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PWS Aquifer Test Information

1.0 Introduction

Aquifer test information for the wells associated with the pumpback well system (PWS) summarized herein includes: 1) the collection and analyses of water level recovery data associated with the shutdown of the pumpback wells on March 25, 2009 at the Yerington Mine Site (Site); historical data produced by Applied Hydrology Associates (AHA) from pumping tests performed after the construction of pumpback wells PW-6 through PW-11 (such data for PW-1 through PW-5 are not available); and 3) the analysis of monitor well recovery data performed by AHA. Only an appendix containing the AHA data has been located, and the report to which it was originally attached is unknown. The location of the Site is shown on Figure B-1, and the pumpback wells are depicted on Figure B-2. The results of the aquifer test data analyses provide background information for the performance of the aquifer tests described in the Supplemental PWS Characterization Work Plan.

The PWS, which consists of 11 four- and six-inch diameter PVC-cased extraction wells, was installed, and has been operated to limit the migration of mine-related groundwater near the northern boundary of the Site (Figure B-2). These wells were installed in two phases: Pumpback wells PW-1, PW-2, PW-3, PW-4 and PW-5 were installed in the fall of 1985 and began operation in March 1986. Pumpback wells PW-6, PW-7, PW-8, PW-9, PW-10 and PW-11 were installed in 1998. During operation, groundwater extraction rates from these wells vary from less than one gallon per minute (gpm) to approximately 13 gpm.

2.0 Data Collection Following PWS Shutdown

Water level data were collected from nine of the 11 pumpback wells during the water level recovery period. These data were analyzed to estimate transmissivity and hydraulic conductivity values in the shallow aquifer underlying the northern margin of the Site. Water level data were collected manually using electronic water level probes in wells PW-8, PW-9 and PW-11, and were collected with data logger/pressure transducer installations in six of the remaining wells.

Data from two of the PWS wells were not analyzed. The water level in PW-7 had fully recovered before manual data collection began, and there were therefore no data to analyze from this well. The transducer for well PW-10 was inadvertently set to begin recording data on the day following the shutdown and, therefore, did not collect recovery data for this well.

Prior to the PWS shutdown, the pumpback wells had operated on a nearly continuous basis for a period in excess of 15 months, although some of the pumps were shut down for brief periods to address maintenance issues. The frequency of maintenance-caused shutdowns varied from well to well, with some wells experiencing no shutdowns during the approximately 15-month period, and some wells having as many as 18 shutdown periods during the same period.

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3.0 Aquifer Test Analyses for PWS Recovery

The Theis (1935) recovery method was used to analyze the water level recovery data. This method consists of plotting the residual drawdown in the well versus the ratio of *t/t'*, where *t* is the elapsed time since pumping began, and *t'* is the elapsed time since pumping ceased. The residual drawdown is plotted on an arithmetic y axis, and the ratio of *t/t'* is plotted on a logarithmic x axis. A straight line is then fit through the plotted water level recovery data, and the slope of the line is measured to estimate aquifer transmissivity.

Transmissivity is defined as the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of one, and has units of length^2/time. Similarly, hydraulic conductivity is defined as the ability of aquifer materials to transmit water, but does not consider aquifer thickness. As a result, hydraulic conductivity is expressed in units of length per unit time (e.g., feet per day), or velocity. The Theis recovery method of analysis is valid for the late-time water level recovery data from confined, unconfined, and leaky confined aquifers (Theis, 1935; Hantush, 1964; Neuman, 1975, Kruseman and de Ridder, 2000).

Transmissivity estimates for the wells were calculated from the Theis recovery method according to the following equation:

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

Where:

T = transmissivity;
Q = pumping rate; and,
Δs = change in residual drawdown over one log cycle of t/t'.

Based on the calculated values for transmissivity, the hydraulic conductivity (K) is then estimated according to:

$$K = \frac{T}{b}$$

Where:

b = aquifer thickness in feet.

The Theis recovery method is considered a valid technique for estimating aquifer transmissivity (Kruseman and de Ridder, 2000) provided that:

- The aquifer is confined, leaky or unconfined;
- $t > 25r^2S/T$; and,
- $t' > 25r^2S/T$

The parameter *S* in the above conditions is the aquifer storage coefficient, which describes the volume of water that an aquifer releases from storage per unit surface area of aquifer per unit decline in hydraulic head (Kruseman and de Ridder, 2000), and *r* is the radius of the wells. A value of *S* of 0.01 (dimensionless) was assumed for the shallow aquifer based on literature values for an unconfined aquifer (Kruseman and de Ridder, 2000).

Estimates of *S* can only be calculated in aquifer tests where drawdown data are collected and analyzed from a monitoring well used in an aquifer test, which has not occurred for the pumpback wells. The range of *S* for an unconfined aquifer is given as 0.01 to 0.3, and for a confined aquifer the value ranges from 5.0 E-03 to 5.0 E-05 (Kruseman and de Ridder, 2000). For an unconfined aquifer the storage coefficient is actually termed the specific yield (*Sy*), which is defined in the same manner as *S*, but describes gravity drainage of aquifer pores rather than water produced from elastic storage of the aquifer. These conditions previously described were met for all of the analyses presented herein.

Based on preliminary analyses, including the well construction data and short duration of the constant rate pumping interval, the data are strongly influence by the effects of well bore storage. According to Papadopulous and Cooper (1967) the effects of well bore storage can be neglected when:

$$t \geq 250(r_w^2/T)$$

where:

t = time since start of pumping
r_w = effective radius of the well
T = aquifer transmissivity

The effective radius of the well (r_w) is a function of the well screen and gravel pack, the development or health of the well, and overall well efficiency as a function of the linear and non-linear aquifer and well losses. When the borehole diameter is utilized as the effective well radius, the critical time at which the test data sets depart from the effects of well bore storage approaches the end of the pumping periods. However, when the well casing diameter is assumed for the effective well radius, the effect of well bore storage diminishes earlier in the pumping test data sets. Little data is available for the well screen, gravel pack, and grain size distribution of the aquifer material in the vicinity of the pumpback wells, which makes the assumed effective well radius speculative.

Assuming the late time data of the pumping tests are not affected from well bore storage, the Cooper-Jacob straight line method of pumping test analyses can also be used to evaluate the pumping test data. The Cooper-Jacob method of analysis (Cooper and Jacob, 1946; Jacob, 1946; Jacob, 1950) is based on the work of Theis, and is similar to the recovery method calculations. In the Cooper-Jacob straight line method, drawdown is plotted arithmetically against the $\log_{10}$ of time. After the well has been pumping for sufficient time, a straight line can be fit to the data.

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The slope of the straight line and the x-intercept (time) are used to estimate aquifer coefficients based on the following equations:

where: $$T = \frac{2.3Q}{4\pi(h_0 - h)} \qquad S = \frac{2.25\,Tt_0}{r^2}$$

T = Transmissivity
S = Storativity
Q = Discharge
h_0-h = drawdown over one log cycle
t_0 = time intercept
r = radial distance from the pumping well to the monitoring well

The pumping rates used in the water level recovery analyses for the PWS well tests were estimated by averaging the recorded pumping rates from March 16, 2009 to March 25, 2009. This period was selected because most of the wells had been in continuous operation during that period and water levels in the pumpback wells were equilibrated with the current pumping rates. The ratio of elapsed time since the start of pumping to elapsed time since the end of pumping (i.e., t/t') was set equal to the 10-day period over which pumping rates were averaged. Pumping rates utilized in analyses of the AHA tests directly represent the reported pumping rates at the time the testing was conducted. Aquifer thickness, *b*, was estimated for each well from well construction and water level records by subtracting the lower-most well screen elevation from the static water level elevation measured on March 24, 2009. One exception to the method of determining aquifer thickness was made for PW-9, for which the well log indicates a confining (i.e., clay) layer from 33 to 46 feet bgs. For PW-9, the aquifer thickness was based on the thickness of the sand layer between the bottom of the clay layer and the bottom of the well. The aquifer test data for the recovery period are summarized in Table C-1.

Table C-1. Summary of Test Data

Well ID	Data Set	Aquifer Thickness[1] (feet)	Pumping Rate (gpm)	Duration of Pumping (minutes)
PW-1	PWS	20.5	13.40	14,400
PW-2	PWS	18.4	8.00	14,400
PW-3	PWS	20.1	4.50	14,400
PW-4	PWS	23.2	2.50	14,400
PW-5	PWS	21.0	4.40	14,400
PW-6	PWS	13.2	2.50	14,400
PW-8	PWS	16.0	0.22	14,400
PW-9	PWS	5.0	1.40	14,400
PW-11	PWS	8.4	0.69	14,400

[1] Aquifer thickness at the time of recovery test

4.0 Discussion of Results

The Theis recovery methods of analyses were used to estimate transmissivity and hydraulic conductivity values for the shallow zone of the alluvial aquifer following the PWS shutdown in March 2009.

As presented in Table C-1, the saturated thickness of the shallow zone of the alluvial aquifer in the area of the pumpback wells can vary, which results in a wide range (i.e, almost two orders of magnitude) of calculated transmissivity values. However, with the exception of well PW-8, the calculated hydraulic conductivity values remain fairly consistent (30 to 83 feet/day). The results from the PWS recovery tests are summarized in Table C-2.

Table C-2. Summary of PWS Recovery Test Results

Well ID	Time Ratio[1] t/t	Drawdown Increment[2] (feet)	Estimated Transmissivity ($feet^2$/day)	Estimated Hydraulic Conductivity (feet/day)
PW-1	0.350	0.30	1600	78
PW-2	0.015	0.35	800	43
PW-3	0.420	0.22	700	35
PW-4	1.100	0.12	700	30
PW-5	0.001	0.13	1200	57
PW-6	NA	0.08	1100	83
PW-8	11.500	0.40	20	1.3
PW-9	5.750	0.16	300	60
PW-11	0.180	0.09	300	36

1 Ratio of elapsed time since start of pumping and elapsed time since start of recovery. Pumping time assumed to be 10 days.
2 Drawdown increment over one log cycle of the recovery curve.

Graphical depictions of recovery test analyses for the PWS wells are provided as Figures B-4 through B-12. A discussion of the test data for each well is provided below.

- The water level recovery in PW-1 (Figure B-4) showed no unusual behavior. Recovery was monitored for 1,926 minutes and provided a sufficient curve for interpreting the recovery test data.
- The water level recovery in PW-2 (Figure B-5) also showed no unusual behavior. Recovery was monitored for 1,863 minutes and provided a sufficient curve for interpreting the recovery test data.
- The water level recovery in PW-3 (Figure B-6) showed no unusual behavior. Recovery was monitored for 1,871 minutes and provided a sufficient curve for interpreting the recovery test data.

- The recovery curve for PW-4 (Figure B-7) indicated some fluctuation in the late-time portion of the recovery. Recovery was monitored for 1,871 minutes, but the fluctuations in the later time data require the straight line interpretation to be fit to the middle of the data set. The cause of the late time fluctuations in water levels is not apparent, although natural variations in water levels and atmospheric conditions may have influenced the water levels in PW-4.
- The water level recovery in PW-5 (Figure B-8) showed a slight variation in the late time data. However, the slopes of the straight line fit to the data both before and after this fluctuation are parallel, and produce the same aquifer parameter values. Recovery was monitored for 1,886 minutes and provided a sufficient curve for interpreting the recovery test data.
- Water level recovery in PW-6 briefly exhibited anomalous behavior (Figure B-9), with the water level recovery curve initially rising and flattening, then declining by about 0.3 feet before resuming a nearly-flat recovery curve. Disregarding the early-time anomalous behavior of the curve, a straight line fit to late time data produced values within the range of the other pumpback wells. Despite the early time behavior, recovery for PW-6 was monitored for 1,891 minutes and provided a sufficient curve for interpreting the late time data.
- Water level recovery in PW-8 showed some fluctuations between about 1.8 hours and 2.1 hours (ratio t/t' approximately 110 to 138) into the recovery period (Figure B-10), but resumed normal recovery behavior after this time. Although the water level recovery in this well did not display a distinctive prolonged late-time segment on the curve as the other wells, recovery was monitored for 3,149 minutes and provided a sufficient curve for interpreting the late time data.
- The water level recovery in PW-9 began small fluctuations at t/t' of about 90 (approximately 2.7 hours since shutdown). These fluctuations continued through the end of the water level monitoring period (Figure B-11). An average fit of the straight line interpretation was made through the fluctuating recovery data set. Although the recovery data fluctuated slightly, recovery was monitored for 3,144 minutes and the average fit of the straight line interpretation produced similar coefficients as other wells in the aquifer.
- The water level recovery in PW-11 displayed generally normal behavior, with minor water level fluctuation near the end of the 3,205-minute monitoring period (Figure B-12). Water level recovery provided a sufficient curve for interpreting the late time data.

5.0 Historical PWS Aquifer Test Results

Limited constant-rate aquifer test and analytical data are available for pumpback wells PW-6, PW-7, PW-9, PW-10 and PW-11, following the installation of these wells, in November and December 1998 (AHA, 1999). Drawdown was measured only in the pumping wells (i.e., not in nearby monitor wells or piezometers). Well PW-8 was not analyzed because the pumping rate in the well could not be maintained. Aquifer test analyses consist of pumping drawdown analyses, and do not include recovery analyses. Test data were analyzed using two techniques, the Theis (1935), and Cooper-Jacob (1946) methods.

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Additional historical aquifer test data are available from recovery tests measured in monitor wells W5AA-2S, W5AB-1S and W5AB-2S, and piezometer W5BBS (Figure B-3). The data are contained in an appendix to an AHA document entitled *Appendix B Pump Test Field Forms* (the AHA document is not available).

PWS aquifer test results are presented in Table C-3. Hydraulic conductivity estimates provided below are based on an assumed saturated thickness of 20 feet, which is equal to the length of the well screens in the pumpback wells. Aquifer thickness data presented in Table C-1, which represented conditions in March 2009, may not be applicable to the conditions in the PWS in 1998 (i.e., decreased saturated thickness due to declining water levels, as described in the Supplemental PWS Characterization Work Plan). Given the same transmissivity value, a smaller saturated thickness would yield a larger estimate of hydraulic conductivity.

Table C-3. Summary of Historical PWS Aquifer Test Results

Well ID	Method of Analysis	Aquifer Test Pumping Rate	Transmissivity ($feet^2/day$)	Estimated Hydraulic Conductivity[1] (feet/day)
PW-6	Theis	4.0	307	15
	Cooper-Jacob		457	23
PW-7	Theis	4.2	143	7
	Cooper-Jacob		216	11
PW-9	Theis	3.3	170	9
	Cooper-Jacob		166	9
PW-10	Theis	2.7	145	7
	Cooper-Jacob		224	11
PW-11	Theis	4.9	493	25
	Cooper-Jacob		640	32

[1]Estimated hydraulic conductivity is based on an assumed saturated thickness equal to the screen lengthy of 20 feet. The actual saturated thickness at the time of testing may have been less than 20 feet, which would increase the estimated hydraulic conductivity.

Results of transmissivity estimates often vary between methods of analysis, and between pumping test and recovery test data analyses. Recovery test data are more reliable because recovery occurs at a constant rate, whereas maintaining a constant discharge rate during pumping is difficult to achieve in the field (Kruseman and de Ridder, 2000).

The Theis and Cooper-Jacob methods were also used to analyze the AHA recovery data sets, summarized in Tables C-4 and C-5. However, initial results from the Cooper-Jacob method provided values for aquifer transmissivity that were consistently and significantly greater than those estimated from the monitor well recovery test data. This consistent relationship indicates: 1) that the effective well radius is likely closer to that of the borehole than that of the well screen;

and 2) support for the assumption that the pumping test data were influenced by the effects of well bore storage. The Cooper-Jacob plot of the pumping test data is provided as Figure B-13, which shows nearly flat drawdown curves. This indicates that the short-duration pumping tests were not of sufficient length to deplete the effects of well bore storage.

Table C-4. Summary of Monitor Well Test Conditions

Well ID	Data Set	Aquifer Thickness (feet)	Pumping Rate (gpm)	Duration of Pumping (minutes)
W5AA-2	AHA	14.0	9.96	118
W5AB-1	AHA	26.0	9.72	420
W5AB-2	AHA	16.0	9.79	400
W5BB	AHA	30.0	9.78	70

Table C-5. Summary of Monitor Well Recovery Test Results

Well ID	Time Ratio[1] t/t	Drawdown Increment[2] (feet)	Estimated Transmissivity (feet2/day)	Estimated Hydraulic Conductivity (feet/day)
W5AA-2	2.500	0.20	1800	129
W5AB-1	2.300	1.95	200	8
W5AB-2	5.0E-06	0.18	2000	125
W5BB	1.800	0.28	1200	40

1 Ratio of elapsed time since start of pumping and elapsed time since start of recovery. Pumping time assumed to be 10 days.
2 Drawdown increment over one log cycle of the recovery curve.

The aquifer hydraulic parameters estimated from the recovery test results are similar to those of the PWS data set for the recovery period following the March 2009 shutdown. A discussion of the test data for each well is provided below:

- The water level recovery W5AA-2 (Figure B-14) showed no unusual behavior. Although the monitored recovery period for this well is fairly short (99 minutes) compared to the other recovery tests, the drawdown at the end of the pumping period was greater than five feet. At the end of the monitored recovery period, drawdown was measured at 0.01 feet. The well had recovered to within 10 percent of the static water level, and the late time recovery data, although of short duration, provides a sufficient curve for interpreting the data.
- The water level recovery in W5AB-1 (Figure B-15) showed no unusual behavior. Recovery was monitored for 717 minutes and provided a sufficient curve for interpreting the recovery test data.

- The water level recovery in W5AB-2 (Figure B-16) showed no unusual behavior. Recovery was monitored for 896 minutes and provided a sufficient curve for interpreting the recovery test data.
- The water level recovery in W5BB (Figure B-17) showed no unusual behavior. Although the monitored recovery period for this well is fairly short (40 minutes) compared to the other recovery tests, the drawdown at the end of the pumping period was greater than twelve feet. At the end of the monitored recovery period, drawdown measured at 0.07 feet. The well recovered to within 10 percent of the static water level and the late time recovery data, although of short duration, provides a sufficient curve for interpreting the data.

6.0 Summary and Conclusions

The test results reported herein represent water level data collected in pumping and monitor wells. Aquifer tests that are monitored in multiple piezometers allow for both time-drawdown and distance drawdown analyses, which should be performed to assess pumpback well effectiveness (Kruseman and de Ridder, 2000). Aquifer tests conducted in the PWS wells and the four monitoring wells in Table C-4 indicate:

- Aquifer transmissivity varies from about 20 feet^2/day at PW-8 to about 2,000 feet^2/day at W5AB-2;
- Aquifer hydraulic conductivity vary from 1.3 feet/day at PW-8 to 129 feet/day at W5AA-2; and,
- Differences in analytical results between pumping and recovery testing

Pumping test results for the northern bank of pumpback wells (PW-6 through PW-11; not including PW-7), and recovery test results for monitor well W5AB-2S, indicate lower hydraulic conductivity and transmissivity values in the area of PW-8. This area corresponds to: 1) a transition from more widely spaced to more closely spaced groundwater elevation contours (Figures 3-2 through 3-7 of the Supplemental PWS Characterization Work Plan); and 2) the highest TDS concentrations in the shallow zone in the area of the pumpback wells, which appear relatively constant over time and are co-spatial with the ‘wet areas’ of the Lined Evaporation Pond (see Figures 3-24 through 3-29 of the Supplemental PWS Characterization Work Plan).

7.0 References Cited

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