APPENDIX E

EXTRACTION WELL PUMP TEST RESULTS AND MODFLOW MODEL SUMMARY

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Memorandum

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To: John Edwards, Anchor Environmental

Subject: NW Natural Gasco, Pump Test Analysis and MODFLOW Model Summary

Summary of Results

Three lines of investigation were conducted to determine aquifer properties. Water level data from extraction well PW-4 pump tests were evaluated using several analytical methods. Tide lag data measured in the shoreline monitoring wells were used to calculate hydraulic conductivity. Potentiometric surface gradient data were also used to evaluate hydraulic conductivity. The results of these analyses were incorporated into a groundwater flow model used to predict the effectiveness of nearshore extraction wells to contain site groundwater.

Analysis of pump test data produced estimates of hydraulic conductivity that are significantly lower in the nearshore shallow alluvium than in the nearshore intermediate and deep alluvium. The pump test data indicate that the shallow alluvium has an estimated hydraulic conductivity on the order of 10 ft/d while the intermediate and deep alluvium has a hydraulic conductivity on the order of 200 ft/d.

Analysis of tidal fluctuations at nearshore shallow, intermediate and deep wells showed that hydraulic conductivity in intermediate and deep alluvium is 20 to 50 times greater than the hydraulic conductivity in the shallow alluvium.

An analysis of gradients was conducted as another line of evidence to compare hydraulic conductivity in upland alluvium to nearshore alluvium. This analysis showed a marked contrast between hydraulic conductivity in upland alluvium compared to alluvium closer to the river. Combining this information with the pump test and tidal analysis shows that the upland alluvium and shallow nearshore alluvium have similar low hydraulic conductivity compared to the nearshore intermediate and deep alluvium.

A groundwater flow model was developed and calibrated to site water levels. Model calibration to nearshore wells was attained by using significantly higher hydraulic conductivity values in the intermediate and deep nearshore alluvium than in the shallow and upland alluvium. This is consistent with pump test analyses, analysis of tidal fluctuations, and analysis of groundwater gradients across the site.

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1.0 Pump Test Analyses

The PW-4 pump test consisted of pumping the shallow screen interval (PW-4-85) and intermediate screen interval (PW-4-118) both individually and together. The test included separate step-drawdown tests on each screen interval and a combined constant rate test on both screen intervals. The tests were conducted in July 2007 and included extensive continuous (one-minute frequency) monitoring of water levels in the pumping wells and observations wells for extended periods before, during, and after pumping. A summary of the rate and duration of tests is provided in the following table.

Test	Pumping Rate (gpm)	Duration (minutes)
PW-4-85 Step-Drawdown Test		
Step 1	20	240
Step 2	30	251
Step 3	40	954
PW-4-118 Step-Drawdown Test		
Step 1	30	240
Step 2	40	240
Step 3	50	521
Constant Rate Test		
PW-4-85	40	420
PW-4-118	50	420

Water levels during the tests were affected by river stage changes, which were primarily due to tidal fluctuations during the test period. Determining ambient water levels to determine drawdown at the test wells proved to be challenging.

1.1 PW-4-85 Step-drawdown Test

For this test, it was observed that water levels at PW-4-85, PW-4-118 and MW-20-120 were nearly identical prior to the test. During pumping, the water levels at PW-4-118 and MW-20-120 were identical and neither showed any significant change in water level due to pumping of PW-4-85 (Figure 1-1). Consequently, water levels at PW-4-118 were used as static water levels for computing drawdown at PW-4-85 (Figure 1-2).

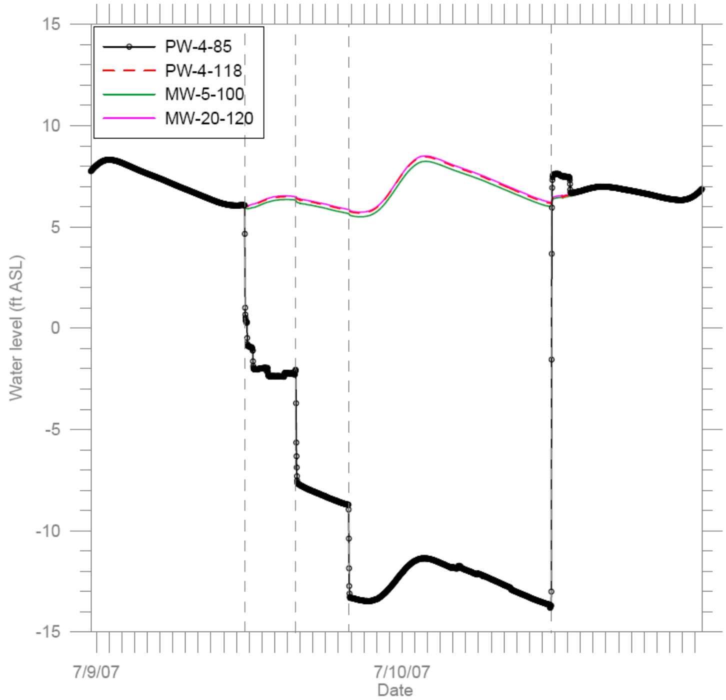

Figure 1-1 Water levels measured during the PW-4-85 Step-drawdown Test

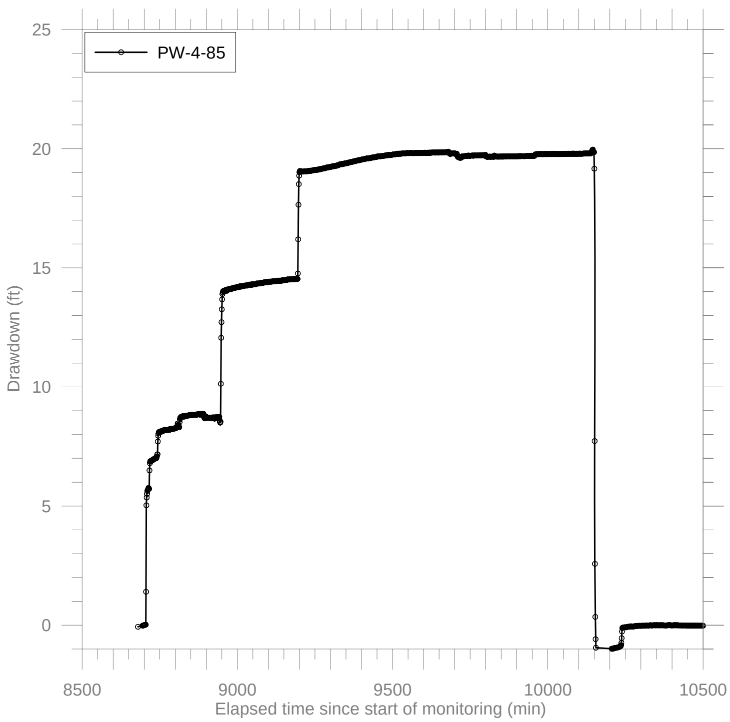

Figure 1-2 Drawdown computed during the PW-4-85 Step-drawdown Test

Drawdown during the PW-4-85 step-drawdown test was analyzed by several methods to estimate transmissivity: specific capacity and Theis analyses both including and neglecting nonlinear well losses. The specific capacity test assumes a specific capacity and discharge relationship given by (Jacob, 1947):

$$\frac{s_w}{Q} = B + CQ$$

Where: s_w is drawdown at a pump rate step (ft);
Q is the pump rate (gpm);
B is the inverse of the specific capacity (SC^{-1}); and
C is a well loss coefficient given by the slope of the line.

A plot of this relationship is shown on Figure 1-3. The intercept is 0.365, which gives a specific capacity of 2.74 gpm/ft, and the slope (well loss, C) is 0.0036 ft/gpm^2.

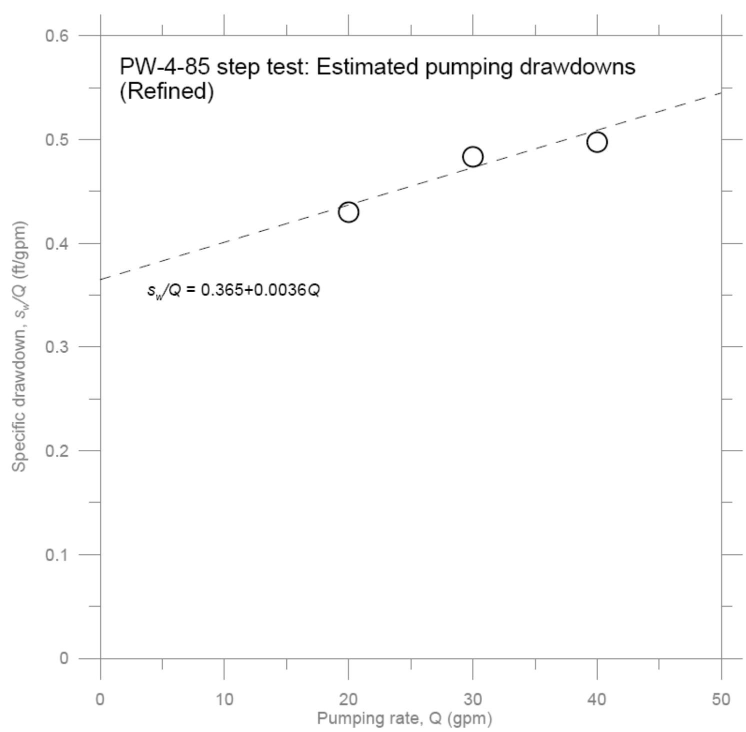

Figure 1-3 Regression analysis for specific capacity analysis with well loss

The low value of the well loss coefficient indicates that the specific capacity can be approximated as a constant value given by the average value over the three steps, which is approximately 2.3 gpm/ft.

In both cases, transmissivity was computed from the relationship (Driscoll, 1986):

$$T = 270\frac{Q}{s_w}$$

Where: T is transmissivity in ft^2/d; and
Q/s_w is specific capacity, SC, in gpm/ft.

Transmissivity was estimated with the generalized Theis (1935) analysis for various combinations of storage coefficient, skin loss factor, and well loss coefficient. The best combination of parameters included storage coefficient of 10^{-4} (confined), well loss of 0.0036 ft/gpm^2 (from the specific capacity analysis), and skin loss of 0.2823. This yielded a transmissivity estimate of 5900 ft^2/d. A plot of this Theis analysis is shown in Figure 1-4.

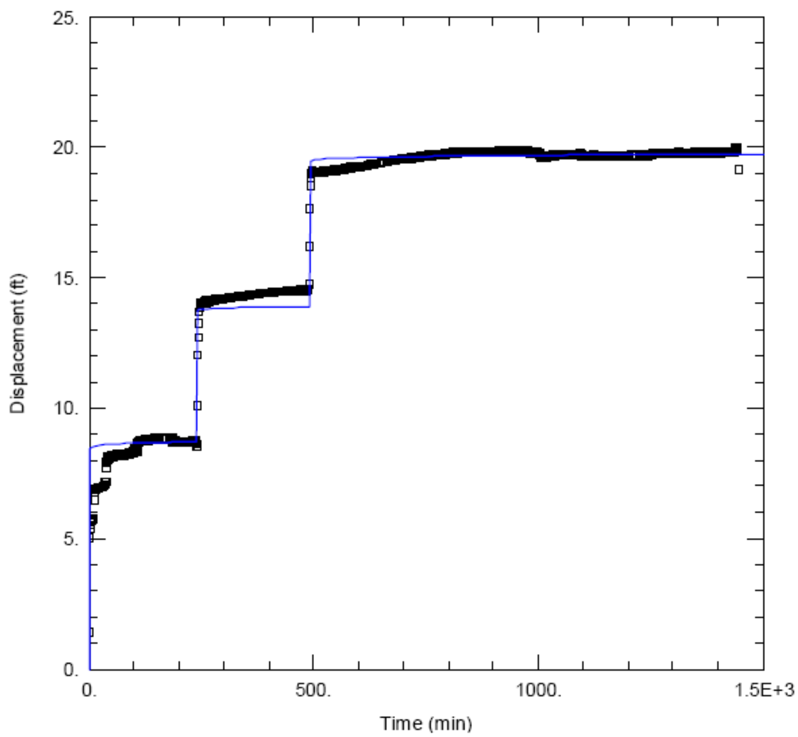

Figure 1-4 Theis analysis (blue line) compared to data (black symbols)

The results of the analyses of the PW-4-85 step-drawdown test are presented on the following table.

Analysis	Transmissivity (ft^2/d)	Thickness[1] (ft)	Hydraulic Conductivity (ft/d)
Specific capacity with well loss considered	730	10	73
Specific capacity without considering well loss	570	10	57
Theis solution	5900	70	84

1) For specific capacity calculations, the appropriate thickness is the screen interval since the screen is short relative to aquifer thickness. The Theis solution included a skin loss term and consequently the aquifer thickness is the appropriate value to use.

1.2 Constant Rate Test: PW-4-85 Analysis

As in the step-drawdown test, the initial problem was determining an ambient water level for computing drawdown. Water level data from MW-5-100, MW-20-120 and MW-5-175 were compared to water level data from PW-4-85 and PW-4-118 before, during and after pumping. MW-5-175 was the least affected by pumping (Figure 1-5).

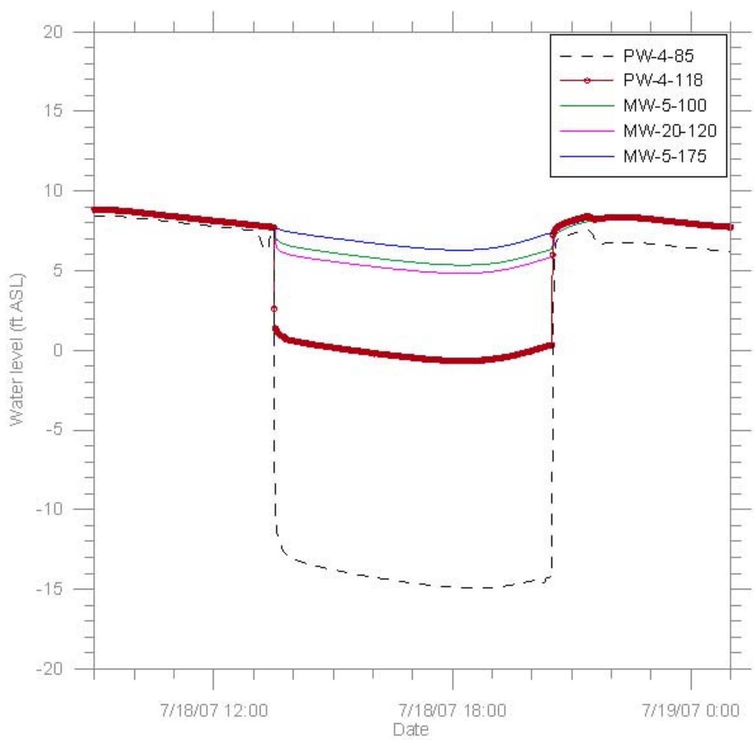

Figure 1-5 Water level response during PW-4 constant rate test

Consequently, water levels from this well were assumed to represent the water levels at PW-4-85 that would have been observed if the well had not been pumped, and were used to estimate the drawdowns caused by pumping the well. The estimated drawdowns are plotted in Figure 1-6.

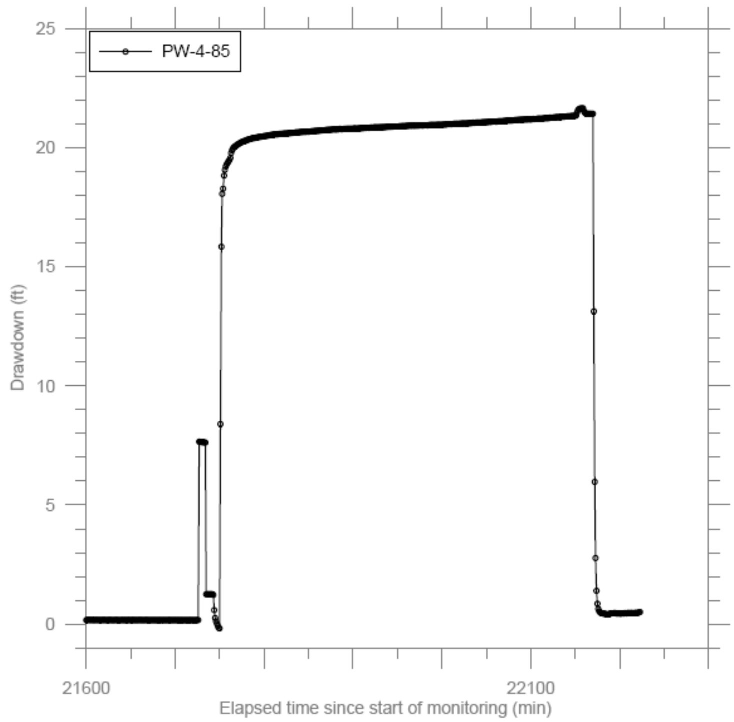

Figure 1-6 Drawdown at PW-4-85 during the constant rate test

Drawdown at PW-4-85 during the constant rate test was used to compute transmissivity using several approaches. First, the drawdown at the end of pumping was added to the specific capacity data used in the step-drawdown test and the transmissivity was recomputed. The results of the constant rate pumping test were consistent with the results from the step test. Consequently, including the constant rate test in the specific capacity analysis did not change the previously estimated transmissivity of 730 ft^2/d.

A second set of analyses was conducted using the Cooper-Jacob straight line method using early time and late time data. These analyses are shown in Figure 1-7. The flatter slope in the late time data may be an effect from the nearby river boundary and consequently, the early time data may be more representative of aquifer transmissivity.

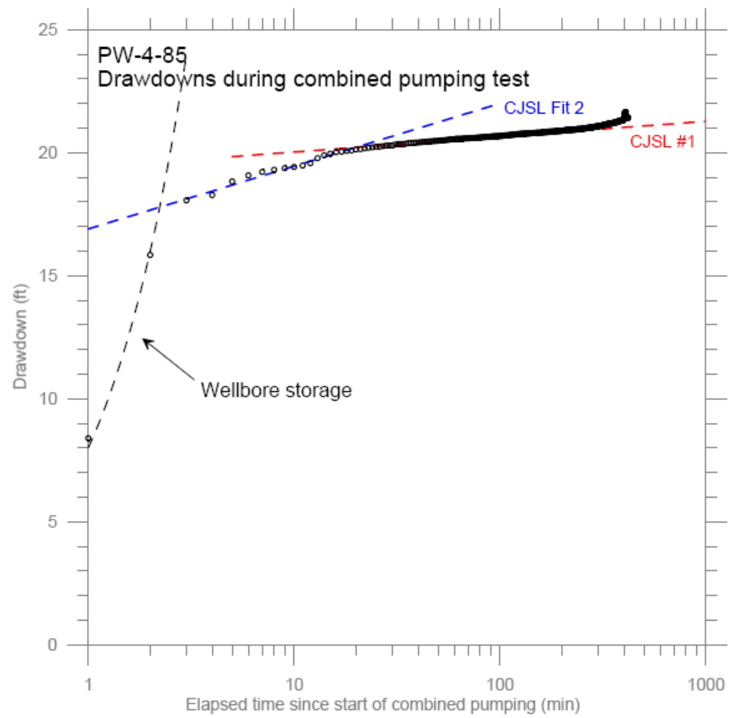

Figure 1-7 Time periods used for the Cooper-Jacob analysis

The results from the PW-4-85 constant rate test analyses are presented on the following table.

Analysis	Transmissivity (ft^2/d)	Thickness[1] (ft)	Hydraulic Conductivity (ft/d)
Specific capacity	730	10	73
Cooper-Jacob late time	2300	70	33
Cooper-Jacob early time	550	70	8

1) For specific capacity calculations, the appropriate thickness is the screen interval since the screen is short relative to aquifer thickness.

The Cooper-Jacob analysis showed significantly different results between the early time and late time analyses. The higher transmissivity in the late time may indicate an effect from the river boundary; therefore, the early time data (first 10 minutes of pumping) is a better representation of the response to pumping of the aquifer in the immediate vicinity of the well. Because the aquifer equilibrates so quickly and the time periods for the step test are long relative the equilibration time, it is likely that the specific capacity results are also affected by the river boundary.

1.3 PW-4-118 Step-drawdown Test

As in the case of the PW-4-85 test, the initial tasks were to identify a well that was not affected by pumping at the test well, relate those water levels to ambient water levels at the test well, and then use that relationship to compute drawdown during the test. Water levels at MW-5-100 and MW-20-120 showed an effect from pumping of PW-4-118, while MW-5-175 did not. The water levels at MW-5-175 are almost identical to water levels at PW-4-118 before and after the test. Therefore, the water levels at MW-5-175 during the test period were used directly to compute drawdown at the test well. Water level data from the PW-4-118 step-drawdown test is shown in Figure 1-8 and interpreted drawdowns are shown in Figure 1-9.

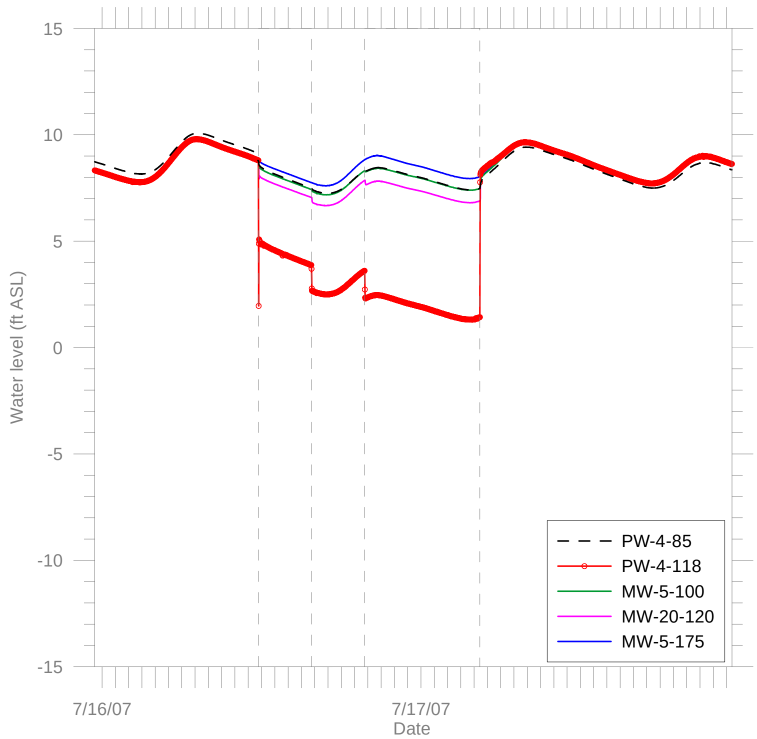

Figure 1-8 Water level data at the PW-4-118 test well and monitoring wells

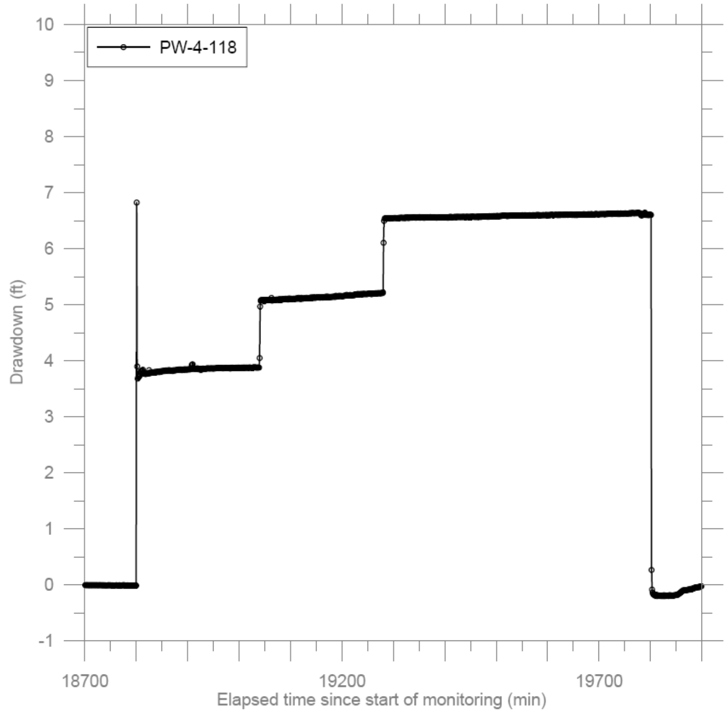

Figure 1-9 Computed drawdown at PW-4-118

Drawdown at PW-4-118 was analyzed using two methods: specific capacity analysis and Theis analysis. In contrast to the results from the PW-4-85 step testing, the results from PW-4-118 suggested that the specific capacity did not change with the pumping rate. Specific capacity at each step was approximately 7.8 gpm/ft, which translates to a transmissivity of about 2,100 ft^2/d.

The Theis analysis was conducted with a storage coefficient of 10^{-4} (confined). The specific capacity results indicate that the well loss coefficient is negligible so this was not included in the analysis. The estimated transmissivity is 16,000 ft^2/d. A plot of the results of the Theis analysis is shown in Figure 1-10.

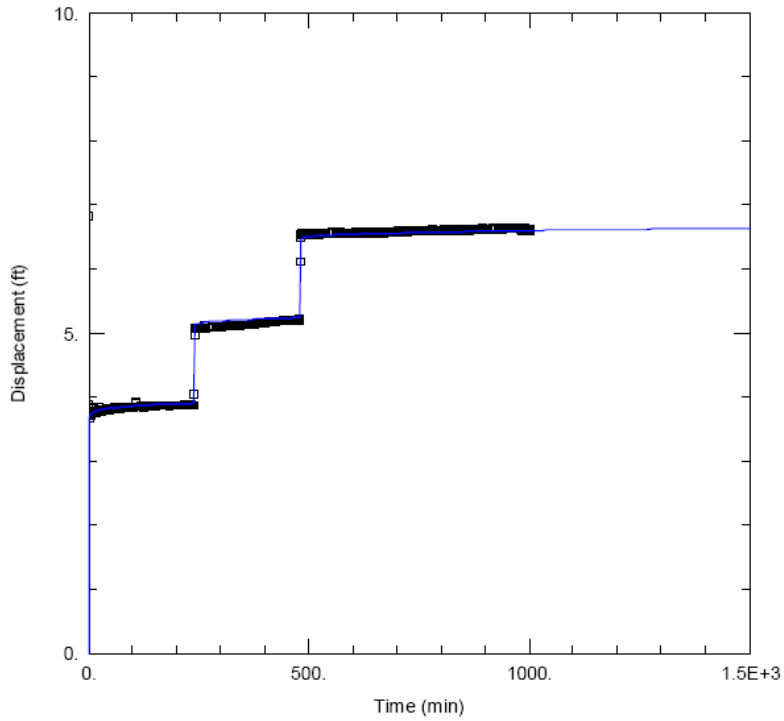

Figure 1-10 Theis analysis (blue line) compared to data (black symbols)

The results from the analysis of PW-4-118 step-drawdown test are summarized on the following table.

Analysis	Transmissivity (ft^2/d)	Thickness[1] (ft)	Hydraulic Conductivity (ft/d)
Specific capacity	2100	10	210
Theis solution	16000	100	160

1) For specific capacity calculations, the appropriate thickness is the screen interval since the screen is short relative to aquifer thickness. For the Theis analysis the aquifer thickness is the appropriate value to use.

1.4 Constant Rate Test: PW-4-118 Analysis

Drawdown was computed from water levels at MW-5-175 (see Section 1.2). The resulting drawdown at PW-4-118 is shown in Figure 1-11.

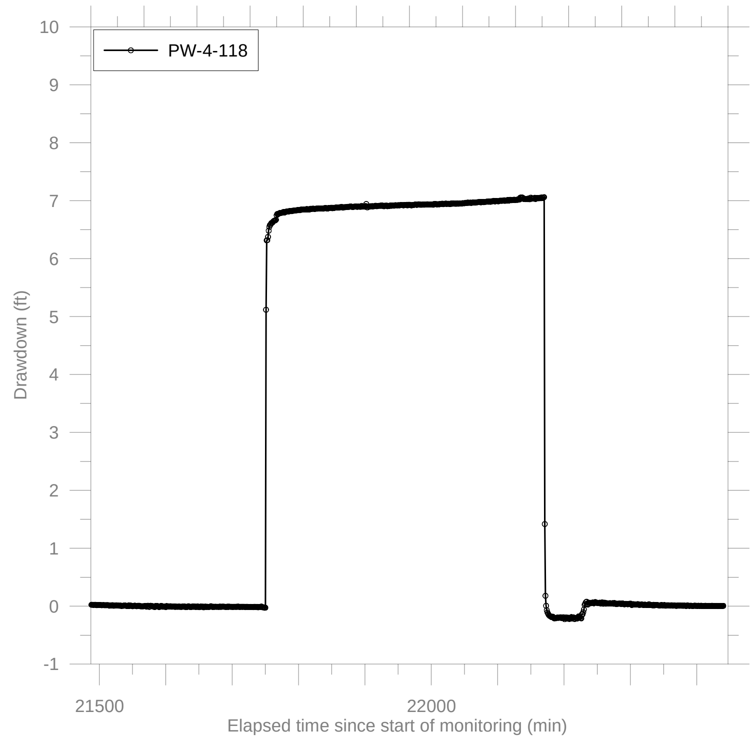

Figure 1-11 Drawdown at PW-4-118 during the constant rate pump test

Drawdown at PW-4-118 was analyzed using the specific capacity analysis and Theis analysis. The specific capacity for this pump test is 7.092 gpm/ft, which is close to the specific capacity from the step-drawdown test of 7.481 gpm/ft. The specific capacity yields a transmissivity of 1,900 ft^2/d.

The Theis analysis was conducted using the Cooper-Jacob straight line method as shown in Figure 1-12. This produced a transmissivity of 6,200 ft^2/d, but with a storage coefficient of 3×10^{-20}, which is unreasonably low. This suggests that the Cooper-Jacob analysis does not capture all the processes controlling drawdown at the well. Consequently, the analysis was conducted assuming a more reasonable storage coefficient of 10^{-4} and including skin loss in the analysis. This analysis produced a negative value for the skin loss, which is also not physically realistic.

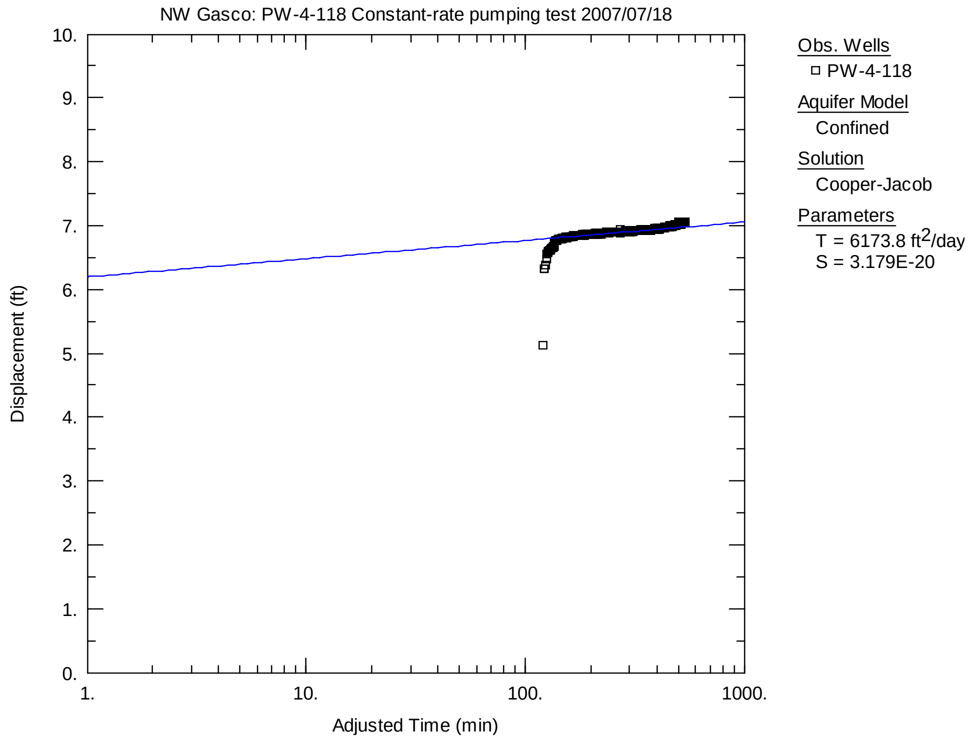

Figure 1-12 Results of Cooper-Jacob analysis on PW-4-118 constant rate test

The non-physical parameter estimates obtained from the transient analyses suggests that the analysis is affected by the influence of the Willamette River. The river is close to the pumping well, and leakage from the river may be induced relatively quickly, causing drawdown to stabilize. The 'true' transient may indeed be the relatively rapid response that is observed within about the first 20 minutes of pumping. In this case, the transient analysis is in effect being used to match quasi-steady drawdown. If this is the case, and in our opinion it is likely, the most representative estimate of transmissivity is developed from the specific capacity data, T = 1,900 ft^2/d.

The estimation of the transmissivity from the specific capacity assumes that the pumping well is open across the entire thickness of the aquifer. The well screen of PW-4-118 is 10 feet long. The aquifer is significantly thicker, and the transmissivity may therefore not be representative of the properties of the full thickness of the tested formation. For a stratified aquifer, as a working hypothesis, we assume that the "effective" thickness of the formation is the length of the well screen (Cooper, Bredehoeft, and Papadopulos, 1967).

$$K_H \approx \frac{T}{L_{eff}}$$

The horizontal hydraulic conductivity of the sediments in the vicinity of the PW-4-118 well screen is estimated by dividing the estimated transmissivity by the length of the well screen:

$$K_H \approx \frac{1{,}900 \text{ ft}^2/\text{d}}{10 \text{ ft}} = 190 \text{ ft/d}$$

1.5 Conclusions

Analysis of the constant rate test at PW-4-85 shows two responses: an early time response and a later time response. The early time response is indicative of conditions close to the pumping well before the influence of the river boundary becomes significant. The later time response is likely influenced by the river boundary. From this, the shallow alluvium is estimated to have a hydraulic conductivity on the order of 10 ft/d while the deeper alluvium has a hydraulic conductivity on the order of 200 ft/d.

Analyses of the PW-4-85 and PW-4-118 step-drawdown and constant rate tests show a considerable difference in the hydraulic conductivity in the shallow and deep alluvium. In both tests, the influence of the river boundary appears to affect the pump tests as seen in the rapid equilibration of the water levels with time.

2.0 Tidal Fluctuation Analysis

Water level data collected by transducers after the PW-4 pump test are show in Figure 2-1. This figure illustrates the tidal efficiencies at the various wells. Water levels at the wells follow the stage fluctuations in the river, but are attenuated and delayed in time compared to the river stage fluctuation. The attenuated fluctuation in the wells compared to the river tidal fluctuation is referred to as the tidal efficiency and is usually reported as a percentage of the river stage fluctuation. The delay in the peak water levels in the well compared to the timing in the river is referred to as the lag time.

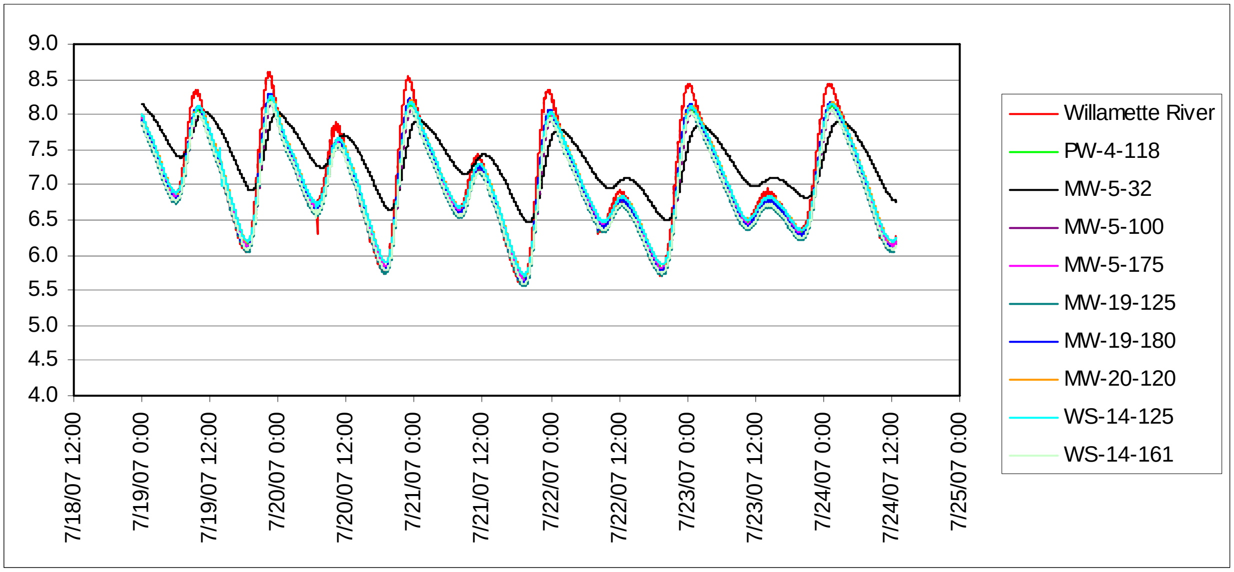

Figure 2-1 Water level and stage record at selected wells and on the Willamette River

Figure 2-1 shows that most wells track the river tidal stage very closely and with little lag time. Only MW-5-32 shows a markedly lower tidal efficiency and longer lag time. The intermediate and deep wells have tidal efficiencies ranging from 86 to 91 percent while the tidal efficiency at MW-5-32 is only 55 percent. The intermediate and deep wells have similar lag times on the order of 20 to 30 minutes, while the lag time at MW-5-32 is on the order of 90 minutes. The tidal efficiencies and lag times suggests that the shallow alluvium has a lower hydraulic conductivity than the intermediate and deep alluvium and that the hydraulic conductivity of the intermediate and deep alluvium are very similar.

Several methods have been developed to calculate hydraulic conductivity from tidal signals (Jacob 1950, Ferris 1951, Carr and van der Kamp 1969). However, tidal calculations can only be used to estimate the ratio of hydraulic conductivity and specific storage, known as the hydraulic diffusivity. The hydraulic conductivity cannot be estimated unless the specific storage is known or computed independently. Carr and van der Kamp (1969) developed a methodology for computing specific storage independently using tidal efficiency and then computing hydraulic conductivity using the time lag of the tidal signal at a well. The tidal efficiency is computed as the ratio of the standard deviation of water level measurements in a well to the standard deviation of stage measurements in the surface water body.

The relationship between specific storage and tidal efficiency is given by:

$$S_s = \frac{\theta\beta\gamma}{1 - TE_{true}}$$

Where: θ is porosity;
β is the compressibility of water;
γ is the specific weight of water; and
TE_{true} is the tidal efficiency corrected from the lag time.

$$TE_{true} = TE_{app} * \exp\left[\frac{2\pi * lag}{t_0}\right]$$

Where: TE_{app} is the measured tidal efficiency at a well;
lag is the measured tidal lag time at a well; and
t_0 is the tidal period.

It is clear from this relationship that TE_{true} must be less than one and that as it approaches one, S_s goes to infinity. This also means that the hydraulic conductivity K must also go to infinity since the ratio K/S_s is a constant in the tidal equation. If TE_{true} is greater than one, S_s becomes negative, which cannot be correct as a negative specific storage has no physical meaning. Unfortunately, this often happens for wells with high tidal efficiency and indeed happens in the present case.
Despite the unrealistic tidal efficiency, an estimate of K can still be made by substituting TE_{app} for TE_{true} in the equation for S_s above. Since TE_{true} is always greater than TE_{app}, the value of K will be under-estimated. Estimates of K are shown in the following table for different values of distance from the shoreline and porosity for deep and shallow wells.

Parameter	**Deep Case 1**	**Deep Case 2**	**Shallow Case 1**	**Shallow Case 2**
Lag time (minutes)	30	30	90	90
Tidal efficiency (dimensionless)	.90	.90	.55	.55
Specific gravity, γ (N/m^3)	9800	9800	9800	9800
Compressibility of water, β (m^2/N)	4.60E-10	4.60E-10	4.60E-10	4.60E-10
Porosity, θ	0.3	0.2	0.3	0.2
Specific storage, S_s (m^{-1})	1.4E-5	9.0E-6	3.0E-6	2.0E-6
Specific storage, S_s (ft^{-1})	4.1E-6	2.8E-6	9.2E-7	6.1E-7
Distance from Shore (ft)	280	305	280	305
Hydraulic conductivity, K (ft/d)	31	24	0.8	0.6

The *K* values shown on the table represent minimum values of *K* based on the tidal analysis. The tidal computation of *K* presented above depends on several parameters. Predicted *K* increases with increasing distance from shore, porosity and TE_{true} and with decreasing lag time. The distance from shore is the distance at which the tidal boundary acts on the aquifer, which may not be at the shoreline, but could be some distance offshore. TE_{true} is not actually known, and for high values of TE_{app} the TE_{true} correction can produce values close to one and raise the predicted *K* substantially. Consequently, computing *K* from TE_{app} carries a substantial caveat that the actual *K* could be considerably higher, but it does provide a lower bound estimate of *K*. However, comparing the computed *K* for the deep alluvium aquifer to the computed *K* for the shallow alluvium aquifer, the *K* of the deep alluvium is estimated to be 30 to 50 times greater than the *K* of the shallow alluvium. Results showing that *K* is substantially higher in the deep alluvium than in the shallow alluvium are consistent with the pump test analysis and are discussed further in the next section.

3.0 Analysis of Water Level Gradients

Water level gradients cannot be used to compute hydraulic conductivity or transmissivity unless the groundwater flow rate is known. However, the change in gradient can be directly related to the change in *K* if the groundwater flow rate is assumed to be constant and aquifer thickness is known. That is, if there are no significant changes in groundwater flow across the site, then changes in gradient can be related to changes in transmissivity and the aquifer thickness allows the transmissivity to be converted to an estimate of *K*.

Water level gradients were analyzed along a transect from MW-12-36 to MW-4-57 using time-averaged water level data collected from November 1998 through December 2005 (Figure 3-1).

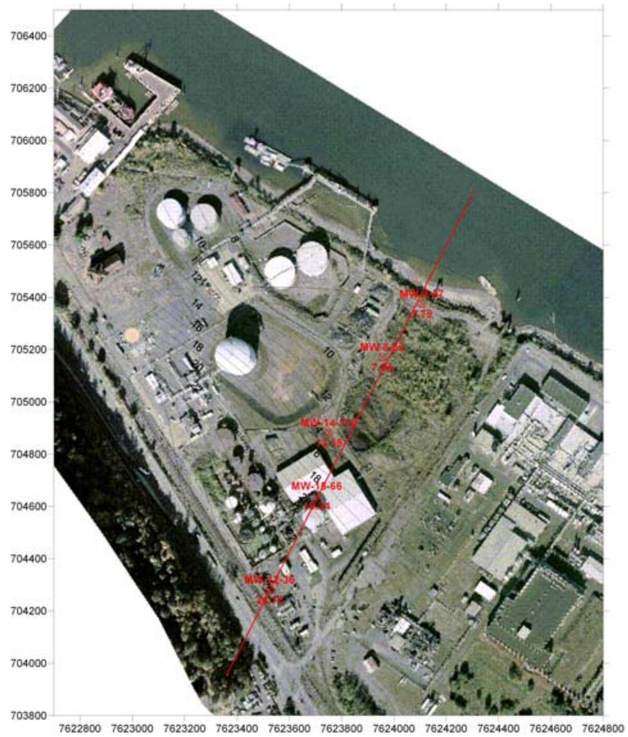

Figure 3-1 Location of Transect for Gradient Analysis

The time-averaged water level profile along this transect is shown on Figure 3-2.

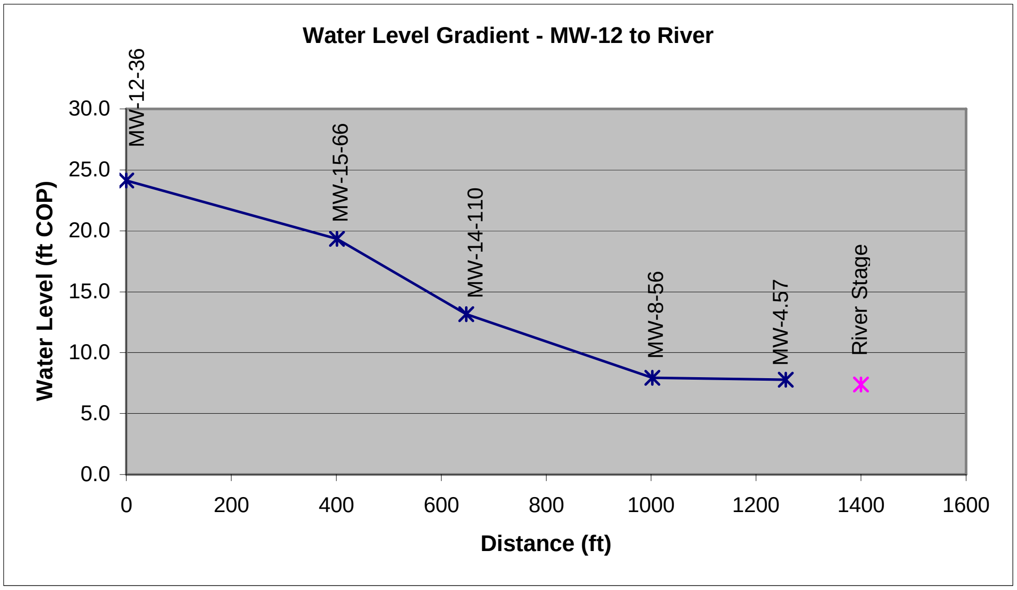

Figure 3-2 Water Level Profile from MW-12 to the River

The change in the water level profile is a function of the groundwater flow rate and the transmissivity. If the groundwater flow is assumed to be constant along the flow transect and the transect is approximately parallel to the groundwater flow direction, then the following relationship applies:

$$(Kbi)_1 = (Kbi)_2$$

where $(Kbi)_1$ is the product of the hydraulic conductivity, thickness and gradient between a pair of wells and $(Kbi)_2$ is the hydraulic conductivity, thickness and gradient between a second pair of wells.

The pair of wells do not need to be adjacent to each other and index notation is arbitrary so the upgradient well can be 1 and the downgradient well 2 or the reverse. The previous equation can be rearranged to:

$$\frac{K_2}{K_1} = \frac{(bi)_1}{(bi)_2}$$

This equation shows that the change in gradient can be used to relate the change in hydraulic conductivity along the transect. The results of this analysis are presented in the following table.

Well ID	Ave WL (City Datum)	Thickness (ft)	Distance (ft)	Average Thickness *b* (ft)	Gradient *i*	*bi*	K_2/K_1	Well Pairs
MW-12-36	24.12	17	401	24	0.011925	0.292172	0.30	MW-12 to MW-15 and MW-15 to MW-14
MW-15-66	19.34	32	246	38	0.025115	0.954353	0.70	MW-15 to MW-14 and MW-14 to MW-8
MW-14-110	13.15	44	354	92	0.014698	1.352237	14	MW-14 to MW-8 and MW-8 to MW-4
MW-8-56	7.94	140	254	154	0.000617	0.095271		
MW-4-57	7.79	169						

From this analysis, the hydraulic conductivity close to the river should be on the order of 20 to 45 times greater than the hydraulic conductivity upland from the river. However, from the pump test and tidal analyses, we saw a similar difference between the hydraulic conductivity of the nearshore shallow alluvium and the nearshore intermediate and deep alluvium. Putting all the information together, it is clear that the upland alluvium and the nearshore shallow alluvium have relatively low hydraulic conductivity while the nearshore intermediate and deep alluvium has a substantially higher hydraulic conductivity.

It is also worth noting in Figure 3-2 that the water level at MW-4-57 is very close to the river stage. This indicates that there is a strong connection between the river and the aquifer, which is also evident in the tidal response. This suggests that contact between the river and the aquifer is through higher *K* sandy material and that nearshore silt or silt lenses in the aquifer do not significantly affect the connection between the river and the aquifer. If silty sediments affected the connection between the river and the aquifer, there would be a greater water level drop between the aquifer and the river.

4.0 Groundwater Model Analysis

A groundwater flow model has been developed to evaluate groundwater flow in greater detail and to provide a tool for evaluation of Feasibility Study (FS) alternatives. The modeling approach has been presented to DEQ, so only an overview of the model setup and calibration is presented here.

The model extends from the BNSF bridge to the downstream end of the Gasco property and from the bluff west of the property to the east side of the navigation channel in the Willamette River. The overall model area is shown in Figure 4-1.

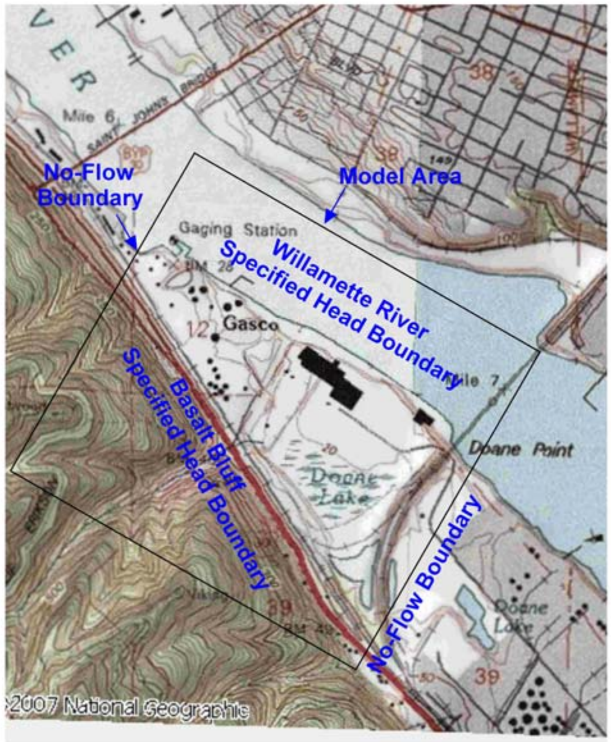

Figure 4-1 Groundwater model area

The model grid consists of 107 rows, 116 columns, and 14 layers. The rows and columns are uniformly spaced with 40 feet on a side. The 14 layers consist of one unconfined fill layer, which includes the Willamette River constant head, two silt layers and 11 layers in the alluvium. The layers in the alluvium were set up to test various FS alternatives with shoreline walls and/or extraction wells completed at different depths. Model cross sections are shown in Figures 4-3 and 4-4. Cross section locations are shown in Figure 4-2

Model boundary conditions are shown in Figure 4-1. Specified heads are used for the river boundary and in the fill and shallow alluvium along the southwest model boundary. No-flow boundaries are applied to the northwest and southeast. The top model boundary is a recharge boundary, which is discussed below. The model extends vertically to the basalt, which is treated as a no-flow boundary consistent with previous studies of the Portland Basin (SSPA, 1993; Morgan and McFarland, 1996; CH2M-Hill, 2001; SSPA, 2004).

Figure 4-2 Location of model cross sections

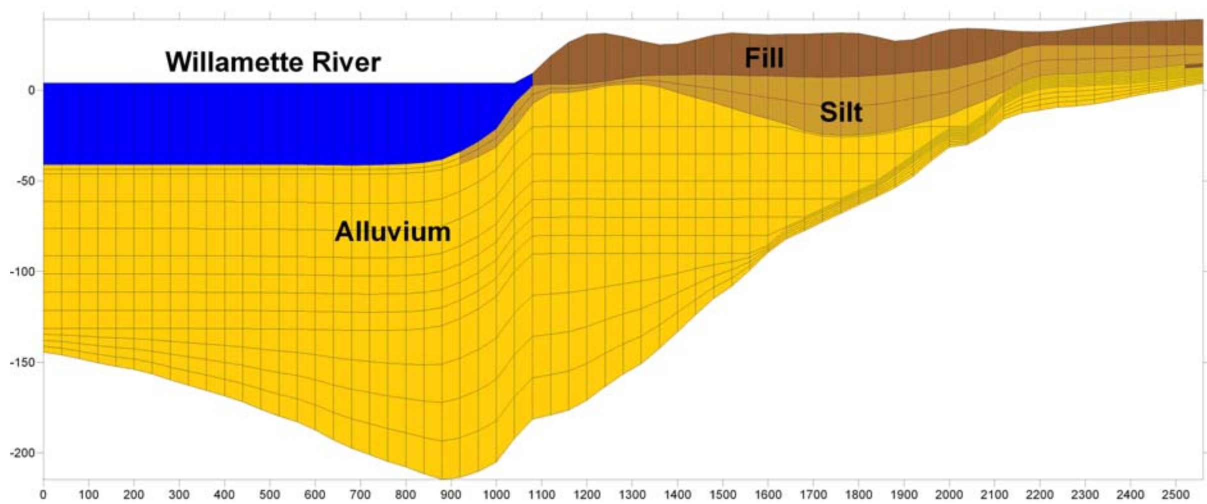

Figure 4-3 Cross section through model column 39

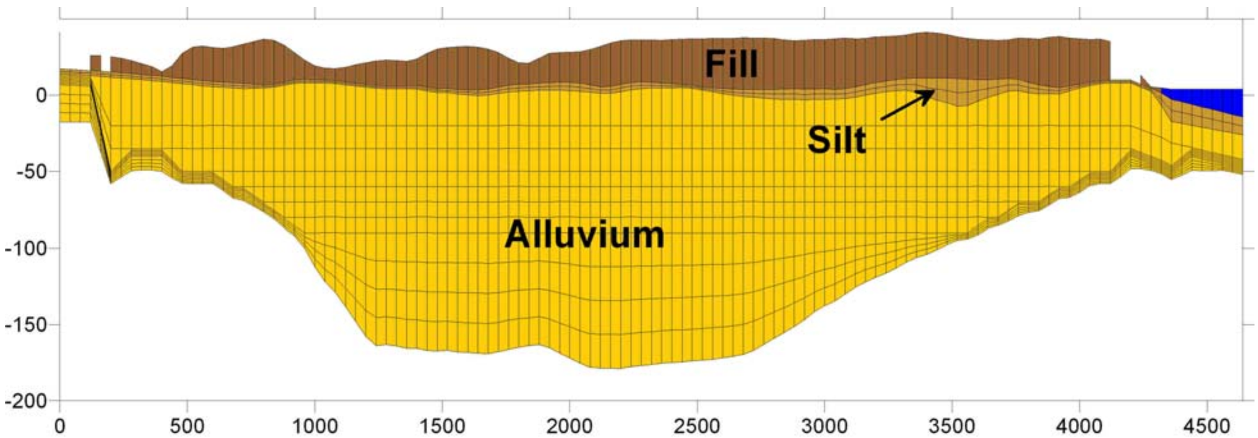

Figure 4-4 Cross section through model row 31

The model was calibrated to water level data averaged over the period from November 1998 to December 2005. Hydraulic conductivity values in the fill, silt and alluvium were adjusted during calibration as were the upgradient constant head boundary condition and areal recharge.

Recharge primarily affected water levels in the fill, which limits the range of recharge. The calibrated recharge was approximately 10 inches per year or about 25 percent of annual precipitation. A comparison of model results to average water levels on the site is shown in Figure 4-5.

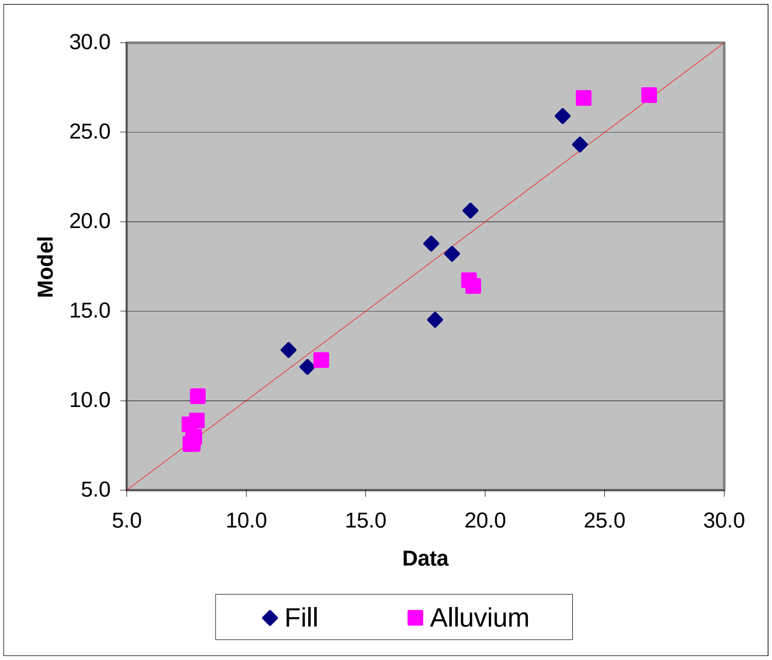

Figure 4-5 Model to data comparison for model calibration

The most difficult water levels to match between the model and data are the cluster of wells near the river. These wells have approximately the same water levels although they range in location from approximately 150 feet to over 400 feet from the river. The low gradient between these wells and the river indicates a high hydraulic conductivity zone between nearshore wells and the river. Consequently, a high hydraulic conductivity zone between the intermediate level wells and the river was incorporated in the model. A list of model parameters is given in the following table.

Parameter	Value
Recharge (in/yr)	10.5
Hydraulic conductivity – Fill (ft/d)	10
Hydraulic conductivity – Silt (ft/d)	0.5
Hydraulic conductivity – Upper Alluvium near river and Upland Alluvium (ft/d)	10
Hydraulic conductivity – Intermediate and deep Alluvium near and under River (ft/d)	300

The model is reasonably calibrated and suitable for evaluating FS alternatives. The model has presently been used to evaluate the following alternatives:

- groundwater pumping without a wall

- groundwater pumping with a wall completed to 65 feet below ground surface
- groundwater pumping with a wall completed to 90 feet below ground surface

The model was setup with 10 wells along the shore line (Figure 4-6) with each well pumping at 20 gpm. The wall simulations were conducted with low permeability cells between the wells and river.

Figure 4-6 Location of wells in the containment analysis

Nearshore walls were simulated by changing the hydraulic conductivity in a row of model cells between the extraction wells and the shoreline. The wall is represented by a hydraulic conductivity of 0.01 ft/d. A model cross section showing the orientation of the wall and extraction wells is shown in Figure 4-7.

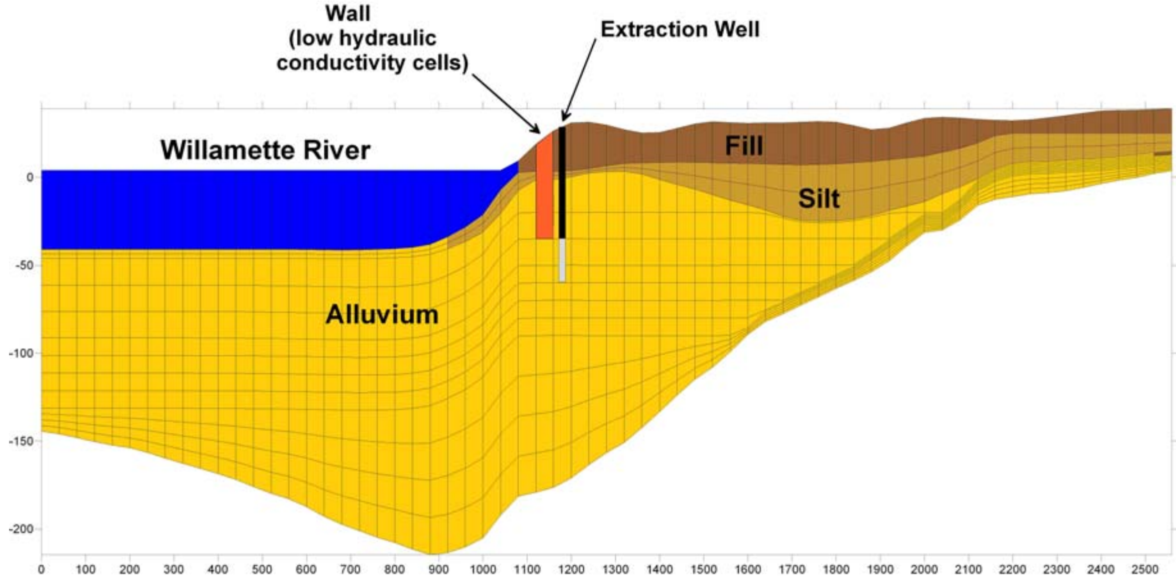

Figure 4-7 Model cross section showing relationship between extraction wells, nearshore wall, and model layers.

Containment was evaluated using the particle tracking code, Path3D (Zheng 1988; SSPA 2001). Particles were started at shallow, intermediate and deep elevations to evaluate the vertical as well as the horizontal extent of capture. In each of the above cases, containment was achieved at 20 gpm per well. Particle path lines in a containment analysis are shown in Figure 4-8. Containment is indicated by all particles reaching a well instead of the river.

Figure 4-8 Example of successful containment

To evaluate the significance of the wall and wall depth on pumping, the pump rate was systematically reduced until containment was no longer achieved. In all three cases particle breakthrough occurs between 12 and 14 gpm. The narrow range in pump rates for breakthrough indicates that the wall does not have a significant effect on groundwater containment. This is due to the considerable saturated thickness below even the deepest wall simulated.

The capture zone analysis was also used to evaluate the depth of capture. One of the objectives of the modeling analysis was to determine the pump rate necessary to capture to approximately 130 feet bgs based on the vertical extent of contamination in the aquifer. The capture zone analysis showed that a pump rate of 20 gpm per well was sufficient to capture the full vertical extent of the aquifer and that fine tuning the pump rate to only capture to a specific vertical zone was not practical. This is due to the tendency for breakthrough to occur horizontally around the edges of the wellfield even though the capture zone extends to the base of the aquifer in the center of the wellfield.

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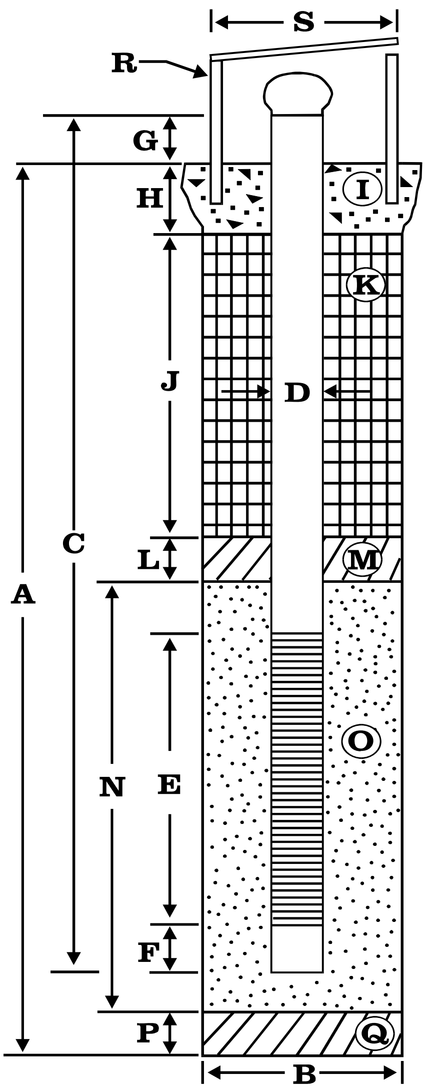
WELL DETAILS

Project Number:	000029-02	Boring/Well No.:	PW-4-85
Client Name:	NW Natural	Top of Casing Elev.:	26.82
Project Name:	GASCO	Ground Surface Elev.:	25.2
Location:	Portland, Oregon	Installation Date:	6/20/07
Driller:	Boart Longyear	Permit/Start Card No.:	191823



Depth (feet)	Elev. (ft, msl)
NA	NA
1.6	26.82
0.0	25.2
10	15.2
67.2	-42.0
69.5	-44.3
75.0	-49.8
85.0	-59.8
95.0	-69.8
85.0	-59.8
95.0	-69.8

EXPLORATORY BORING

A. Total depth: 95 ft.
B. Diameter 16 in.
Drilling method: Cable Tool

WELL CONSTRUCTION

C. Well casing length: 96.6 ft.
Well casing material: mild steel
D. Well casing diameter: 8 in.
E. Well screen length: 10 ft.
Well screen type: Continuous Slot Stainless
Well screen slot size: 0.035 in.
F. Well sump/end cap length: 10 ft.
G. Well casing height (stickup): 1.6 ft.
H. Surface seal thickness: 10 ft.
I. Surface seal material: Cement Grout
J. Annular seal thickness: 57.2 ft.
K. Annular seal material: Cement Grout
L. Filter pack seal thickness: 2.3 ft.
M. Filter pack seal material: Sugar Sand
N. Sand pack thickness: 15.5 ft.
O. Sand pack material: 10x20 Silica Sand
P. Bottom material thickness: 10 ft.
Q. Bottom material: Cement Grout
R. Protective casing material: NA
Well centralizer depths: NA ft.
S. Protective casing diameter: NA in.

NOTES:

Horizontal Datum: NAD83(91)

Installed by: Craig Wells

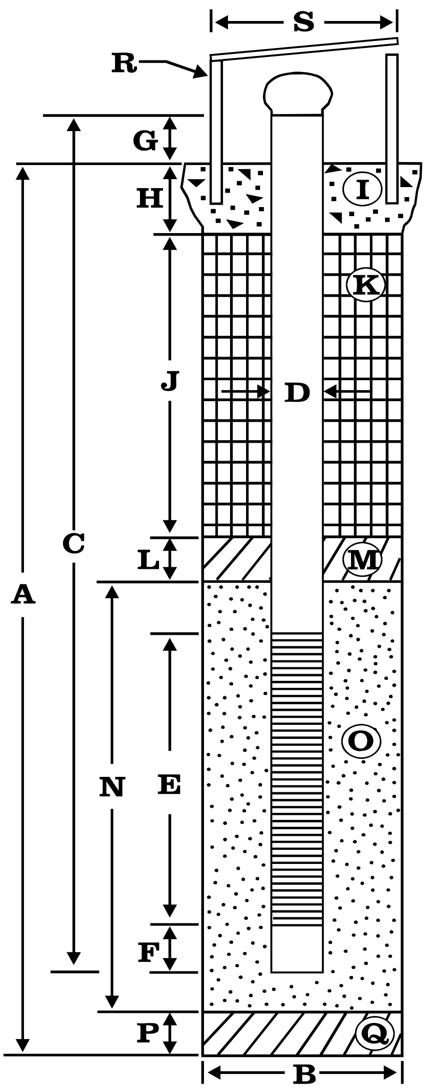
Reviewed by: John J. Renda

Date: 7/10/07

ANCHOR ENVIRONMENTAL, L.L.C.

WELL DETAILS

Project Number:	000029-02	Boring/Well No.:	PW-4-118
Client Name:	NW Natural	Top of Casing Elev.:	27.01
Project Name:	GASCO	Ground Surface Elev.:	25.5
Location:	Portland, Oregon	Installation Date:	6/13/07
Driller:	Boart Longyear	Permit/Start Card No.:	191822



Depth (feet)	Elev. (ft, msl)
NA	NA
1.51	27.01
0.0	25.5
2.0	23.5
102	-76.5
104	-78.5
108	-82.5
118	-92.5
128	-102.5
118	-92.5
128	-102.5

EXPLORATORY BORING

A. Total depth: 128 ft.
B. Diameter 16 in.
Drilling method: Cable Tool

WELL CONSTRUCTION

C. Well casing length: 129.51 ft.
Well casing material: mild steel
D. Well casing diameter: 8 in.
E. Well screen length: 10 ft.
Well screen type: Continuous Slot Stainless
Well screen slot size: 0.035 in.
F. Well sump/end cap length: 10 ft.
G. Well casing height (stickup): 1.5 ft.
H. Surface seal thickness: 2 ft.
I. Surface seal material: Cement Grout
J. Annular seal thickness: 100 ft.
K. Annular seal material: Cement Grout
L. Filter pack seal thickness: 2 ft.
M. Filter pack seal material: Sugar Sand
N. Sand pack thickness: 24 ft.
O. Sand pack material: 10x20 Silica Sand
P. Bottom material thickness: 10 ft.
Q. Bottom material: Cement Grout
R. Protective casing material: NA
Well centralizer depths: 39, 92, 121 ft.
S. Protective casing diameter: NA in.

NOTES:

Horizontal Datum: NAD83(91)

Installed by: Craig Wells

Reviewed by: John J. Renda

Date: 7/10/07