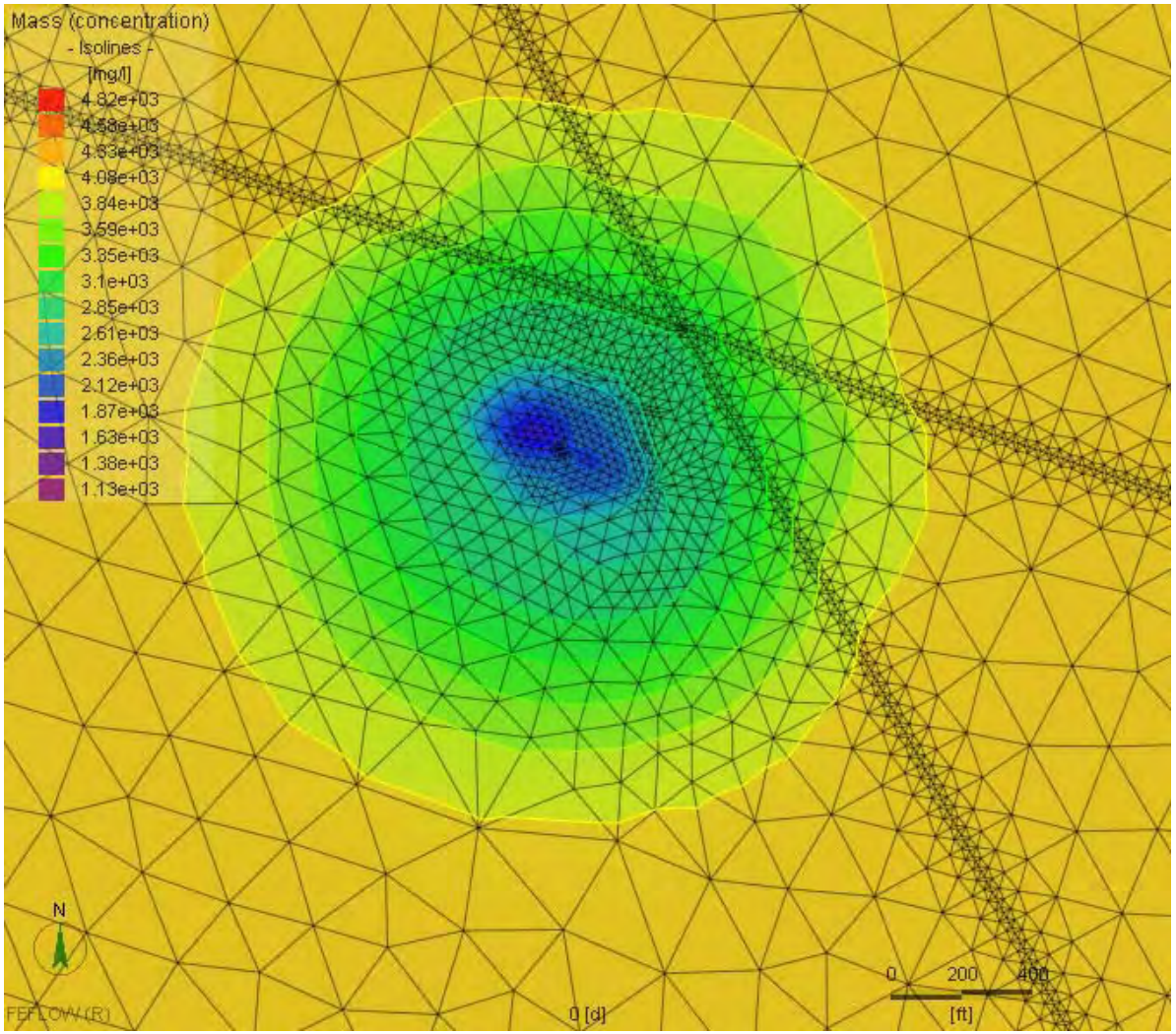
Golder Associates



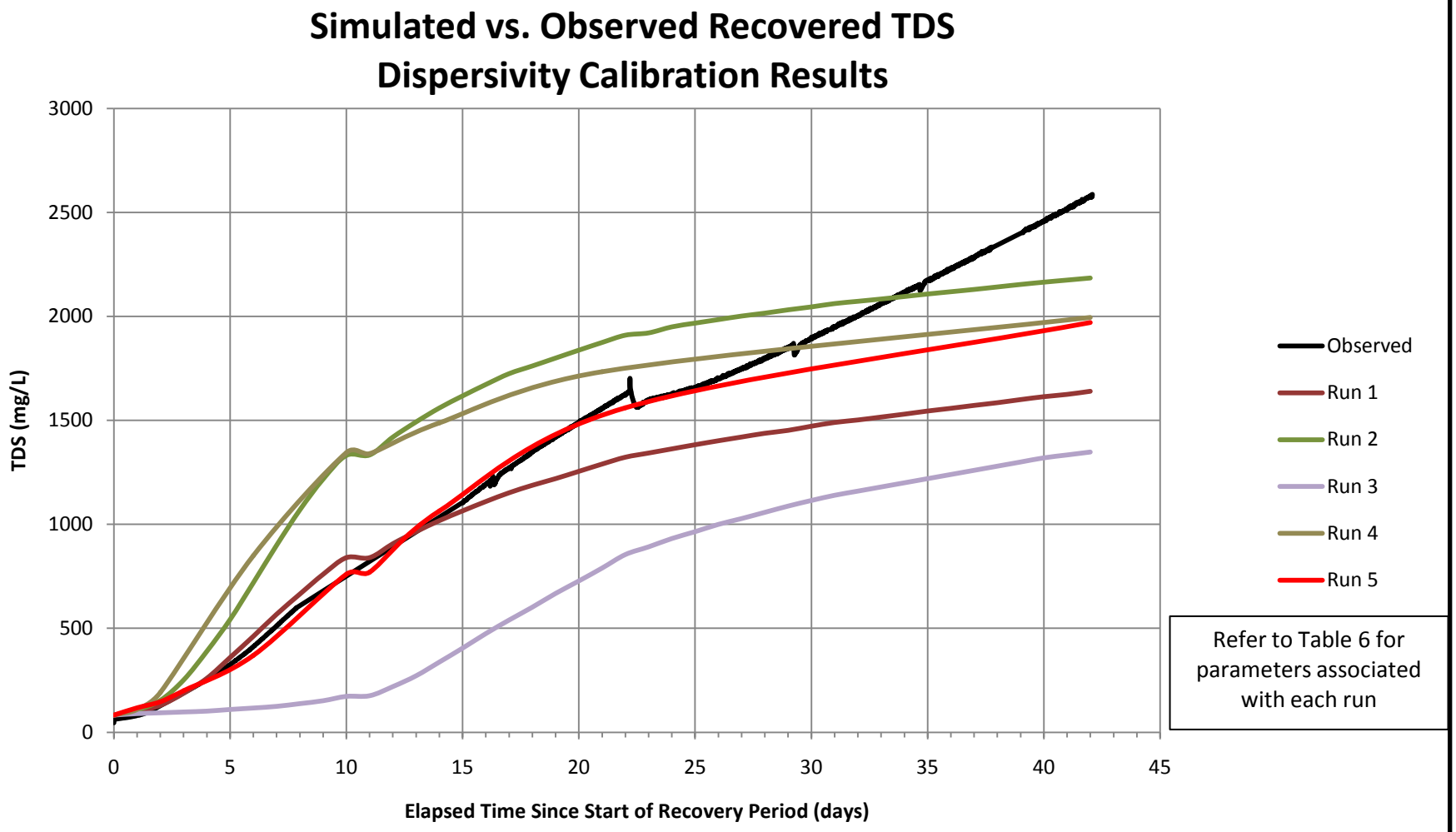
Golder Associates	Title: Dispersivity Calibration for Cycle 5	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study; Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas; Date: September 2010	FIGURE	13



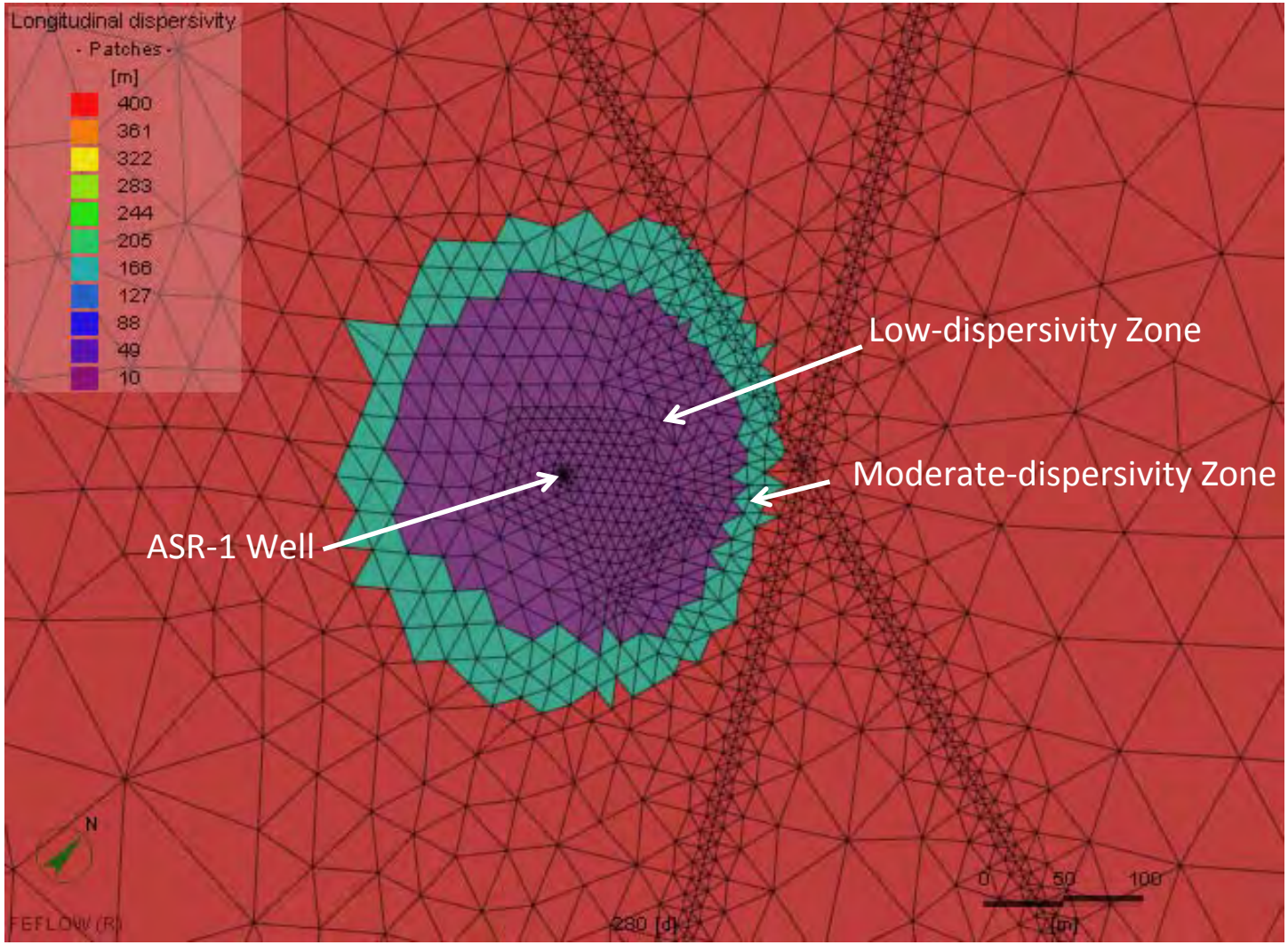
Golder Associates	Title: Final Calibrated Dispersivity Zone (Cycle 5)	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	14



Golder Associates	Title: Low-TDS stored water plume at end of Cycle 5 simulation	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 15



Golder Associates	Title: Dispersivity Calibration for Cycle 7	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study; Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas; Date: September 2010	FIGURE	16



Golder Associates	Title: Final Calibrated Dispersivity Zones (Cycle 7)	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	17

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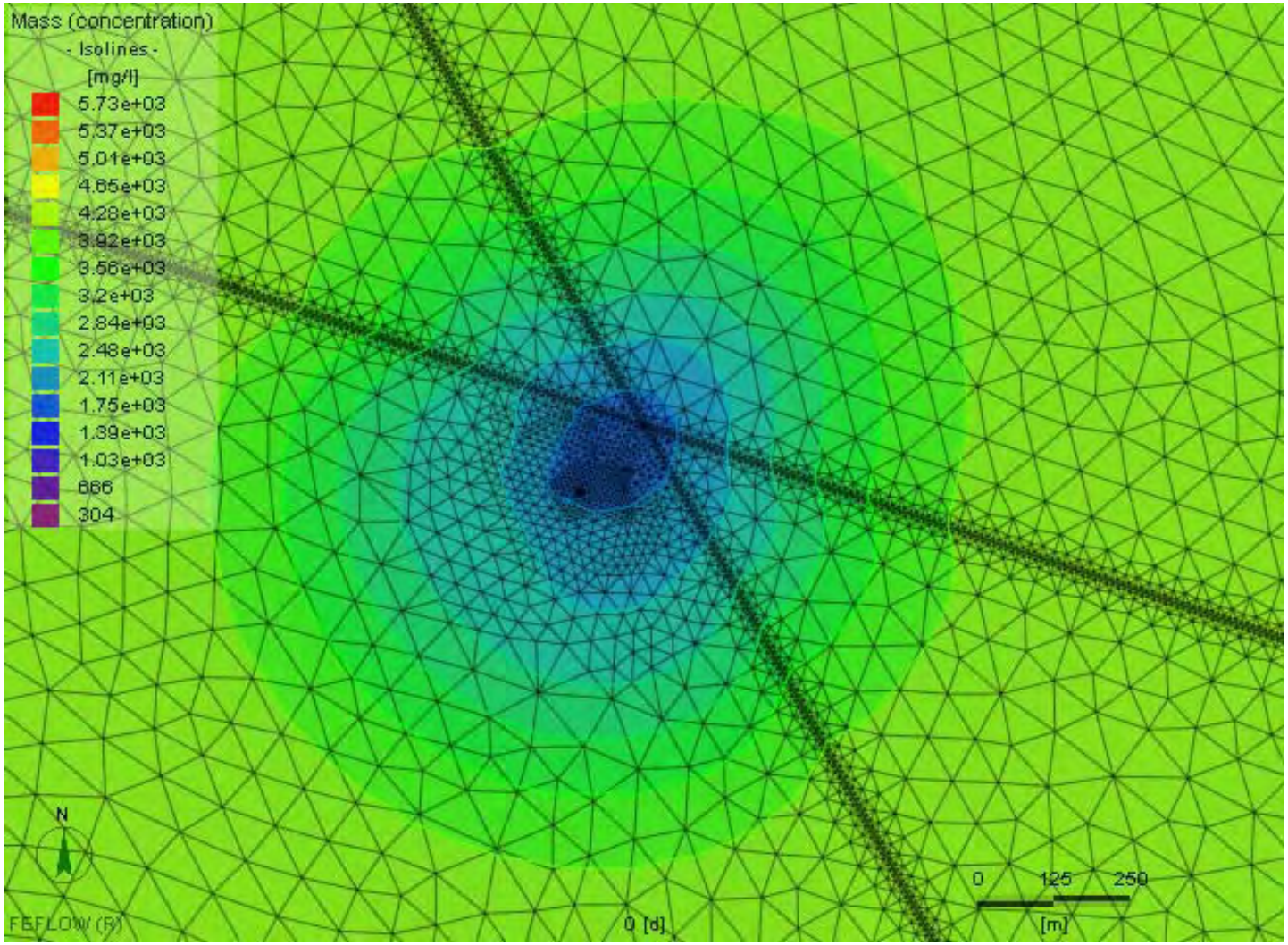
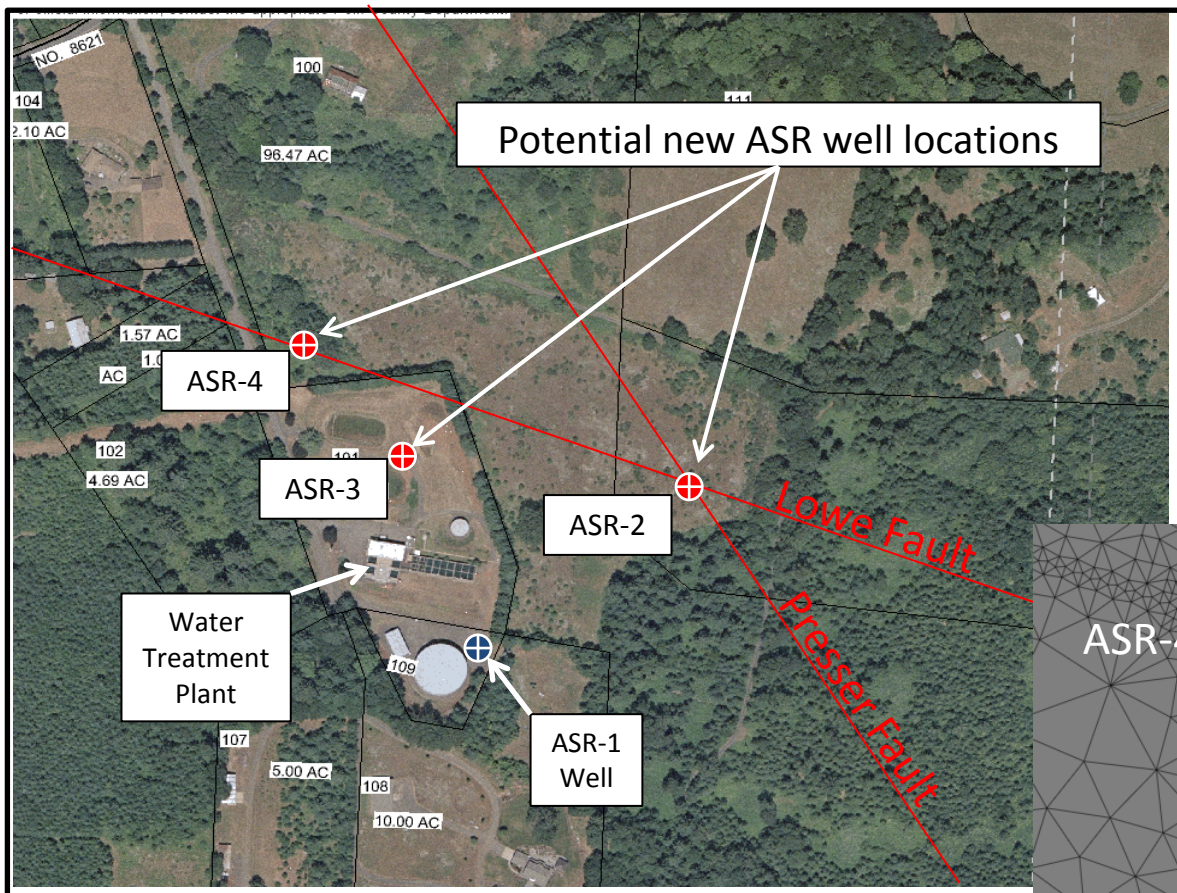
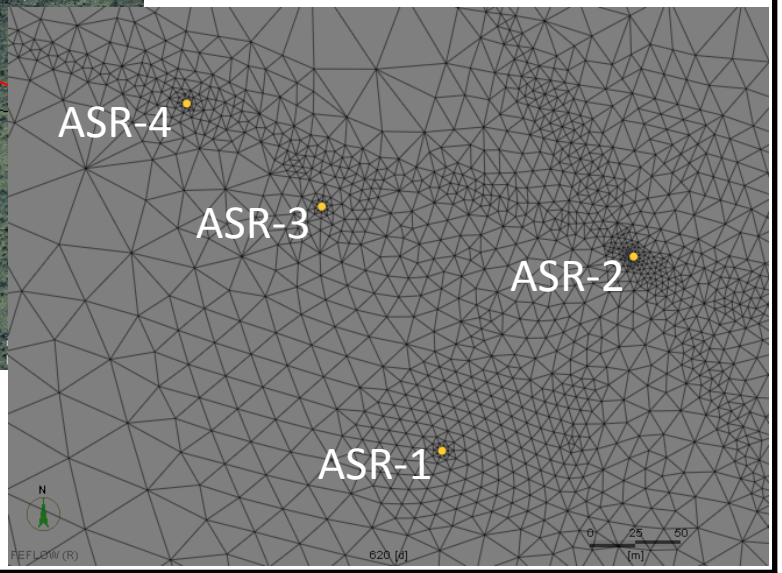


Golder Associates	Title: Low-TDS stored water plume at end of Cycle 7 simulation	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 18

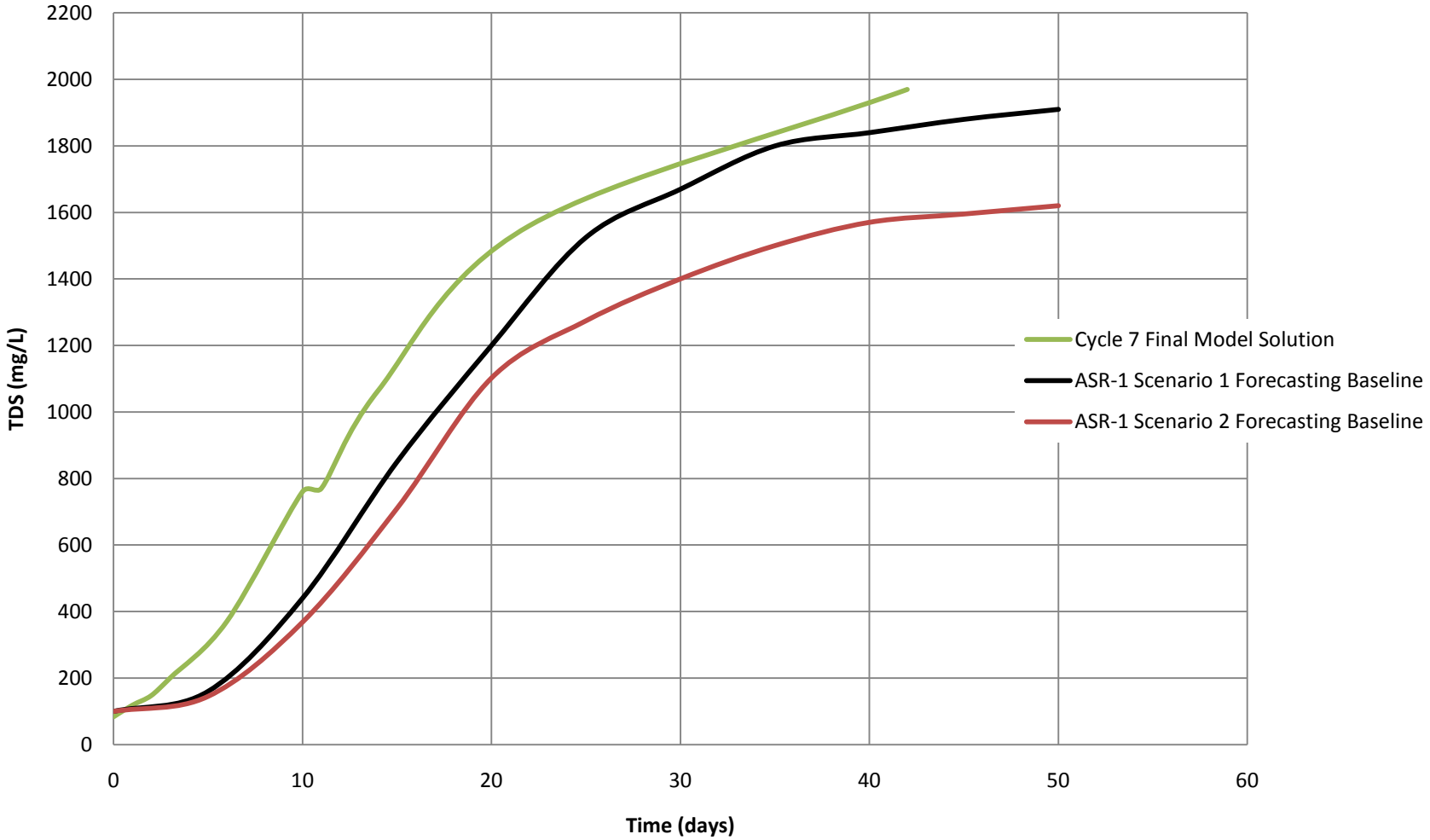


Well Representation Within Mesh

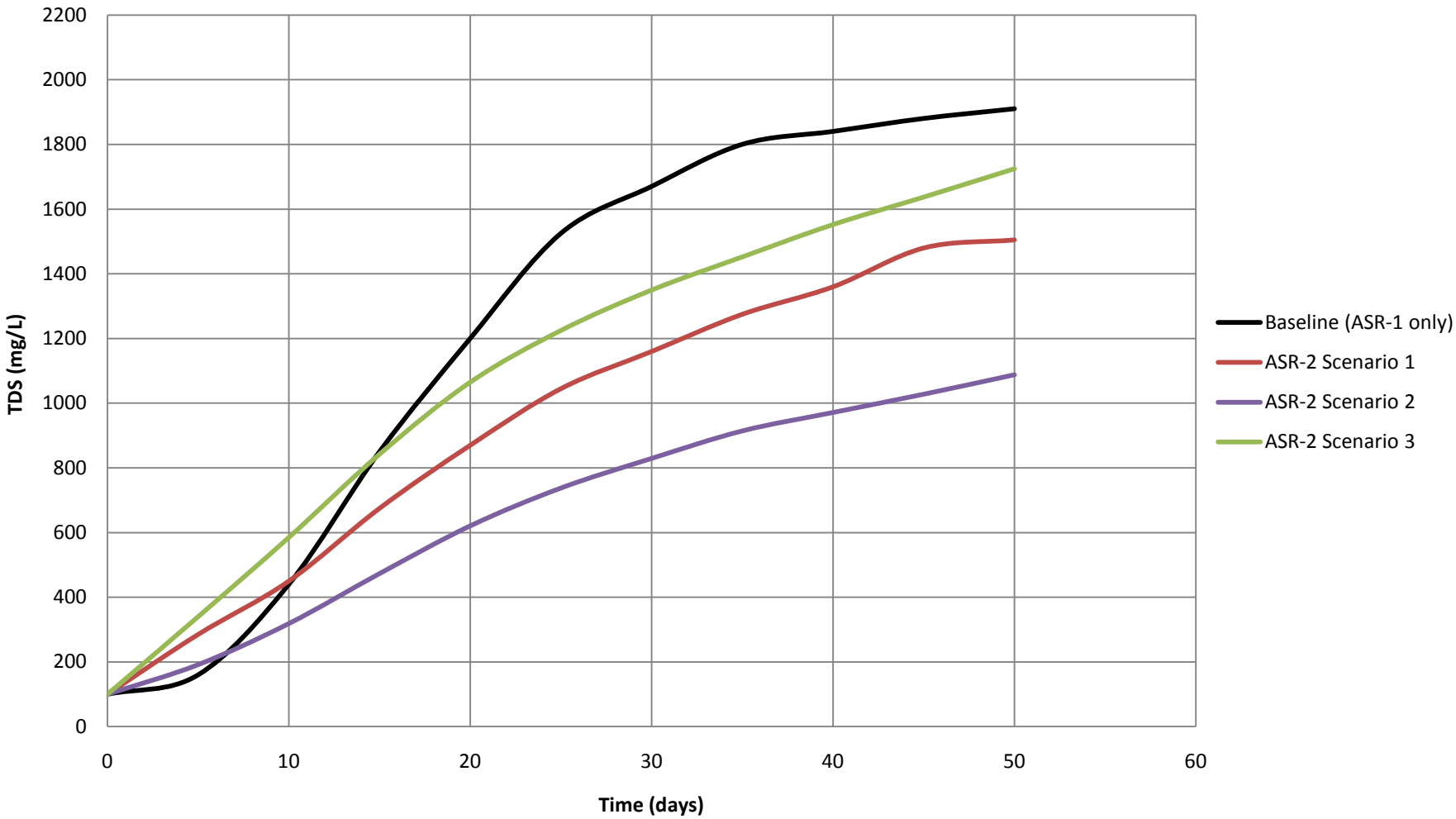


Golder Associates	Title: Potential new well locations	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 19

Recovered TDS: ASR-1 Forecasting Simulation

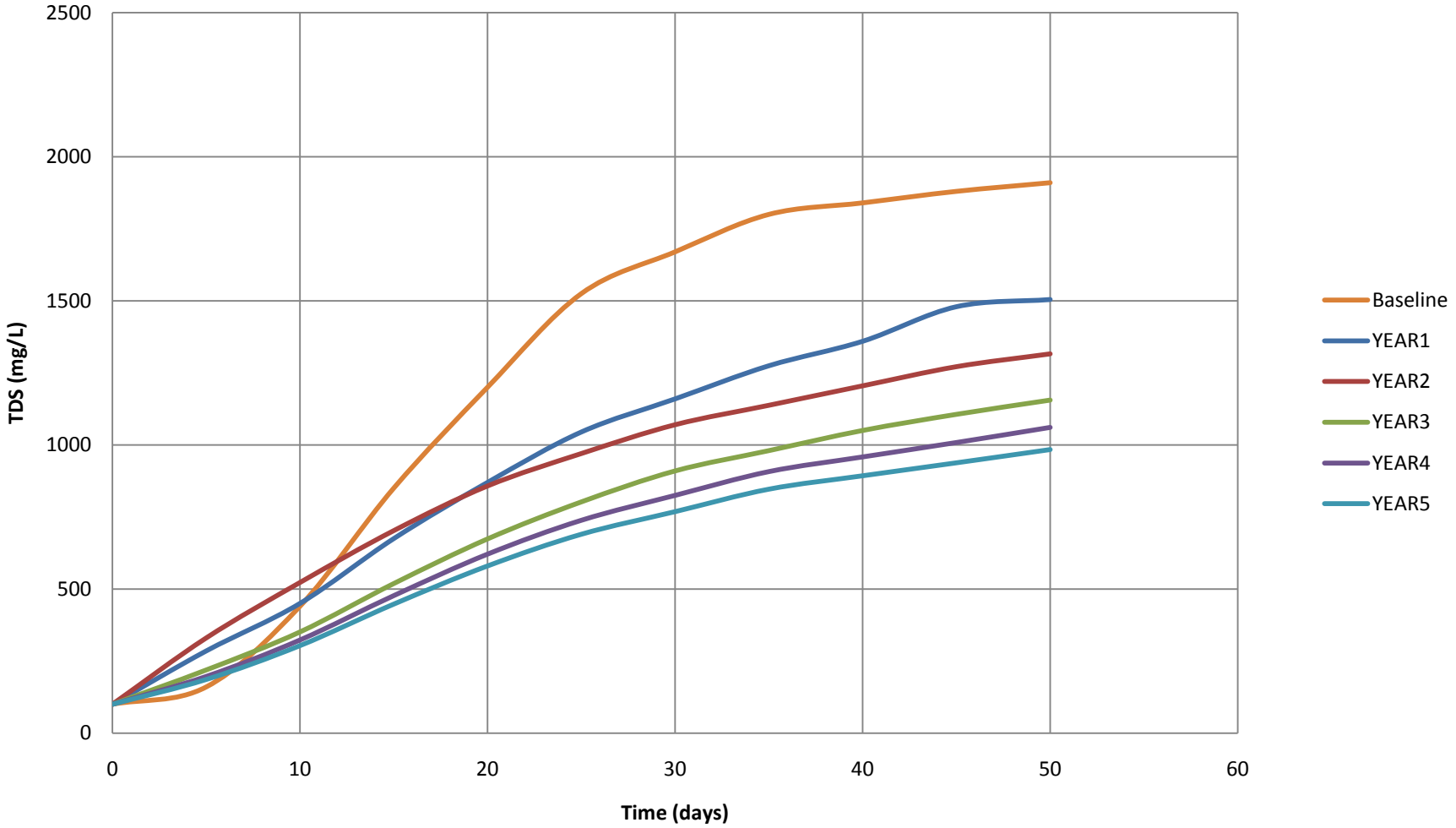


Golder Associates	Title: Recovered TDS: ASR-1 Forecasting Simulation	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	20

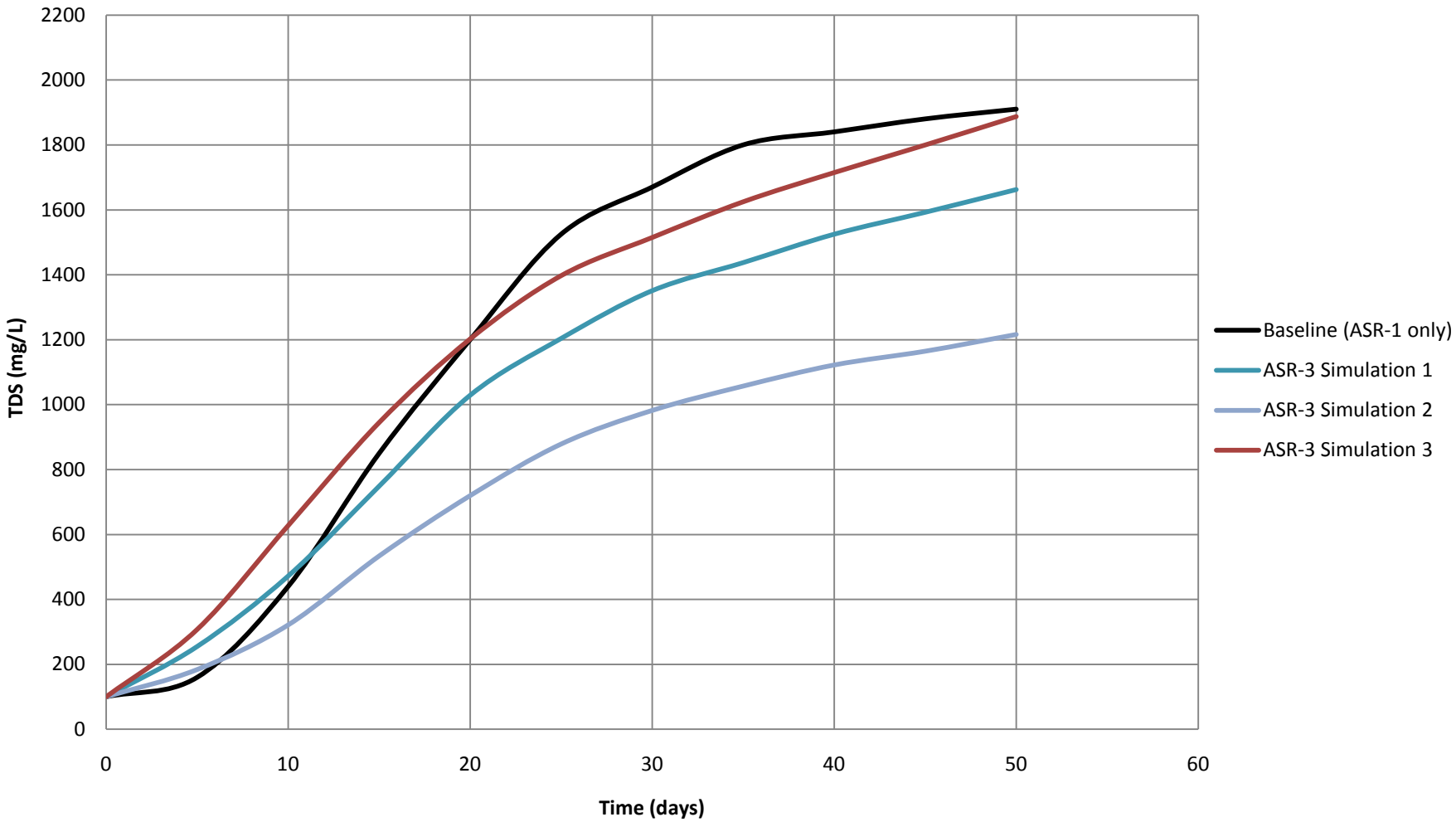


Golder Associates	Title: Average Recovered TDS: ASR-1 and ASR-2	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study; Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas; Date: September 2010	FIGURE	21

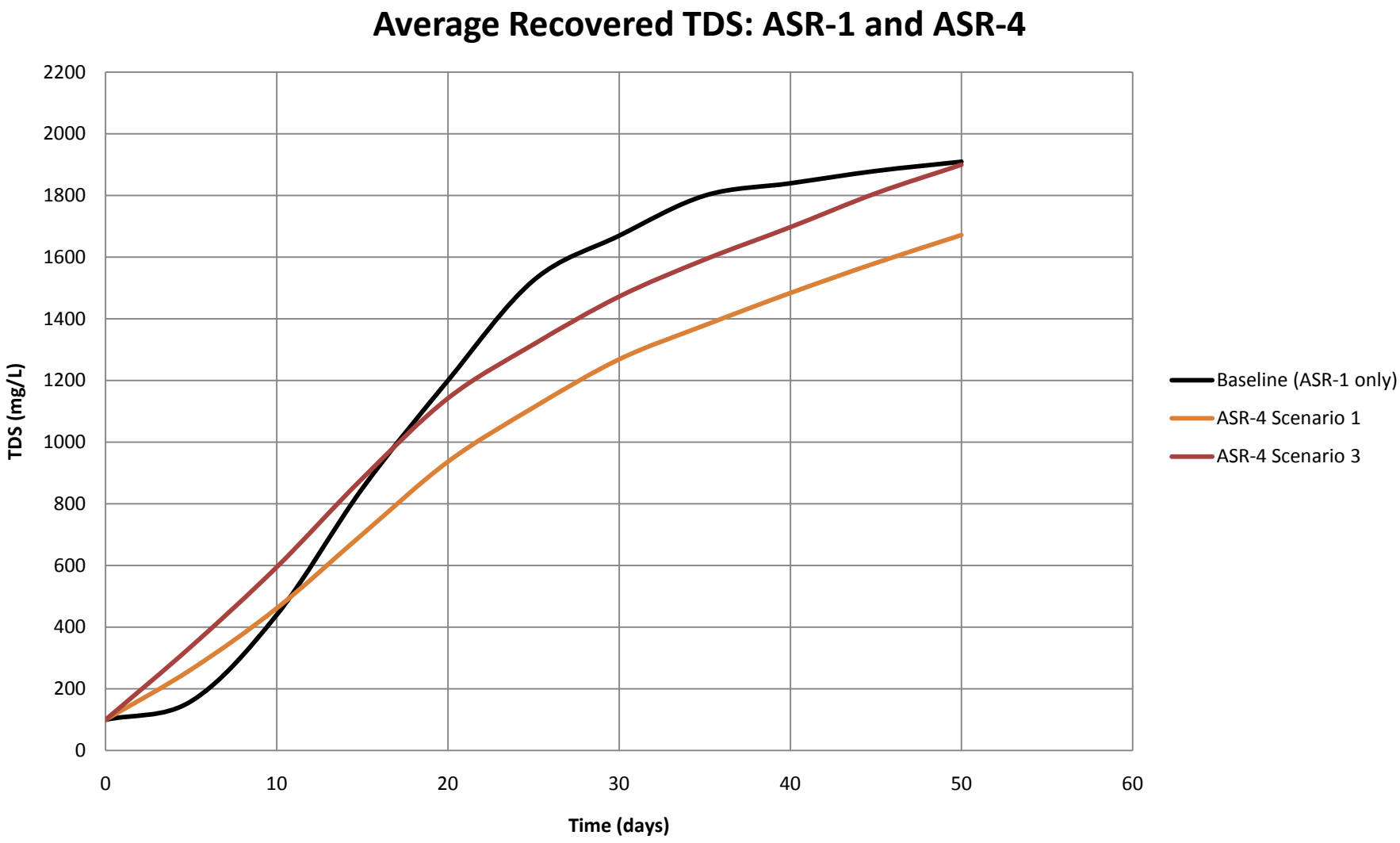
Average Recovered TDS: ASR-1 and ASR-2 5-Cycle Simulation



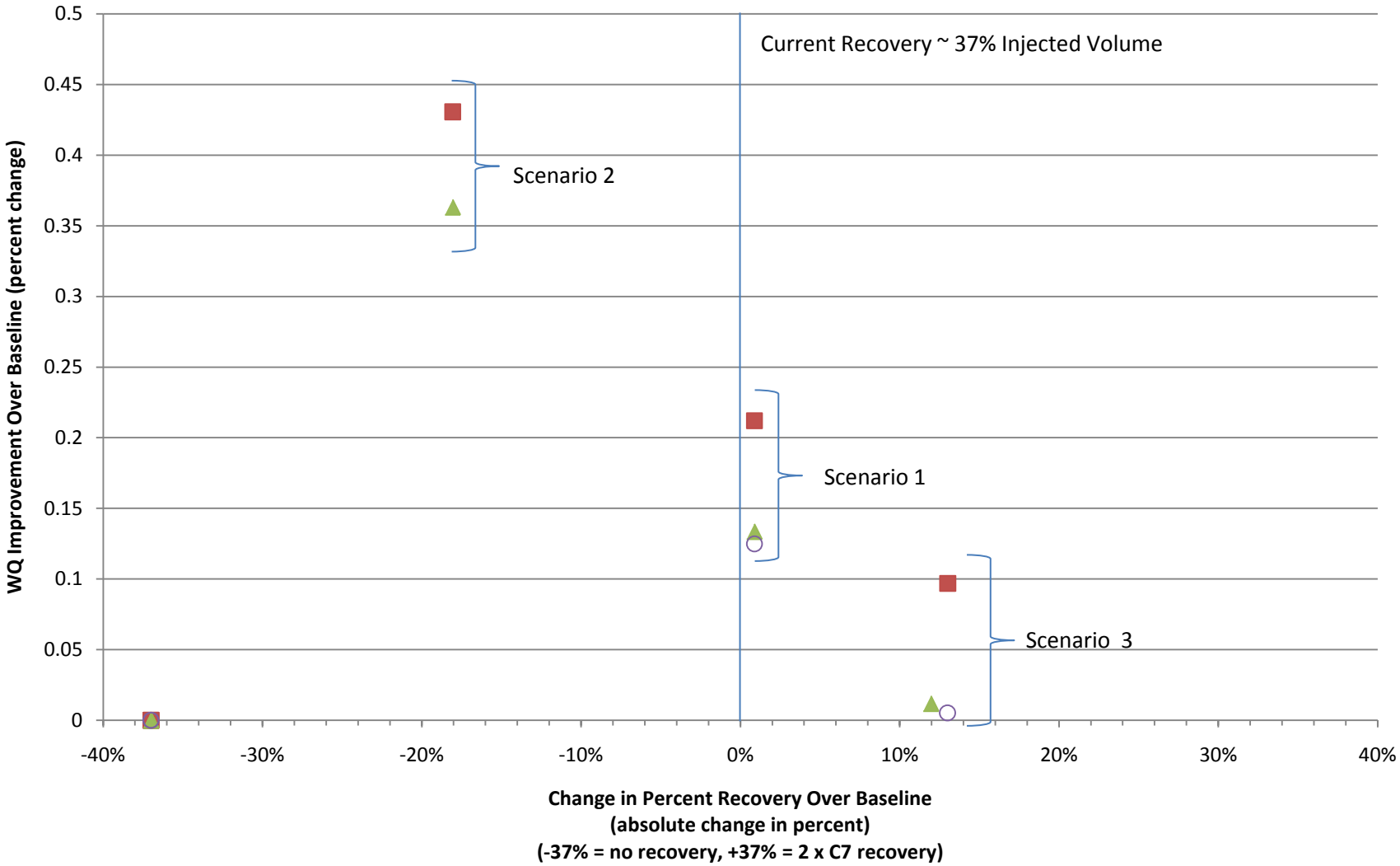
Golder Associates	Title: Average Recovered TDS: ASR-1 and ASR-2 5-Cycle Simulation		Drawn: SLH
			Checked: JTI
	Project Name: ASR Feasibility Grant Study	Project No.: 0539747-400.04	Reviewed: PAB
	Client Name: City of Dallas	Date: September 2010	FIGURE 22



Golder Associates	Title: Average Recovered TDS: ASR-1 and ASR-3	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	23



Golder Associates	Title: Average Recovered TDS: ASR-1 and ASR-4	Drawn	SLH
		Checked	JTI
	Project Name: ASR Feasibility Grant Study / Project No.: 0539747-400.04	Reviewed	PAB
	Client Name: City of Dallas / Date: September 2010	FIGURE	24



Golder Associates

PW1 + PW2
PW1 + PW3
PW1 + PW4

Title	Summary of Forecasting Simulation Results	Drawn	SLH
Project Name	ASR Feasibility Grant Study	Checked	JTI
Project No.	0539747-400.04	Reviewed	PAB
Client Name	City of Dallas	FIGURE	25
Date	September 2010		