WRIA 44/50

Foster Creek and Lower Moses Coulee Level 2 Hydrogeologic Assessment

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Prepared for:

Foster Creek Conservation District
103 North Baker
Waterville, WA 98858

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1.0 SUMMARY AND CONCLUSIONS

Hydrogeologic field investigations were performed in both Foster Creek and Moses Coulee areas to gather data for water rights applications and for modeling efforts. The field investigations included a well inventory, water level survey, aquifer tests, and the instrumentation of wells for long-term water level data collection.

As part of the well inventory, approximately 28 out of 66 wells in Foster Creek, and 27 out of 41 wells in Lower Moses Coulee were field-located and permission for use was obtained. During the water level survey, a synoptic round of water levels was collected to develop a water-level map of each study area. Water level measurements were successfully made in 22 wells in the Foster Creek area on April 9 and 10, 2003. Water level measurements were successfully made in 15 wells in the Lower Moses Coulee on April 7 and 8, 2003. Lower Moses Coulee was found to have three hydraulic gradient zones, likely a result of the underlying basalt topography.

The shallowest groundwater levels measured in Moses Coulee were approximately 85 feet below ground surface. The depth to water in Douglas Creek is less than ten feet from ground surface. This indicates that, while Douglas Creek likely contributes water to the underlying aquifer, pumpage in the aquifer should not affect surface water levels or flow.

Long-term groundwater level monitoring equipment was permanently installed in six Foster Creek wells and five Moses Coulee wells. These data will be useful in assessing the effects of spring recharge events, changes in hydraulic gradient, and water level increases or declines over time. No groundwater decline is currently indicated in either area.

Three aquifer tests were performed in the Foster Creek area and two were performed in the Lower Moses Coulee. These data, combined with pre-existing test data, yield ranges of transmissivity from 69 to 268,000 gpd/ft in Foster Creek, and 311,000 to 2,904,000 gpd/ft in Lower Moses Coulee. One storativity value of 0.08 was estimated in Lower Moses Coulee.

A groundwater flow model was developed to assess the groundwater flux entering Lower Moses Coulee. The model indicated that the groundwater flux into the Coulee is 44.5 cfs or 75 percent of the original estimate for the Lower Moses Coulee area in the Level 1 Basin Assessment.

2.0 INTRODUCTION

This assessment was completed for the Water Resource Inventory Area (WRIA) 44/50 Planning Unit. The WRIA 44/50 Planning Unit was formed under the auspices of the Watershed Planning Act (HB 2514; Chapter 90.82 RCW). Foster Creek Conservation District is the lead agency for the Planning Unit.

The 1998 Legislature passed Engrossed Substitute House Bill 2514 (The Watershed Management Act) to provide a framework to collaboratively solve water related issues. This bill, along with the associated grants program, is designed to allow local citizens and local governments to join with tribes and state agencies to develop watershed management plans for entire watersheds.

This framework is based on geographic areas known as Water Resource Inventory Areas (WRIAs), or watersheds. Locally established "planning units" are to assess each WRIA's water supply and use and recommend strategies to satisfy water supply needs. In addition, the opportunity is also provided for local planning units to address the closely related issues of improving water quality, protecting and enhancing fish and wildlife habitat, and, in collaboration with the Department of Ecology (Ecology), to set instream flows.

2.1 PURPOSE AND OBJECTIVES

The WRIA 44/50 Planning Unit completed the Level 1 Technical Assessment in April 2003. The Technical Assessment identified data gaps in information used to develop the assessment. This Level 2 Assessment was initiated to fill those data gaps and others identified by the Planning Unit. Objectives of this Level 2 study included:

- Collect basic hydrogeologic data in Moses Coulee and the Foster Creek regions to aid in water rights applications.
- Evaluate the hydraulic connection between Douglas Creek and the underlying alluvial aquifer and assess whether increased irrigation affect streamflow.
- Assess the magnitude of groundwater inflow into the Lower Moses Coulee through use of a groundwater flow model.

3.0 PREVIOUS INVESTIGATIONS

Many geologic and hydrogeologic investigations have been conducted in the study area by private consultants, public agencies, and academic researchers. Most of the following references were obtained from the Washington State Department of Ecology (Ecology) files.

In his article *Several Phases of Geology of the Moses Coulee Area*, (Northwest Science, 1932) Hoffman described the physical appearance, stratigraphy, and history of the Moses Coulee.

George E. Neff authored the *Geologic Report On Ground Water Characteristics of Sagebrush Flats, Rattlesnake Springs and Vicinity* (Undated). This report describes the origin and geology of the Sagebrush Flats and Moses Coulee areas. In addition, the report discusses the contribution of runoff from the Mansfield Plateau drainage system to groundwater in the Lower Moses Coulee.

Dr. Larry Gene Hanson's PhD thesis (1970) was a valuable reference for this project. In addition to the origin and development of Moses Coulee, he detailed the physiography of the Coulee, the bedrock surface and the fill thickness. The thesis includes cross sections of the Coulee and summarizes three geophysical profiles in the lower Coulee.

Two reports describing the drilling of a test well for the Town of Mansfield were filed with Ecology by John Bush in 1972. In addition to drilling activities, Bush described his interpretation of the lithology in the borehole and the stratigraphy from Bridgeport to Moses Coulee.

Multiple reports written by the Department of Ecology on the Sagebrush Flats area were reviewed for this project. Ecology performed a pumping test and analysis in 1975 for Stan Schell located in the flats area. Water level data gathered in the area during the 1976 irrigation season were evaluated and used to calculate the transmissivity and storage coefficient of the aquifer. A map of estimated drawdown at various distances from the pumping well was generated for the second test. The transmissivity values calculated from both tests were consistent.

The United States Geological Survey (1980) investigated the hydrology of the Sagebrush Flat area focussing on its relation to Rattlesnake Springs. The report describes the downward movement of groundwater between basalt flows that occurs through fractures and well boreholes. The report indicates that this downward movement diverts groundwater from downstream discharge points such as Rattlesnake Springs, thereby decreasing the flow at these locations.

In 1980, Ecology evaluated the amount of precipitation and evapotranspiration to calculate annual recharge to the Wanapum and Grande Ronde basalt in the Sagebrush Flats area. A second recharge study for the area was performed in 1981 to assess groundwater availability for water right applications.

Ecology wrote a Completion Report for a test well they installed in Sagebrush Flats in 1984. The report describes the drilling and installation procedure, three pump tests and analyses performed for the well, geophysical logs of the well, and geochemical analyses of selected drill cuttings.

In 2003, Pacific Groundwater Group teamed with Montgomery Water Group and R2 Resource Consultants to prepare the WRIA 44/50 Phase 2 Basin Assessment. The assessment included a characterization of water rights, water use, recharge, streamflow, water quality, and aquatic habitat.

4.0 HYDROGEOLOGIC SETTING

WRIAs 44 and 50 are predominantly underlain by the Miocene basaltic rocks of the Columbia River Basalt Group. In this area, the basalt sequence is generally 2,000 to 3,000 feet thick and has been divided, from oldest to youngest, into two main units. The Grande

Ronde Basalt, which is the thickest, contains as many as 131 flows; and the Wanapum Basalt, as many as 33 flows. Interbed deposits, often consisting of mudstones, siltstone, and sandstone, separate the two basalt formations and may also occur within the two formations.

Individual basalt flows in the Columbia River Basalt Group range from a few tens of feet to about 300 feet in thickness; the average thickness is about 100 feet. Some thick flows that are exposed in canyons and road cuts display extensive fracture patterns due to differential rates of cooling. The tops and the bottoms of flows are typically more permeable than flow interiors because of rubble zones, vesicles, and fractures. These zones form the principal aquifers within the basalt. However, some of these open spaces are filled with clay minerals that decrease permeability. The central parts of most flows are dense and are less permeable. Openings caused by minor vertical cooling fractures provide some limited permeability in the central part of the flows.

The Ellensburg formation and other unconsolidated deposits overlie the basalts in many areas. These deposits are generally less than 50 feet thick on the plateau but may be as much as 300 feet thick on the banks of the Columbia and in Moses Coulee. Unconsolidated alluvial material in the Moses Coulee ranges from large boulders of broken basalt and gravel to fine sand and clay.

The bedrock that underlies the Columbia River Basalt Group consists of pre-Miocene igneous, metamorphic, and consolidated sedimentary rocks.

5.0 FIELD INVESTIGATION

The field investigation consisted of four elements:

- A well inventory was completed to assess the usability of the wells for further elements of the investigation.
- A water level survey was completed to collect a synoptic round of groundwater elevations.
- Aquifer tests were performed to collect data on aquifer parameters.
- Wells were instrumented for long-term water level data collection.

5.1 WELL INVENTORY

A well inventory was performed as the initial phase of the data collection to select wells for water level measurement and aquifer testing. Wells were identified in the Foster Creek and Moses Coulee areas using well logs obtained from Ecology. Figure 1 presents documented wells in the Foster Creek area. Figure 2 presents documented wells in the Lower Moses Coulee area. The well locations were mapped as they appeared on the well logs. On inspection of the well logs, many in the Foster Creek area were excluded from the survey because they were shallow Department of Transportation borings in which no well was installed.

Well owners were contacted by Foster Creek Conservation District staff to obtain permission for well access and to obtain exact well locations. Additionally, well owners were often able to provide supporting information regarding access constraints, recent changes in property ownership and well use, well performance, and the location and ownership of nearby wells not contained in the well log inventory. In Foster Creek, approximately 28 out of 66 wells were field-located and permission for use was obtained. In the Moses Coulee area approximately 27 out of 41 wells were field-located and permission for use was obtained.

5.2 WATER LEVEL SURVEY

A water level survey was performed to collect a synoptic round of water levels for each study area. Water levels were used to develop a water-level contour map of each study area. Water levels were measured using an electronic water level sounder and recorded to the nearest 1/100th of a foot. Measurements were made during non-pumping periods wherever possible and if not, a note was made on the field form to indicate a pumping or recovering water level measurement. Digital photographs of the wells and Global Positioning System (GPS) co-ordinates were also taken at each well location.

Water level measurements were successfully made in 22 wells in the Foster Creek area on April 9 and 10, 2003. Data were not gathered in approximately six wells because of obstructions in either the wellhead or in the well casing that prevented sounder access.

Water level measurements were successfully made in 15 wells in the Lower Moses Coulee on April 7 and 8, 2003. Data were not gathered in approximately six wells because of obstructions in either the wellhead or in the well casing that prevented sounder access.

Erlingson & Associates of East Wenatchee, Washington, provided surveying services in the Moses Coulee area for all wells where water level measurements were obtained. Measuring points on the wellheads were surveyed with GPS equipment and Real Time Kinematic procedures to obtain northing, easting, and elevation data. The surveyed co-ordinates are accurate to 0.1 feet. This level of accuracy was not required for Foster Creek because of the physical size of the area, the distance between measuring points, and the differences in elevation between the wells. Therefore, the latitude, longitude, and elevations of the wellheads in Foster Creek were recorded using a GPS unit during the water level survey.

5.2.1 Results

Groundwater elevation data in the Foster Creek area are presented in Table 1 and graphically in Figure 1. These data have not been contoured because the varying depths and large distances between the wells mean that the wells may not be completed in the same aquifer. Measured groundwater elevations range from over 2100 feet to less than 700 feet. The data indicate groundwater elevations generally mimic topography and groundwater flow is towards Foster Creek.

Water level data gathered in Moses Coulee are presented in Table 2 and are contoured in a groundwater elevation map (Figure 3). Figure 3 indicates that there are three distinct gradient zones with in Lower Moses Coulee. The first zone extends from the Goldy well at the top of the Coulee to the Criss well and has a relatively flat gradient of approximately $4x10^{-4}$ ft/ft. The second zone extends from the Criss well to the Barb well and has a steeper gradient of $3x10^{-3}$ ft/ft. The third zone extends from the Gutschow well to the Moses Coulee Water Association and has a slightly steeper gradient of $6x10^{-3}$ ft/ft.

These changes in gradient are likely due to the subsurface basalt topography. As discussed in Section 6.2 and the accompanying cross section, the depth to bedrock decreases from the top of the Coulee reaching its shallowest point between the Criss and Barb wells, near Palisades. The depth to bedrock then increases from Palisades toward the Columbia River. These three zones mimic the three gradient zones suggesting the hydraulic gradient through the Lower Coulee is structurally controlled.

5.3 GROUNDWATER LEVEL MONITORING

The need for long-term groundwater level monitoring in the Lower Moses Coulee area was identified at the end of the Level 1 Assessment. This task was expanded to include the Foster Creek area in the scoping portion of this phase of work. The monitoring data can be used to develop hydrographs that are useful in assessing an aquifer's response to spring recharge events, changes in hydraulic gradient, and water level increases or declines over time.

5.3.1 Equipment

Solinst-brand Levelogger water level sensors were selected to measure and record water levels and barometric pressure. Loggers have been permanently installed in six Foster Creek wells and five Moses Coulee wells. Leveloggers measure total pressure; therefore, when they are submerged in a well they measure the pressure of the water above the logger plus the pressure of the air. To obtain a true water level measurement, the pressure attributable to the air must be removed from the total pressure measurement. To obtain the necessary data for this correction, one Levelogger was installed in each basin to record barometric pressure.

Foster Creek Conservation staff were trained to use the Levelogger equipment during their installation in Moses Coulee wells. Conservation staff installed the sensors in Foster Creek wells and will continue to download data and maintain the equipment.

5.3.2 Instrumented Wells

In the Foster Creek area, the Hunt, Hemmer, Hammons, Malone, Hanford, and T29R25S35 wells were equipped with long term monitoring equipment in June and July 2003 (Figure 1). These wells were selected based on lateral distribution, access for the Levelogger, permission from the well owner, and lack of a pump. A Levelogger dedicated to collecting barometric pressure was also installed at the Malone well. Although they are used as production wells, the Hemmer and T29R25S35 wells were instrumented because of the limited number of wells available to the project in the Foster Creek area.

The Hemmer well is used for stock watering so the duration of the pumping periods is typically short. In the case of the T29R25S35 well, static water level data will be collected in the non-irrigation seasons. Hydrographs of the data downloaded from the instrumented wells in the Foster Creek area are presented in Appendix A.

In Moses Coulee, Leveloggers were installed in mid May 2003 in wells owned by the Palisades Irrigation District, Steve King, Mike Biram, and two southern Jack Linville wells (Figure 2). The same criteria of lateral distribution, access, permission, and pumping condition were applied to select the wells in Moses Coulee for instrumentation. In an effort to monitor static water level conditions, wells without pumps instrumented although the Biram well is located only 52 feet from an irrigation well. A second Levelogger was installed at the Biram property to measure barometric pressure. Hydrographs of data downloaded from the sensors installed in Moses Coulee wells are presented in Appendix A.

5.4 AQUIFER TESTING

Aquifer tests were conducted in private wells in Moses Coulee and Foster Creek to gather data used to estimate aquifer parameters. Wells were selected based on water level sounder and Levelogger access, permission from the owner, well construction, and ease of flow rate measurement.

The tests generally consisted of three phases:

- Pre-test Phase. This phase lasted at least one day, during which water levels were measured to assess antecedent trends.
- Pumping Phase. This phase lasted up to 4.75 days, during which water levels were measured to assess aquifer response to pumping.
- Recovery Phase. This phase lasted for at least an hour after pumping stopped, during which water levels recovered to pre-pumping conditions.

5.4.1 Cooper-Jacob Method

Graphs of logarithmic time versus drawdown were used to compute the aquifer parameters of transmissivity and storativity (where an observation well was available). Transmissivity reflects the rate water flow through a vertical strip of the aquifer that is a unit width and under a unit hydraulic gradient. Storativity is the volume of water taken into or released from storage per unit change in head per unit area. The following Cooper and Jacob (1946) equations were selected for analysis because they are appropriate for analysis of data collected from pumping well:

$$T = 264Q/\Delta s$$

and

$$S = 0.3Tt_o/r^2$$

Where:

- T = transmissivity, in gallons per day per foot (gpd/ft)
- Q = pumping rate, in gallons per minute (gpm)
- Δs = drawdown over one log cycle
- S = storativity (dimensionless)
- t_o = intercept of the straight line at zero drawdown, in days
- r = distance, in feet from the pumping well

Hydraulic conductivity reflects the ability of the aquifer material to transmit water under a unit hydraulic gradient. Aquifer transmissivity is hydraulic conductivity multiplied by the aquifer thickness. Hydraulic conductivity (K) was calculated using the following equation:

$$K=T/b$$

Where:

b = aquifer thickness

5.4.2 Partial Penetration Corrections

Drawdown data collected from a well that is not screened throughout the entire aquifer may be affected by partial penetration, which distorts flow lines within the aquifer, increasing drawdown. To account for this distortion, the following correction was applied where indicated to drawdown data from wells using the method of Butler (1957) as outlined in Walton (1962).

$$s = C_{pp}s_{pp}$$

Where:

- s = corrected drawdown, in feet
- C_{pp} = a partial penetration constant, from Butler's table
- s_{pp} = observed drawdown, in feet

In Butler's table, the values of partial penetration constants for a pumped well can be looked up based on:

- fractional penetration of the aquifer
- $(r_w/m)(K_v/K_h)^{1/2}$

Where:

rw = nominal radius of the well, in feet
m = saturated thickness of the aquifer, in feet
K_v = vertical permeability of the aquifer, in gallons per day per square feet
K_h = horizontal permeability of the aquifer, in gallons per day per square feet

The ratio of Kv/Kh was assumed to be 0.1 in the Moses Coulee and Foster Creek areas.

5.5 AQUIFER TEST RESULTS

Aquifer tests were performed in existing wells in an effort to maximize hydraulic information about the Foster Creek area and Moses Coulee within the allocated budget. The aquifer tests were performed with the best practices possible given the configuration of the pre-existing wells and discharge systems. However, the use of existing wells introduced some limitations to the tests and the accuracy of the results through the effects of well construction, distribution lines, and variable pumping rates.

The T29R25S35, Biram, and Billingsley irrigation wells are hard lined to distribution lines and laterals. Water levels in these wells respond early in the pumping period to the decrease in pumping rate as the pressure increases in the distribution system. In some cases, the pressure in the distribution system, and therefore the pumping rate, did not stabilize for over 30 minutes. Changing sprinkler sets during the aquifer tests also introduced variability to the pumping rate and therefore to the water level response during pumping. The pumping rates for the irrigation wells were estimated by measuring the pressure at selected sprinkler heads and calculating a total discharge rate from manufacturers specifications. It was not practical to make pressure readings at all sprinkler heads, so they were selected over the range of changes in elevation and distance from the wellhead. These selections were made in the field and were not the result of a thorough study of the irrigation system. In addition, the manufacturer’s specifications were established in ideal test conditions and can be affected by wind and other factors in the field.

5.5.1 Foster Creek Results

The number of wells available for testing in the Foster Creek area was limited because many of those canvassed during the wellhead inventory were domestic supply wells. These wells typically pump directly into a pressure tank so the flow rate is unknown. Tests were conducted in the Hemmer, T29R25S35, and Hammons wells. Additionally, PGG was able to acquire data from a test that the Town of Mansfield had previously conducted in one of their supply wells. Aquifer test results are summarized in Table 3.

5.5.1.1 HEMMER WELL

An aquifer test was conducted in Lee Hemmer’s well in the northeast portion of the Foster Creek area. This well is used primarily for stock watering. The 6-inch diameter well is cased to a depth of 21 feet bgs and the borehole continues without casing to a total depth of 200 feet bgs in fractured basalt. A 1/3 horsepower submersible pump is installed in the well.

Transducer equipment was installed in the well on April 25, 2003 to collect pre-test water level data. The transducer was lowered in the well until an obstruction was encountered at approximately 63 feet below ground surface. The transducer was then pulled back from the obstruction, assumed to be the top of the pump, and installed at approximately 57 feet below ground surface.

The water level data (Figure 4) indicate that the well operated intermittently throughout the pre-pumping period. After being corrected for atmospheric pressure, the data indicate that water levels between pumping periods declined by about 0.25 feet during the period of monitoring.

On the morning of April 28, 2003, the 575 gallon stock tank was drained by siphoning the water to a low spot about 20 feet from the wellhead. Water levels in the Hemmer well were monitored manually while the tank drained and no change was observed over the 48 minutes before the test began. Following siphoning, the water in the stock tank was 1.75 inches deep. The pump test started about an hour later at 11:55. Flow rate was measured using a calibrated 5-gallon bucket and stopwatch as water flowed into the stock tank, and also by measuring the depth of water in the tank as it filled.

Water levels in the Hemmer well were measured manually with a sounder and automatically with the transducer equipment. The initial depth to water in the well was 21.58 feet. During pumping, accurate manual measurements were difficult to obtain because the sounder was either sticking to the inside of the borehole or possibly water discharged from the stock tank before the test was leaking into the borehole and trickling down the sounder. The transducer measurements were observed during the test and after about 10 minutes the readings indicated that the water level in the well had dropped below the transducer. No fluctuations in the appearance of the discharge were observed to indicate the water level had dropped below the pump intake. The transducer equipment was removed from the well and tested in the water in the stock tank for correct operation. The transducer was then reinstalled in the well at the maximum depth possible and the pump was stopped. As the well recovered to pre-test conditions, water could be heard flowing into the well. Water level data for the pre-test and test period are presented in Figure 4.

At 15:50 on April 29, 2003 a second test was conducted in the Hemmer well with the transducer in the deepest position possible. Pre-test water level data was not collected before the second test. The test was performed for 90 minutes at which time the water level dropped below the transducer set at about 80 feet so no additional data could be gathered. Again, the appearance of the water from the discharge pipe did not indicate that the water level had dropped below the top of the pump intake. Drawdown data in the Hemmer well is presented in Figure 5. The well is completed in the basalt aquifer, so partial penetration corrections were not performed. The transmissivity was calculated to be 69 gpd/ft (Table 3). This low transmissivity reflects the bedrock completion of the well.

5.5.1.2 T29R25S35 WELL

A pump test was conducted in an irrigation well located in Township 29 N, Range 25 E, and Section 35 (T29R25S35) in the Foster Creek area. The well log indicates that the well is constructed of 10-inch diameter casing from ground surface to 61-feet bgs, 10-inch diameter 100-slot stainless steel screen to 71 feet bgs, 9-inch diameter casing to 83 feet bgs and finally 10-inch (likely 9-inch) 80-slot screen to the total well depth of 90 feet bgs. The well is completed in sand and gravel. A permanent 50 horsepower submersible pump is installed in the well.

When the transducer was first installed in the well, it was lowered until an obstruction was encountered at depth of 69 feet. This obstruction was interpreted to be the top of the pump assembly indicating a minimum of 30 feet available drawdown from the static water level of 39.31 feet.

Transducer equipment was installed in the irrigation well on April 28, 2003 and began recording pre-test water level data. The well owner reported that the well had not been used this irrigation season but would be briefly turned on later that day to confirm operation. A second, older irrigation well is located 9 feet south of the pumping well but is not accessible and could not be instrumented.

Water level data collected before the test began indicate that the well owner did test the pump briefly on the afternoon of April 28, 2003 (Figure 6). The water level data over the pre-test period were corrected to remove the affects of barometric pressure and reveal that the water level declined by about 0.15 feet initially but was stable for the 17 hours leading up to the test. Calculations indicated this antecedent trend was water levels declining by $2x10^{-5}$ feet per minute. Because of the small magnitude of the pre-test trend, data correction was unnecessary.

The pump test in the T29R25S35 well began at 9:30 on April 29, 2003. Figure 7 presents water level data collected during the test. Pressure gauges at the wellhead indicated that pressure began building within the first minute of pumping and leveled off after nine minutes of pumping. Water levels were measured automatically and manually with a sounder in the pumping well. The depth to water before pumping began was 39.31 feet. Within the first seconds of pumping, the water level in the well dropped about 0.75 feet and then slowly rose by about 0.5 feet. These measurements in the first 8 minutes of pumping reflect the increase in pressure in the system as the irrigation lines filled with water.

When pumping began, one set of 282 Nelson orange sprinklers were operating. After two and a half hours of pumping, the discharge pressure from 9 of these sprinklers was measured. Sprinklers were selected to provide a representative distribution of topography and distance from the well. Pressure readings ranged between 29 psi at the highest point farthest from the well to 52 psi in a topographic low located closer to the well. Based on the pressure readings, a pumping rate of 396 gpm was estimated.

About 9.5 hours (570 minutes) into the pumping period, the well owner switched the operating set of sprinklers and 262 sprinklers operated through the night. No pressure readings were made during this period. No corresponding break in the slope of the drawdown curve is apparent in Figure 7.

About 23 hours (1380 minutes) into the pumping period, the owner switched the operating set of sprinklers again and 276 sprinklers began operating. In this configuration, pressure readings from the nozzles ranged from 25 to 38 psi. Based on these readings, the well was pumping at 339 gpm. An increase in the slope of the drawdown curve is apparent at the time of the sprinkler set change. However, a reduced pumping rate should correspond to a reduction in slope, not the increase that occurred.

In order to continue orchard maintenance, the well owner pumped the older irrigation well periodically throughout the test period. This first occurred between 245 and 262 minutes into the test period and again between 270 and 280 minutes. The older irrigation well operated at about 26 gpm during these periods.

The well owner did not want to stop operating the well until the entire orchard had been irrigated. Therefore, following 24 hours of pumping the transducer equipment remained in the well to gather long-term drawdown information. The water level data (Figure 7) indicate that the pump was off between approximately 13:45 on May 1, 2003 and 7:56 on May 2, 2003. The data also indicate that pumping stopped at 9:04 on May 4, 2003 and did not resume until after the transducer equipment was removed at 14:40 the following day. The maximum drawdown measured in the well was about 3 feet.

The T29R25S35 well does not fully penetrate the aquifer, however, the depth of the bottom of the aquifer is unknown. Therefore, based on the information currently available the drawdown data could not be corrected for partial penetration. The transmissivity of the water bearing material at the T29R25S35 site was calculated to range between 149,000 and 268,000 gpd/ft (Table 3). The large range in transmissivities is a result of the increasing slope of the drawdown curve during the test. Although sprinkler sets were changed during the test which likely changed the pumping rate, the changes noted do not explain the changes in slope. The increased drawdown may be due to a gradual boundary such as a thinning aquifer with distance from the well.

5.5.1.3 Hammons Well

A pumping test was attempted in a well used for stock watering by Chuck Hammon in the northeast portion of the Foster Creek area. Through conversations with the well owner, it was learned that the well casing extended the entire length of the borehole and was not perforated. Standard pumping test analysis methods are not applicable for drawdown data gathered from wells with this type of construction. Therefore, the data have not been analyzed and are not presented.

5.5.1.4 TOWN OF MANSFIELD

Okanogan Drilling & Development Co. of Okanogan, Washington conducted an aquifer test in Well 3 for the Town of Mansfield on October 3, 1990. The well is constructed of 12-inch diameter casing from ground surface to 219 feet below ground and 10-inch diameter casing from 219 to 290 feet below ground surface. The 10-inch casing is perforated between 240 and 280 feet below ground where aquifer materials are described on the driller's log as gravel and basalt. The pump was operated for 16 hours during which time water levels and flow rates were measured. The Town of Mansfield provided copies of the data to PGG.

The drawdown data from Well 3 were plotted by PGG and are presented in Figure 8. The well is completed in the basalt aquifer, so partial penetration corrections were not necessary. Total drawdown after pumping the well for 16 hours at approximately 455 gpm was 45 feet. The transmissivity value estimated from this data is 26,000 gpd/ft (Table 3).

5.5.2 Moses Coulee Results

Aquifer tests were planned for the upper, middle, and lower portion of the Moses Coulee study area in the Billingsley, Biram, and Moses Coulee Water Association wells. In addition, data from a test performed by the Department of Ecology (Ecology) conducted in the Barb well in 1965 was also used. All wells are at least partially completed in the alluvium. The Biram well appears to extend into the underlying basalt. The analytical results are summarized in Table 3.

5.5.2.1 BILLINGSLEY WELL

An aquifer test was conducted in an irrigation well owned by Dave Billingsley that is located in the northern portion of the Lower Moses Coulee. The well is 12-inches in diameter and extends to a depth of 207 feet. The casing is perforated between 178 and 207 feet bgs. The well log indicates the aquifer material is basalt and gravel. A 75-horsepower turbine pump is permanently installed in the well.

Levelogger equipment was installed in the Billingsley well on the afternoon of May 5, 2002 and collected pre-test data at 5-minute intervals. A second logger was installed at the same time near the wellhead to collect barometric data. The pre-test water level was corrected to remove the effects of atmospheric pressure. Between logger installation and the start of the test, the water level in the Billingsley well declined 0.13 feet (Figure 9). Approximately half of that decline occurred within the first two hours of data collection. Calculations indicated this antecedent trend was water levels declining by $4x10^{-5}$ feet per minute. Because of the small magnitude of the pre-test trend, no correction was necessary.

The test began at 8:20 on May 6, 2003. Approximately 28 minutes into the test the pressure gauge at the wellhead indicated that pressure began to build in the discharge system. After 29 minutes of pumping water began flowing from the irrigation gun located approximately 1 mile from the wellhead. Pressure continued building in the discharge system until approximately 44 minutes after pumping began at which point the pressure stabilized at approximately 119 psi. Pressure readings measured in the discharge from the 1.3-inch, smooth bore Nelson irrigation gun indicated the flow rate was approximately 440 gpm.

Water levels were measured automatically with the Levelogger and manually with a sounder during the test. The initial depth to water was 156.33 feet. In the first 28 minutes of pumping the water level drew down about 0.83 feet. Drawdown data in the Billingsley well are presented in Figure 10. The water level then rose by about 0.3 feet when the pipes filled with water and the irrigation gun began delivering water. The water level in the Billingsley well declined for the remainder of the test with a total drawdown of 0.85 feet.

The pumping period ended at 8:25 on May 7, 2003. Water levels were measured automatically and manually for approximately 1 hour of the recovery period at which time the level in the well was about 0.29 feet below the initial static level.

Based on the interpretation discussed in Section 6.2, the bottom of the aquifer is approximately 18 feet below the bottom of the Billingsley well. Therefore, the drawdown data were corrected for partial penetration. The transmissivity of the alluvial aquifer at the Billingsley well was calculated to be 2,904,000 gpd/ft and the hydraulic conductivity calculated is 9954 ft/day (Table 3). These are the greatest transmissivity and hydraulic conductivity values measured in the Coulee and are reflective of the coarse aquifer material.

Recovery data was presented in Figure 10 but not analyzed because the data did not present a consistent slope. This is likely because the well did not have a check valve and the recovery plot reflects water cascading down the well in addition to entering through the screen.

5.5.2.2 BIRAM WELL

An aquifer test was conducted in the Biram irrigation well located near the middle of the Moses Coulee. The 8-inch diameter well casing extends to 170 feet bgs and is perforated between 140 to 162 feet bgs and exposed to gravel. The borehole extends 30-feet below the bottom of the well casing into basalt for a total well depth of 200 feet bgs. A 25-horsepower submersible pump is permanently installed in the well.

An older 8-inch diameter well is located approximately 50 feet west of the pumping well. A drillers log is not available for the older well but the total depth was measured in the field at 135 feet bgs which is just above the perforated section of the pumping well.

Pressure transducer and datalogger equipment was installed in the Biram pumping well on April 25, 2003 to record pre-test water level conditions in 10-minute intervals. The pre-test data (Figure 11) indicate that the water level in the Biram well suddenly increased twice during the monitoring period by about 0.6 feet, likely in response to pumps in nearby irrigation wells shutting off. Calculations indicate the antecedent trend immediately before the test was water levels increasing by $1x10^{-5}$ feet per minute. Because of the small magnitude of the pre-test trend, no correction was necessary.

Pumping began in the well at 12:45 on May 1, 2003. After approximately 2 minutes of pumping water began discharging through the Nelson impact sprinklers. Water levels were measured automatically by Leveloggers and manually with a sounder in the pumping well. For the first hour of pumping, water levels were measured by hand only in the observation well. These manual measurements indicated that drawdown in the observation well was occurring so transducer and datalogger equipment was installed. Drawdown data in both Biram wells and recovery data in pumping well are presented in Figure 12.

Initial depths to water were 122.98 feet and 123.85 feet in the pumping and observation wells at the beginning of the tests. Water levels in the pumping well dropped approximately 1 foot in the first 6 seconds of pumping and then rose about 0.1 feet (Figure 12). This water level was maintained until after about 2 minutes of pumping when the water level rose by another 0.1 feet. This water level increase corresponds to the time the irrigation lines filled and the sprinklers began delivering water. At three minutes into the test, the water level in the well began to decline. The drawdown plot (Figure 12) indicates that after about 200 minutes of pumping, the rate of drawdown increased. The maximum drawdown of 1.68 feet was reached after about 4000 minutes of pumping.

Drawdown data in the Biram observation well is presented in Figure 12. The plot of observation well data also reflects an increase in the rate of drawdown about 200 minutes into the test. The maximum drawdown in the observation well water level of 0.74 feet also occurred after the pumping well had been operating for about 4000 minutes.

The water pressure from 6 sprinklers in the operating set was measured approximately 75 minutes after pumping began. The pressure readings from the 11/64ths-inch sprinkler nozzles indicated a discharge rate of about 5.2 gpm per sprinkler or 208 gpm total. Note that the manufacturer's correlation between pressure, nozzle size, and discharge rate are based on no-wind conditions and a specific nozzle height that may not exist in the field.

The owner changed the operating set of sprinklers after about 18 hours. Pressure readings indicated the discharge rate of about 5.4 gpm per sprinkler, however, with fewer operating sprinklers, the total pumping rate was 190 gpm.

The pumping test continued unattended by Pacific Groundwater Group personnel until pumping stopped at 11:05:30 on May 6, 2003, 7093 minutes since the test began. The water level data from both the pumping and observation wells (Figure 12) indicate that water levels had begun to increase at about 11:00 on May 4, 2003. It is possible these responses correlate to decreasing pumping rates as the well owner changed the operating sprinkler sets. Immediately before the pump was turned off, the water levels in the pumping and observation wells were only 0.96 and 0.19 feet below the initial static water levels.

Water levels were measured automatically and manually for approximately 1.5 hours of the recovery period at which time the water level in the pumping well was 0.1 feet below the initial static water level.

The increased rate of drawdown reflected in the pumping and observation well data suggest that the Biram well is influenced by an aquifer boundary. When the effects of pumping reach a boundary, drawdown in the well increases. Therefore, the slopes of the drawdown curves before 200 minutes into the test reflect the aquifer and the slopes of the curves after 200 minutes into the test reflect the boundary. The transmissivity of the water bearing material at the Biram site was calculated to be between 343,000 and 610,000 gpd/ft. The values for hydraulic conductivity calculated from the test data range from 953 to 1165 ft/day (Table 3). The storativity value estimated from the observation well data is 0.08. These values represent the combined water bearing material at the Biram well because the well is completed in both the alluvial and basalt aquifers. Because the alluvial aquifer is a water table aquifer and the well extends into the basalt, the pumping well data were not corrected for partial penetration.

5.5.2.3 MOSES COULEE WATER ASSOCIATION WELL

A pumping test was attempted in the Moses Coulee Water Association Well 4 in the southern end of the Moses Coulee. However, the ¼ inch diameter sounder encountered an obstruction and broke in the well before the test began. Therefore, no attempt was made in install the larger diameter transducers and the pump test plans were abandoned.

5.5.2.4 ROTH WELL

On September 15, 1965 representatives of the Department of Ecology conducted an aquifer test in the Roth well. The well is 123 feet deep and is perforated between 85 and 115 feet bgs exposing the well to basalt gravel and boulders. The pumping period lasted for approximately 6 hours and water levels were measured manually in the Roth and three observation wells. Ecology estimates that the pumping rate for the test period was 1025 gpm.

The report of the test includes the manual water levels measured in the Roth well during the test but the measurements made in the Barb well are only reported graphically and those made in the other observation wells are only described in the text.

The drawdown data in the Roth well as plotted by PGG are presented in Figure 13. The drawdown plot reflects an initial decline as the irrigation lines were filling, following by an increase in water level when the lines were full and the sprinklers began delivering water, followed by final period of consistent water level decline as pumping continued at a constant rate. Ecology reports that total drawdown in the well was 3.52 feet. The transmissivity values calculated for the alluvial aquifer at the Roth site are 311,000 and 459,000 gpd/ft. The calculated hydraulic conductivity values are 1093 and 1534 ft/day. Because water level data for the observation wells are not available, a storativity value cannot be calculated. Based on the interpretation presented in Section 6.2, the bottom of the Roth well corresponds to the bottom of the aquifer, so the well is considered fully penetrating. The text describes that the water levels in the Barb well declined a total of 0.30 feet during the Roth test.

Ecology reports that water level data in the other observation wells are anomalous and did not draw any conclusions regarding the relationship of these wells to the Roth well.

6.0 DISCUSSION

The following discussion is derived from the field study discussed above as well as references cited.

6.1 FOSTER CREEK

Foster Creek drains approximately 660 square miles. The aquifers typically occur in unconsolidated deposits overlying the basalt and in fractures or brecciated interflow zones that occur between the basalt flows. Aquifer tests indicate that transmissivities range from 69 to 268,000 gpd/ft. This large range represents differences in both the aquifer material and the thicknesses penetrated. Lower transmissivities represent bedrock aquifers, and higher transmissivities represent alluvial material. Thinner aquifers will result in lower transmissivities, thicker aquifers will result in greater transmissivities.

The USGS reports (Whiteman and others, 1994) that the overburden (all materials overlying the Columbia River Basalt Group) ranges in thickness between 50 and 200 feet in regions of WRIA 50. These areas are generally along the Columbia River and Foster Creek near Bridgeport, and south of the East and Middle Foster Creek. Many of the wells along East Foster Creek and north of its confluence with Foster Creek are completed in the unconsolidated sand and gravel. These wells are mostly domestic although one of the areas largest capacity irrigation wells pumps water from the unconsolidated material.

Wells spread throughout the Foster Creek area completed in basalt draw water from fractures or interflow zones that occur between the basalt flows. A Washington State University graduate student identified two thick interbasalt sequences from observations made during drilling of a Town of Mansfield test well. The upper interbed was encountered between 485 and 592 feet below ground surface and consisted of sand interbedded with lesser amounts of siltstone and clay. The lower interbed was encountered between 690 and 755 feet below ground surface and consisted of siltstone and clay with some interbedded sand. At the time of the report, the author acknowledged the interbeds could be potential aquifers but the capacity of the zones was unknown. The current Town of Mansfield production wells are completed in basalt shallower than these interbeds.

According to descriptions on the driller's well logs, a few wells in the area are completed in water-bearing granite underlying the unconsolidated material. These wells are located near Bridgeport, McNeil canyon, and around the northern and eastern limits of the Foster Creek area.

6.1.1 Groundwater Decline

Groundwater decline was assessed by comparing depth to water measurements recorded at the time of drilling on the well log to measurements collected by PGG in April 2003. Because only two data points are used and seasonal fluctuation is unknown, these data should be regarded with caution. Further water level trend data collected as part of the long-term groundwater level monitoring program will provide supplemental data for this analysis.

In the Foster Creek area, well logs report water levels at the time of drilling for 18 of the wells included in the April 2003 water level survey (Table 4). Water levels in April 2003 for two of these wells were within a foot of those reported on the well logs and the change is not considered significant.

Water levels were greater than a foot deeper in April 2003 than recorded on the log for five wells: both Hanford wells, Geringer, Pitts old and new wells, the Bahr well, and the Hammons stock well. These wells are distributed throughout the study area and most of the current water levels are between 2 and 12 feet lower than reported on the well logs. However, water levels measured in the Pitts old well and the Bahr well in April 2003 were 56 and 63 feet lower than those reported on the well logs. Mr. Pitts and Department of Ecology records indicate that the old well went dry in November 1986 and attempts to deepen the well to encounter groundwater were unsuccessful. Well logs indicate the total depth of the well is 5 feet deeper following these attempts. No additional information is available for the Bahr well.

Water levels in nine wells indicate shallower water levels in April 2003 than at the time of drilling. The depth to water measurements in the 8-inch Bonneville Power, Hammons domestic, Malone, Cavadini, and Hemmer wells were between 1 and 12 feet shallower than those reported on the well logs. Measurements in the unused Hammons, both Hunt, and the Watson wells were between 18 and 29 feet shallower in April 2003.

No regional groundwater decline is indicated since there does not appear to be a consistent pattern of decline.

6.2 MOSES COULEE

Lower Moses Coulee, from McCartney Creek to the Columbia River, is approximately 20 miles long and 1 mile wide with steep basalt cliffs rising up to 1500 feet above the valley floor. The first 5 miles of the Coulee from McCartney Creek is oriented east-west, the Coulee then switches to a northeast-southwest trend for the remaining 15 miles to the Columbia River. The surface elevation of the valley floor ranges from 1100 feet (relative to mean sea level, msl) near McCartney Creek to 850 ft msl near the Columbia River.

Moses Coulee was formed about 15,000 years ago when a lobe of the Cordilleran Ice Sheet descended into the Okanogan Valley, blocked the Columbia River, and covered 500 square miles of the Waterville Plateau west of Grand Coulee. The ice-dammed Columbia River backed up to form Glacial Lake Columbia, a huge version of the lake now ponded by Grand Coulee Dam. Lake Columbia's overflow began the formation of Moses Coulee. (From: U.S. National Park Service Website, Ice Age Floods, 2002). The flood events are termed the Missoula Floods.

The basalts in the Lower Moses Coulee area are described in Section 4. Driller's well logs and three seismic profiles conducted in the Coulee were interpreted to develop a longitudinal geologic cross section (Figure 14). The location of this section is shown on Figure 2. The Coulee cuts across multiple anticlinal basalt ridges formed in Pliocene time and is backfilled with course gravel and fine sediments. The Coulee crosses the Badger Mountain anticline near the mouth of Douglas Creek. The depth to bedrock in the vicinity of the anticline is unknown because of the lack of well logs and other sources of geologic information. The cross section illustrates that the depth to bedrock decreases from the top of the Coulee where a seismic profile indicates the depth to bedrock is 380 feet, reaching its shallowest point near Palisades. The shallowest known depth is approximately 200 feet near the Barb well, but bedrock is possibly even shallower near the Badger Anticline. The depth to bedrock then increases from Palisades toward the Columbia River.

Drillers well logs and seismic profiles indicate the depth to bedrock varies from 100 to 400 feet below the alluvium (Figure 14). Where the Coulee crosses the anticlinal ridges, the depth to bedrock is generally less than 200 feet indicating that some of the basalt structures may be reflected in the basalt surface topography despite the intense erosional events of the late Pleistocene.

The alluvial geology of Lower Moses Coulee reflects its formation by high energy flood events. The alluvium consists of unlithified deposits varying in thickness from 150 to 300 feet deposited during the catastrophic Missoula floods. Grain size ranges from large boulders of broken basalt and gravel to fine sand and clay. During a single flood event, coarse boulders and gravel were deposited first followed by the settling out of the finer materials. Each subsequent flood eroded portions of the earlier deposits before depositing more material. The resulting stratigraphy is characterized by coarser materials towards the bottom with lenses of finer materials towards the top.

6.2.1 Aquifers

The Lower Coulee receives runoff from much of the Mansfield Plateau drainage system, an estimated 1000 square miles. McCarteney Creek discharges a perennial flow at the upper end of the Coulee near its confluence with Rattlesnake Creek and Douglas Creek discharges a perennial flow into the lower Coulee near Palisades. Additional discharge of snow melt streams contribute water to the lower Coulee. The primary aquifer used in the Coulee is the alluvial aquifer, although a few wells are completed in the underlying basalt.

The alluvial aquifer is tapped by both irrigation and domestic wells. The aquifer is unconfined, with the water table generally 80 ft or more below the surface of the valley floor. The underlying basalt is generally less permeable and defines the bottom of the aquifer.

Depth is 100 to 400 feet below ground surface. Average groundwater yields to wells in the alluvial aquifer are over 500 gallon per minute (gpm) and in many cases with negligible drawdown reported.

Hydraulic conductivity reflects the ability of the aquifer material to transmit water under a unit hydraulic gradient. Aquifer transmissivity is hydraulic conductivity multiplied by the aquifer thickness. Estimates of transmissivity in the Moses Coulee area, based on aquifer tests described in Section 5.5.2, range from 311,000 to 2,904,000 gpd/ft, hydraulic conductivity ranges from 655 to 9,954 ft/day. An average hydraulic conductivity of approximately 4000 ft/day was derived by calculating averages for each location, and subsequently averaging those values. One storativity value of 0.08 was estimated from the Biram well.

Estimates of hydraulic conductivity for similar alluvial deposits in Spokane and the Pasco Basin provide similar values, from less than 50 ft/day to over 10,000 ft/day (Molenaar, 1988, and Drost and others, 1997). The wide range of values reflects the wide range of grain size and sorting found in these deposits. Coarser materials are generally found in the lowest section of the deposits where the aquifer is fully saturated.

Groundwater in the basalt aquifer moves dominantly through the more permeable interflow zones. These zones typically comprise 5 to 10 percent of the thickness of an individual basalt flow (Whiteman and others, 1994). Whiteman and others (1994) provide estimates of the horizontal hydraulic conductivity ranging from less than 1 up to 6100 ft/day for the basalt aquifer, with a median of about 5 ft/day (based on the open interval portion of well tests).

6.2.2 Groundwater Sources and Sinks

Groundwater sources and sinks represent the various inputs (sources) and outputs (sinks) of water to the groundwater flow system.

6.2.2.1 Recharge

Groundwater recharge is the portion of precipitation that enters the ground and crosses the water table. Estimates of recharge to the Moses Coulee area come from Technical Assessment (PGG, 2003) which used equations derived from the USGS Deep Percolation Model (DPM) for the Columbia Basin (Bauer and Vaccaro, 1990). The DPM estimates recharge using spatial distribution of soil type, geology, solar radiation, temperature, stream flow, vegetation cover, land use and precipitation. Estimates range from 0.5 to 5 inches/year for the Moses Coulee area with most of the valley ranging from 0.5 to 1 inches/year.

6.2.2.2 Surface Water

The main surface water sources to groundwater are Douglas Creek (baseflow ranges 12-14 cubic feet per second [cfs]) and McCartney Creek (baseflow ranges 1-3 cfs). Both these creeks lose all their water to the alluvial aquifer. McCartney Creek loses most of its surface water just upstream from the Moses Coulee study boundary, while Douglas Creek loses its water as it flows down Moses Coulee for varying lengths depending on flow. During storm water runoff events the creek has been known to flow all the way to the Columbia River. Douglas Creek is not in direct hydraulic connection with the underlying groundwater in the alluvial aquifer beneath Moses Coulee (see Section 6.2.4). An unsaturated zone approximately 100 ft thick exists between the bed of the creek and the water table.

The Columbia River (normal pool elevation 570 ft msl) is the main discharge point for both the alluvial and basalt aquifers.

6.2.2.3 PUMPING WITHDRAWALS AND WATER USES

Groundwater withdrawal rates are based on estimates for all domestic and irrigation use in the Moses Coulee area. Most wells withdraw groundwater from the alluvial aquifer. Domestic use is based on an assumed rate of 2 acre-feet/yr (af/yr). Consumption was assumed to be 20 percent for domestic use because most of the water is likely returned via septic recharge. A total of 17 domestic wells withdraw a total of 6.8 af/yr (0.009 cfs) (includes an estimated 20 percent efficiency).

Irrigation use is based on an assumed rate of 3 ft/yr for every acre of irrigation land. The irrigated land is broken up into tracts irrigated by 1 to 5 wells. The irrigation area for each tract was provided by local residents or was calculated from a Douglas County Transportation and Land Services GIS coverage of irrigation land. Groundwater withdrawal rates for a particular district were split evenly between the number of wells in a particular tract. A consumptive use of 80 percent was assumed for irrigation. A total of 21 irrigation wells supplying water to a total of 1545 acres withdrawals a total of 3708 af/yr (5.1 cfs) (includes the consumptive use of 80 percent).

The Palisades Irrigation District near Palisades uses surface water from Douglas Creek to irrigate 590 acres. Total withdrawal is 2 cfs (includes the estimated 80% consumptive use), which is about 15% of the total average baseflow in the creek.

6.2.2.4 SPRINGS

Springs have been observed discharging from discrete interflow zones in the basalt aquifer along the base of the cliffs facing the Coulee. Like Douglas and McCartney creeks this surface water quickly recharges the permeable alluvial aquifer and therefore represents a source for the alluvial aquifer. A number of springs are identified on the USGS 1:24,000 topographical map in the Moses Coulee area. Spring discharge rates have not been monitored in the Moses Coulee study area, rates from Rattlesnake Springs (approximately 2 miles up the Coulee from the study boundary) have been monitored for approximately one year with rates ranging from 1.5 to 2 cfs (Aug. 2002 to July 2003). Lower rates (0.3 cfs) were observed in 1978 (Walters, 1980).

Subsurface groundwater flow from the basalt aquifer to the alluvial aquifer likely occurs along discrete interflow zones similar to those observed in spring discharge. The rates and occurrence of discharge points are likely to be greater in the subsurface where the basalt aquifer becomes more fully saturated and intermediate and deep flow paths are intersected by valley walls.

6.2.3 Groundwater Flow Directions

Groundwater in the alluvial aquifer beneath Moses Coulee is recharged by three sources: direct precipitation, surface water infiltrating from Douglas and McCartney Creeks, and discharge in the subsurface from the underlying basalt. Groundwater flow directions in the alluvial aquifer are dominantly horizontal towards the Columbia River, with groundwater discharging to either the Columbia River or pumping wells.

Groundwater flow in the basalt aquifer is more poorly understood. Due to its great thickness (up to 3000 ft thick) there are likely multiple aquifers within the basalt unit with multiple groundwater flow paths. Flow paths in the basalt aquifer may be either shallow or deep. Shallow flow paths take place near land surface, are more likely to be unconfined, are strongly influenced by surface topography, and extend relatively short distances between recharge and discharge points. These shallow flow paths are likely intercepted by the Moses Coulee and are estimated in the model presented in Section 7.0. Deep flow paths take place well below the lands surface, are more likely to be confined, are relatively unaffected by surface topography, and extend relatively long distances between recharge and discharge points. These flow paths likely bypass the Moses Coulee alluvium and discharge directly to the Columbia River. This water would account for the difference between recharge to the Moses Coulee catchment area and the flux into the Coulee estimated in the model discussed in Section 7.0.

6.2.4 Surface Water / Groundwater Interaction – Moses Coulee

Douglas Creek enters the Moses Coulee north of Palisades where the Coulee turns westward. The creek flows intermittently and currently discharges completely to the underlying groundwater before it reaches the mouth of the Coulee or the Columbia River. The Department of Ecology (Department of Ecology, 1988) has stated that the creek is or has been in continuity with the alluvial aquifer. Water levels measured during the survey (Section 5.2) were compared to those recorded on the well logs to assess whether they indicated present or historic continuity. Continuity is used here to indicate that no unsaturated zone exists between the stream and the groundwater.

The shallowest groundwater levels measured in Moses Coulee in both April 2003 and reported on the well logs were approximately 85 feet below ground surface. All other well logs reported groundwater depths greater than 85 feet. Depth to water in Douglas Creek is within ten feet of ground surface. The high transmissivity of the underlying aquifer and the large separation between surface and groundwater levels indicate that groundwater in the Moses Coulee is currently not in continuity with Douglas Creek and that groundwater was also not in continuity with the creek when the wells were drilled. This relationship can be inferred from the cross section presented in Figure 14. This figure indicates the degree of distance between the water table and the ground surface where the streambed is located.

6.2.5 Groundwater Decline

Groundwater decline was assessed by comparing depth to water measurements recorded at the time of drilling on the well log to measurements collected by PGG in April 2003. Because only two data points are used and seasonal fluctuation is unknown, these data should be regarded with caution. Further water level trend data collected as part of the long-term groundwater level monitoring program will aid in this analysis.

In Moses Coulee, well logs report water levels at the time of drilling for 12 of the wells included in the April 2003 water level survey (Table 4). Measurements in April 2003 indicated a deeper water level than recorded on the well log in five wells: Barb, Criss, King, Collins, and Bosnar. The difference in the Barb well (0.56 feet) is within the accuracy of the measurement reported on the log and is therefore not significant. The water level measured in the Criss well in April 2003 was about 2 feet deeper than reported on the well log which may be attributable to the use of different measuring points. When water levels are measured after drilling the measuring point is typically the ground surface. Water levels in April were measured relative to the top of the well casing which are commonly 2 to 3 feet above the ground.

Water levels at the time of drilling were reported for the King, Collins, and Bosnar wells in early March 1999. The water levels measured in April 2003 were between 5 and 8 feet lower than those in 1999. Because the measurements were taken at the same time of year, this difference can't be explained by seasonal variation but longer term variation is possible.

Measurements in April 2003 indicated a shallower water level than recorded on the well log in 7 wells. The water levels measured in April 2003 were between 4 and 10 feet higher than those recorded on the well logs for the Moses Coulee Water Association Well #4, Gutschow, the northern Biram pumping well, the Billingsley, and Bosnar wells. The magnitudes of these differences are similar to those with currently deeper water levels. The well log levels for all but the Water Association well were reported for March or May, so the differences are not seasonal.

Comparing the historic to recent water level data for the Palisades Irrigation District and middle Linville well indicate water levels are presently 22 and 44 feet higher than reported on the logs. A change of this magnitude is unlikely given the high conductivity of the subsurface material in the Coulee and changes in other wells. It is questionable whether the measurements reported on the well logs accurately reflect the static water level at the time.

No regional groundwater decline is indicated since there does not appear to be a consistent pattern of decline.

7.0 MOSES COULEE GROUNDWATER MODEL

A computer groundwater flow model was developed to assess the groundwater influx into Lower Moses Coulee. The model was constructed using the U.S. Geological Survey finite difference modeling code “MODFLOW” (McDonald & Harbough, 1988) and the commercially available graphical users interface “Groundwater Vistas” (Environmental Simulations, Inc.). The model simulates a groundwater flow system by using a series of mathematical equations that describe the physical process occurring in the system. The solution to a groundwater flow model is the spatial distribution of the groundwater head (the elevation of the water table in an unconfined aquifer). From the head solution, groundwater fluxes are calculated by the model.

7.1 MODEL CONFIGURATION

The modeling effort was focused on the alluvial aquifer, which is the main aquifer used in the Lower Moses Coulee area. The alluvial aquifer was represented as a single, homogeneous layer based on the predominantly horizontal groundwater flow paths and the limited information of the spatial heterogeneity in the aquifer. The aquifer was modeled steady-state (configuration of water table does not change with time) to represent long-term average conditions. Fluxes from the basalt aquifer to the alluvial aquifer were specified using flux boundaries.

7.1.1 Model Grid

The model domain (Figure 15) consists of a grid defined by 345 rows and 340 columns with an equal cell spacing of 250 ft. The total area covered by the grid is 263 square miles; however, most of the area in the model domain is inactive (defined by no flow cells and not included in the computer simulation). The active part of the model domain (about 20 square miles) represents the outwash-filled portion of Moses Coulee from the Billingsley Ranch to the Columbia River.

The bottom elevation of the outwash aquifer was defined by the top surface of the underlying basalt aquifer, which varies in depth from less than 100 ft to over 300 ft below the valley. The shape of the underlying basalt surface was important because it constrains the thickness of the alluvial aquifer, which influences the aquifer transmissivity and the shape of the water table. A contour map of the underlying basalt surface was created by interpolation from data points used in the construction of the axial cross-section (Figure 14). The perpendicular cross-section was assumed to be box-shaped, although it is more likely to be U-shaped. The interpreted surface slopes from about 730 ft asl to 400 ft asl along the axis of the Coulee, except as it crosses the Badger Mountain anticline where it rises up to 860 ft asl.

The top elevation of the model layer was set to a constant value of 1125 ft, an arbitrary value selected so that it would remain above the simulated water table. The simulated water table defines the top of the alluvial aquifer.

7.1.2 Boundary Conditions

Except for the boundary represented by the Columbia River, the model is bounded by specified flux boundaries along all edges of the active domain to simulate flow from the basalt aquifer to the alluvial aquifer (Figure 15). Specified flux conditions are achieved by assigning positive flux values (volume of water into the model per time) to individual model cells.

7.1.2.1 SPECIFIED FLUX MODEL BOUNDARY

The specified flux cells along the model boundary simulate groundwater discharge from the basalt aquifer to the alluvial aquifer. The total flux apportioned along the boundary was initially set at 60.6 cfs based on the total groundwater inflow to the Moses Coulee basin estimated in the Level 1 Basin Assessment (59.3 cfs) plus additional flux (1.3 cfs) near the top of the Coulee where the stream flow in McCartney Creek is assumed to recharge the alluvial aquifer (Reach 2 in Figure 15). The McCartney Creek flux is a measured quantity and was not changed during the calibration process.

Because groundwater likely discharges from discrete interflow zones within the basalt, the amount of discharge to the alluvial aquifer is partly controlled by the number of interflow zones bisected by valley incision, with areas of deep incision bisecting more interflow zones than areas of shallow incision. Areas where the depth to basalt bedrock is greatest should therefore receive more discharge. Consequently, the boundary was divided into seven zones (Reach 2 through 8 in Figure 15) and relatively less flux was assigned to cells along the boundary where the valley crosses the Badger Mountain anticline (Reach 5) and progressively increased both up gradient and down gradient as the depth to the basalt surface increases (Reaches 2, 3, 4, 6, 7 and 8). During the calibration procedure we adjusted the total flux rate while maintaining the same relative distribution to the different zones described above.

7.1.2.2 CONSTANT HEAD BOUNDARY

The Columbia River is the regional discharge point for groundwater flow in the Moses Coulee area and is represented in the model by a constant head boundary set at 570 ft asl, the normal pool elevation. The constant head boundary sets the head at the boundary and influences the solution in the remaining part of the model domain.

7.1.3 Surface Water Seepage

Surface water seepage from Douglas Creek provides water to the alluvial aquifer in the Moses Coulee study area. During most of the year Douglas Creek flows for varying distances downstream from where it first enters the Coulee before going completely dry. However, the creek can flow all the way to the Columbia River during intense storm events or spring snow melt. Stream discharge in Douglas Creek has been monitored at a gauging site just upstream of the study area since August 2002 and averages about 13 cfs. The Palisades Irrigation District uses about 2 cfs of this discharge. Douglas Creek is likely not hydraulically connected to the groundwater system because the depth to groundwater reported on well logs is greater than 85 feet (Section 6.2.4). Therefore seepage from Douglas Creek was simulated with a specified flux boundary (Figure 15). Since Douglas Creek loses all of its water to the alluvial aquifer during most of the year before reaching the Columbia River, we assigned the total average discharge less the water used by the Palisades Irrigation District (11 cfs). The 11 cfs flux was distributed into 180 model cells by decreasing the rate in each adjacent cell linearly from where Douglas Creek first enters Moses Coulee to approximately 7 miles downstream (Figure 15).

7.1.4 Recharge

A uniform precipitation recharge rate of 3 in/yr, or approximately 4 cfs, was assigned to the entire active model domain based on average values reported in the U.S. Geological Survey Deep Percolation Model (Bauer and Vaccaro, 1990). This represents about 30% of the average annual precipitation.

7.1.5 Pumping Wells

Thirty-eight irrigation and domestic wells were included in the model simulation (Figure 15). Well locations were identified from well logs or personal communication with local residents. Pumping conditions are simulated in the model by assigning a negative flux to the model cell with a well. The negative flux for each well was assigned values described in Section 6.2.2.3. Total average annual groundwater withdraw from pumping wells in the model is about 5.1 cfs (2289 gpm).

7.1.6 Horizontal Hydraulic Conductivity

Pump tests performed in the Lower Moses Coulee represent three point estimates of the alluvial aquifer transmissivity (see Section 5.5.2). Based on estimates of the saturated aquifer thickness in the vicinity of these test wells, horizontal hydraulic conductivities are estimated at 924, 1287 and 9954 ft/day, with an average of 4055 ft/day. Such a large range in hydraulic conductivity for unconsolidated aquifers is not uncommon. Other pump tests in similar material have resulted in values ranging from less than 50 ft/day to over 50,000 ft/day (Whiteman and others, 1994; and Drost and others, 1997). Groundwater flow in heterogeneous aquifers is typically dominated by discrete zones of high hydraulic conductivity, which form preferential flow paths in the groundwater flow system.

Currently, there are insufficient data in the Moses Coulee area to map the spatial variability in the hydraulic conductivity of the alluvial aquifer. Therefore, the average hydraulic conductivity from the three pump tests (4000 ft/day) was used as a bulk average for the entire aquifer.

7.2 MODEL CALIBRATION

Calibration of the flow model refers to variation of model parameters in order to most closely simulate field-measured heads (head targets) and or fluxes (flux targets). During the calibration process, various model input parameters are changed within a range of possible values until a best match is found between field-measured and simulated output values.

In the Lower Moses Coulee groundwater model, 10 field-measured heads were used as target values. These heads were measured in April 2003 as part of the well survey described in Section 5.2. Model calibration was performed through trial and error by adjusting the specified fluxes along the model boundary until the modeled heads best matched the field-measured heads. Other model input parameters, such as hydraulic conductivity, recharge, Douglas Creek specified flux, and pumping rates, were not changed during the calibration. The rate of recharge is relatively small and does not significantly affect the model solution and the Douglas Creek flux and pumping rates are measured or relatively well known values.

7.3 MODEL RESULTS

A plot of modeled versus measured heads provides a graphical way of displaying the model results for different boundary flux values (Figure 16). A perfect fit would plot along the straight line. Selection of a best-fit solution is not straight forward because the distribution of the data points in Figure 16 is nonrandom. Heads in the upper and lower parts of the Coulee tend to be modeled too high (above the line) and heads in the middle part of the Coulee tend to be modeled too low (below the line). This tendency is likely a result of varying hydraulic conductivity throughout the Coulee, or the configuration of the underlying basalt surface, which has a strong control on the slope of the water table in the alluvial aquifer.

The simulated water table configuration (Figure 17) is similar to the configuration of the measured water table (Figure 3) with the slope relatively flat at the upper and lower ends of the Coulee, but much steeper through the middle part of the Coulee. The steep slope in the water table through the middle part of the Coulee is controlled by the sloping surface of the underlying basalt down gradient of the Badger Mountain anticline (Figure 14). Our interpretation of the underlying basalt surface in the model was based on limited well log descriptions and is therefore not well defined. The current interpretation may result in the modeled heads being too high in the upper and lower parts of the Coulee and too low in the middle part of the Coulee. The elevation of the underlying basalt surface is an important parameter in simulating the water table because it is used to calculate the saturated thickness of the alluvial aquifer and its transmissivity.

The absolute residual mean (ARM) can be used to quantitatively determine a best-fit solution. The residual is the difference in feet between observed and measured heads and the ARM is the mean of the absolute values of all residuals. Based on the ARM values, the best-fit solution was obtained with the boundary flux rate set to 44.5 cfs (ARM = 20.32 feet). This flux is about 75% of what was originally estimated for the Lower Moses Coulee area in the Level 1 Basin Assessment. However, because the transmissivity of the system is relatively high, changes in groundwater flux have only small changes on the ARM and ARMs for other flux values are only slightly higher. These other flux values may also be valid solutions given other sources of control on groundwater levels. For example, the underlying basalt surface and heterogeneities in the alluvial aquifer may represent significant controls on water levels in the alluvial aquifer. Currently, both these parameters are poorly defined for the Lower Moses Coulee area.

To assess the sensitivity of the head solution to changes in the hydraulic conductivity the boundary flux was set to the best estimate of 44.5 cfs and the hydraulic conductivity was varied between 1000 and 10,000 ft/day. The results of this sensitivity analysis indicate the head solution is relatively insensitive to hydraulic conductivity for values greater than 2000 ft/day (Figure 18). The reason the model is relatively insensitive to changes in boundary flux and for hydraulic conductivity values greater than 2000 ft/day is likely due to the aquifer's high transmissivity at these conductivity levels. Water levels in highly transmissive aquifers do not respond to stresses to the extent that they do in low transmissive aquifers. Other input parameters, Douglas Creek influx (11 cfs), McCartney Creek influx (1.3 cfs), and areal recharge (4 cfs) were not varied during the calibration process. Reasonable ranges for these parameters are much smaller than for hydraulic conductivity and therefore the model solution is likely to be less sensitive to changes in these parameters.

7.3.1 Effects of Groundwater Pumping

During well pumpage the water level in the aquifer around the well declines and forms a cone of depression in the water table. The amount of drawdown in the aquifer is controlled by the rate and duration of pumping, and the transmissivity of the aquifer. These effects were simulated by the Lower Moses Coulee model.

The drawdown in the water table around pumping wells simulated by the model was negligible. The largest simulated drawdown, about 3 ft, occurred around wells with the highest pumping rates (343 gallons per minute). However the simulated drawdown represents an average drawdown in a 250 ft x 250 ft cell. Local drawdown in the vicinity of the well would be somewhat greater. A more accurate estimate of drawdown in the vicinity of the well would require refining the grid spacing in the computer model. Nevertheless, drawdown is fairly minimal due to the high transmissivity of the aquifer.

7.4 MODEL LIMITATIONS

Limitations of the current model arise from the limited understanding of the subsurface basalt topography and the heterogeneity of alluvial aquifer hydraulic conductivity. There are likely to be discrete zones of high hydraulic conductivity dominating the flow system, whose geometry and transmissivity properties are poorly understood and the top surface of the underlying basalt is likely more complex than our current interpretations.

The current model is also limited to two-dimensional groundwater flow. Vertical flow within the alluvial or basalt aquifer may be an important component of groundwater flow that is unaccounted for. The current model also does not explicitly model the basalt aquifer. This makes the model unsuitable for evaluating the effects of stresses imposed on the basalt aquifer.

Finally, the current model is steady-state and would have to be modified for transient simulations. Transient simulations require estimates of aquifer storage properties and recalibration, and would be necessary for simulating potential aquifer storage and recovery.

8.0 RECOMMENDATIONS

Below are recommendations to improve the model design and alternative approaches to define the groundwater influx. Improvements to the model design include:

- Assess the depth to bedrock in the Coulee with additional geophysical surveys or borings.
- Perform additional model simulations using different configurations of the underlying basalt surface to better understand the sensitivity of the model solution to this parameter.
- Perform additional aquifer tests in the Moses Coulee area to improve the understanding of the heterogeneity in the alluvial aquifer. This would allow the addition of zones and layers to the current model to simulate important heterogeneities.
- Assemble existing and new data for the basalt aquifer to build a conceptual model for the basalt aquifer and explicitly incorporated into the model to simulate flux rates between the two aquifers as a head dependent boundary instead of a specified flux boundary.
- Enlarge the model domain to incorporate surrounding basins to allow the incorporation of observed stream flow as a flux target during the model calibration to better constrain the model solution.

Additional approaches that would provide conformational information include analysis of geochemistry and spring data. Comparison of the groundwater chemistry in the basalt and alluvial aquifers would add additional information about groundwater flux. If the groundwater in the alluvial aquifer is dominated by a surface water source, it is likely to have a different chemical composition from the groundwater in the basalt aquifer. For example, higher concentrations of sodium are associated with deeper and older groundwater in the basalt aquifer where water has had more time to chemically interact with the rock material (Bortleson and Cox, 1986 and Steinkampf and Hearn, 1996). Stable water isotopes (^{18}O, ^{2}H) can also be used to differentiate surface water sources from groundwater sources and radioactive isotopes such as carbon-14 and Tritium (^{3}H) can be used to differentiate younger water from older water (Drever, 1997). Additionally, nitrates and orthophosphates from fertilizers dissolved in the water typically indicate a large surface water component. These chemical analyses may be used to determine the relative amounts of influx from both sources. Since the surface water influx to the alluvial aquifer is fairly well known, this analysis could be used to estimate a groundwater influx from the basalt aquifer.

Analysis of spring discharge in the Lower Moses Coulee area would also contribute additional information. Spring discharge is a measurable groundwater flux occurring along discrete basalt interflow zones. Measuring spring discharge at a few select locations in the Lower Moses Coulee and calculating the contributing areas would allow assessment of the relationship between spring discharge and area. Contributing areas can be approximated by assuming the surface drainage area is similar to the groundwater drainage area. The relationship between discharge and area could then be applied to the entire Lower Moses Coulee basin as an estimate of groundwater influx.

9.0 REFERENCES

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Table 1. Foster Creek Water Level Survey Data

WELL NAME	Measuring Point* Longitude	Latitude	Elevation	Depth to Water (ft)	WL Elevation (ft)
Bahr	48.0044806	119.2313528	2244	123.53	2120.47
Bonneville Power - 48-inch	47.9828139	119.6469861	2382	6.03	2375.97
Bonneville Power - 8-inch	47.9832556	119.6488250	2376	4.93	2371.07
Cavadini	48.0190778	119.5042306	2198	51.85	2146.15
Geringer	47.8766333	119.5766444	2214	90.38	2123.62
Gross - On Hill	47.9682833	119.6501306	1070	39.14	1030.86
Gross - Well house	47.9686333	119.6504389	968	30.35	937.65
Hammons - Domestic	48.0343833	119.4937444	2241	24.82	2216.18
Hammons - Not used	48.0492500	119.4774611	2126	7.19	2118.81
Hammons - Stock	48.0198889	119.4646444	2018	37.66	1980.34
Hanford - Not used	47.9855111	119.6473833	896	18.41	877.59
Hanford - Pumping	47.9890972	119.6364583	955	44.01	910.99
Hemmer	48.0036806	119.3595194	2178	21.6	2156.4
Hunt - 6-inch	47.8156194	119.3611222	2087	196.46	1890.54
Hunt - 8-inch	47.8146250	119.3612750	2087	15.43	2071.57
Malone	47.9477306	119.5085667	1663	13.79	1649.21
Mansfield Well 1	47.8097500	119.6435000	2323	226.5	2096.5
Mansfield Well 3	47.8168333	119.6314722	2300	199.93	2100.07
Pitts - new	47.7967861	119.2987583	2244	88.68	2155.32
Pitts - old	47.7969056	119.2987750	2192	86.24	2105.76
T28R25S35	47.9702028	119.6530667	971	39.22	931.78
USCE - 6 inch	48.0003222	119.6464056	709	15.31	693.69
USCE - In Park	48.0025194	119.6529500	787	73.17	713.83
Watson	47.9371778	119.5386139	2280	34.87	2245.13

*By PGG GPS equipment

Table 2. Moses Coulee Water Level Survey Data

WELL NAME	Unique Well Identification No.	Center of Well* Northing	Center of Well* Easting	Measuring Point* Northing	Measuring Point* Easting	Measuring Point* Elevation	Depth to Water (ft)	WL Elevation (ft)
MCWA		121087.6	1844065.3	121087.6	1844065.3	838.3	253.46	584.8
LINVILLE NO. 1		123116.5	1845707.4	123116.5	1845707.4	849.0	251.9	597.1
LINVILLE NO. 2		130283.1	1853584.5	130283.0	1853584.1	890.0	209.24	680.8
SAUSEVILLE		135631.2	1859236.5	135631.0	1859236.2	906.5	168.85	737.7
BIRAM NO. 1		140672.5	1861869.7	140672.8	1861869.5	920.3	122.76	797.6
BIRAM NO. 2		140652.9	1861917.0	140653.1	1861917.2	920.8	121.72	799.1
GUTSCHOW		143948.3	1862896.4	143948.3	1862896.4	930.1	103.4	826.7
BARB		147801.6	1865005.5	147802.8	1865005.1	946.4	85.56	860.8
CRISS	AGG364	156729.1	1868545.2	156729.0	1868545.3	978.7	87.14	891.6
COLLINS		157850.3	1868983.2	157850.1	1868983.4	984.9	93.2	891.7
KING	AET969	157826.0	1869573.5	157826.0	1869573.5	981.7	90.04	891.6
BENNETT		165671.0	1874388.3	165670.8	1874388.4	1022.3	130.4	891.9
PALISADES		164417.0	1875877.9	164417.0	1875877.9	1029.4	137.45	892.0
JORDAN		164382.0	1878844.8	164382.0	1878844.8	1034.6	91.93	942.6
BOSNER		163154.2	1883280.8	163154.0	1883280.7	1040.0	146.28	893.7
BILLINGSLEY		163736.7	1890752.1	163736.7	1890752.1	1053.7	156.2	897.5

*Locations surveyed by Erlandsen & Associates, Water Levels measured 4/2003
Datum as reported on ACAD figure
Horizontal Datum NAD 83/91
Vertical Datum NGVD 1929

Table 3. Summary of Transmissivity and Hydraulic Conductivity Values

Study Area	Well Test	Data Set	Material Description	Transmissivity	Hydraulic Conductivity
Foster Creek	Hemmer		Basalt underlain by clay	69	
Foster Creek	T29R25S35	Early Test	Gravel and sand	268,000	
		Mid Test		149,000	
Foster Creek	Town of Mansfield		Basalt and gravel	26,000	
Moses Coulee	Billingsley			2,904,000	9954
Moses Coulee	Biram	Early Test	Gravel and basalt	499,000	953
		Recovery		610,000	1165
		Observation Well, Early Test		343,000	655
Moses Coulee	Roth	Drawdown	Basalt gravel	311,000	1039
		Recovery		459,000	1534

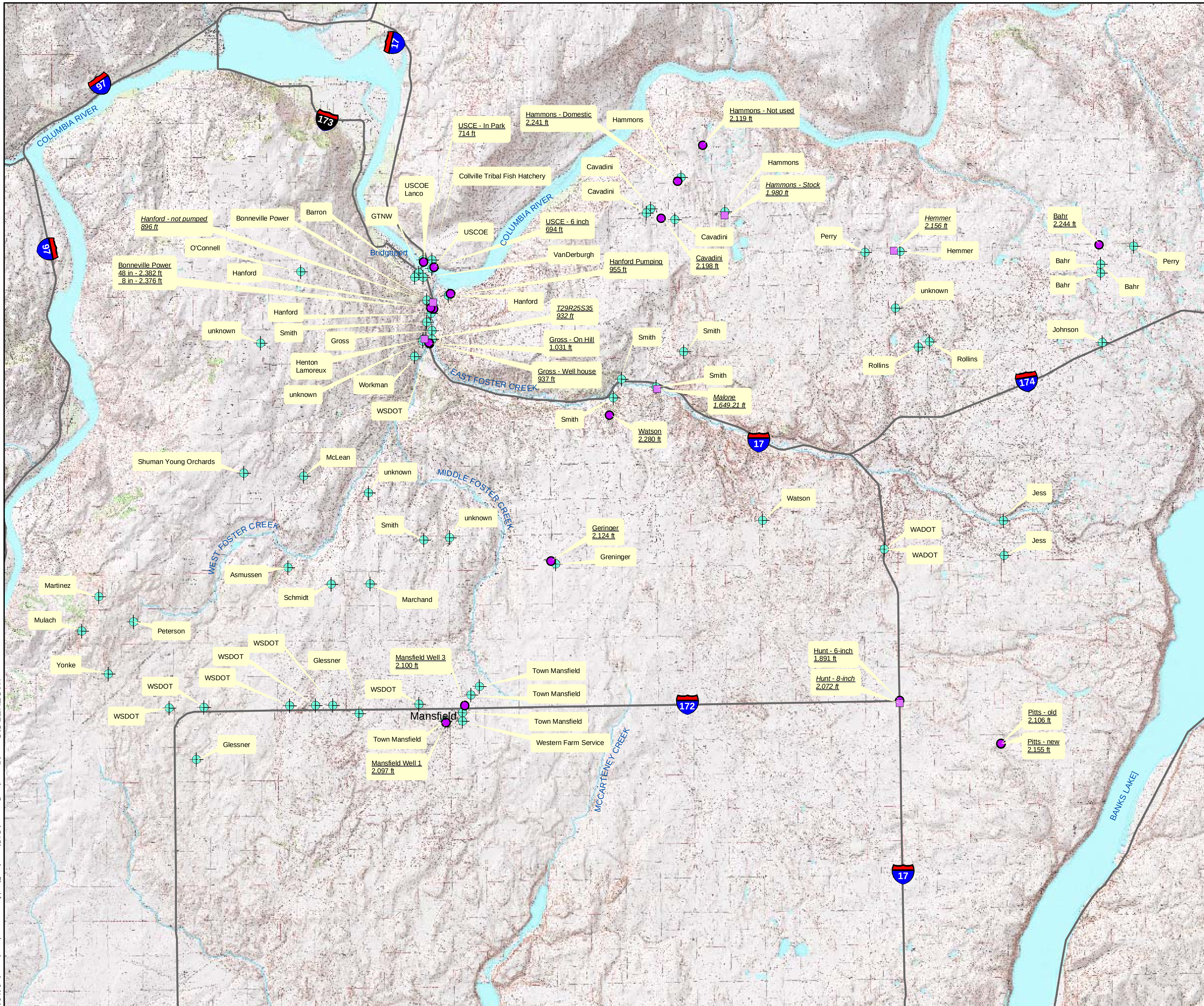
Transmissivity values in gallons per day per foot (gpd/ft)
Hydraulic Conductivity values in feet per day (ft/d)

Henton Data Sets — *Early Test, duration of pumping between 10 and 200 minutes*
Mid Test, duration of pumping between 200 and 1500 minutes

Biram Data Sets — *Early Test, duration of pumping between 5 and 100 minutes*

Figure 1
Foster Creek
Well Locations and Groundwater Elevations

Level 2
Hydrogeologic Assessment



- Wells
- Water Level (label is underlined)
- Level Logger Installed (*label is underlined and italicized*)
- Rivers & Streams
- Water Bodies
- State Routes

1:179,757

Miles: 0, 1.5, 3

Feet: 0, 7,500, 15,000

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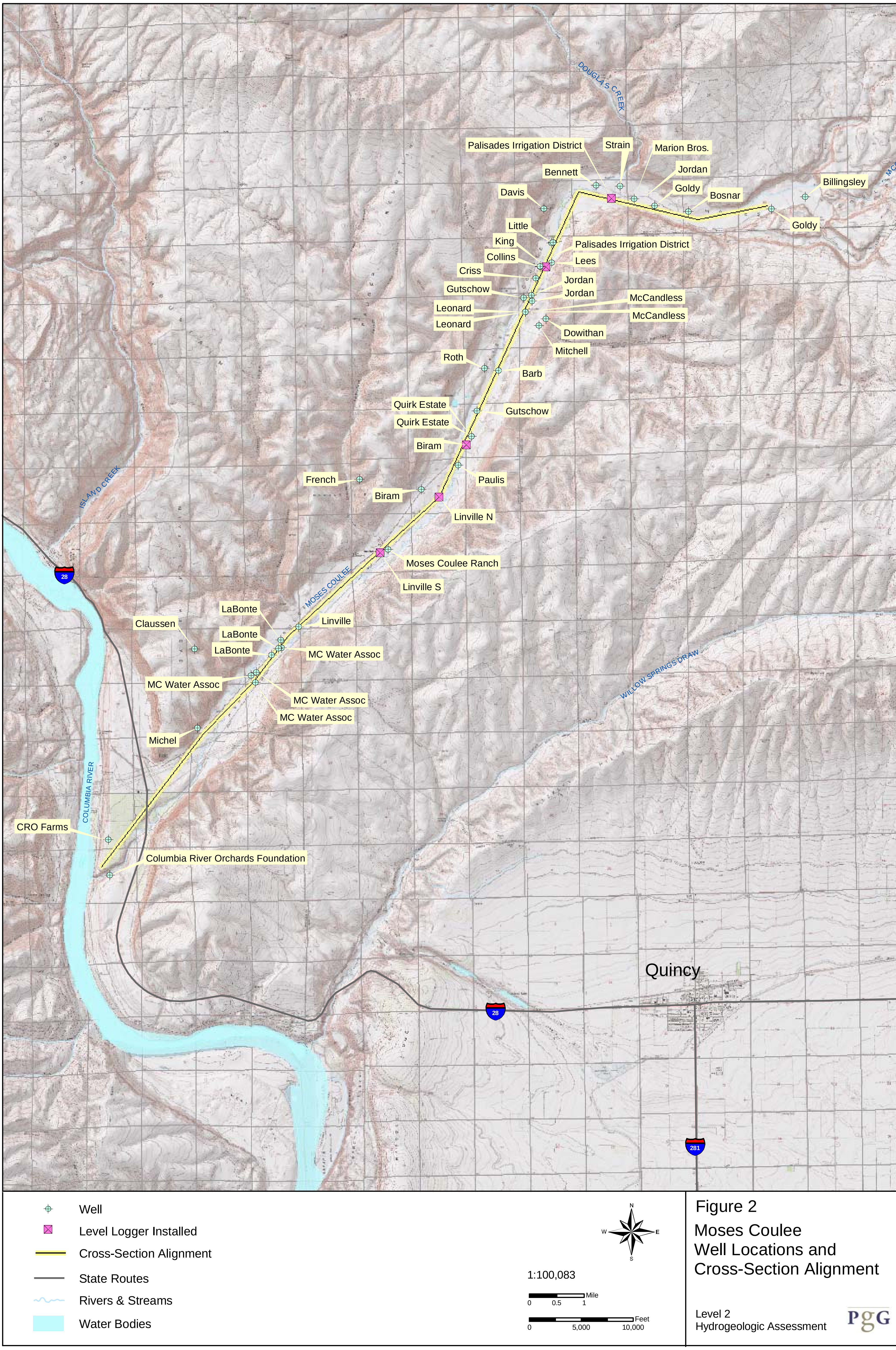

Figure 2
Moses Coulee
Well Locations and
Cross-Section Alignment

Level 2
Hydrogeologic Assessment

PgG

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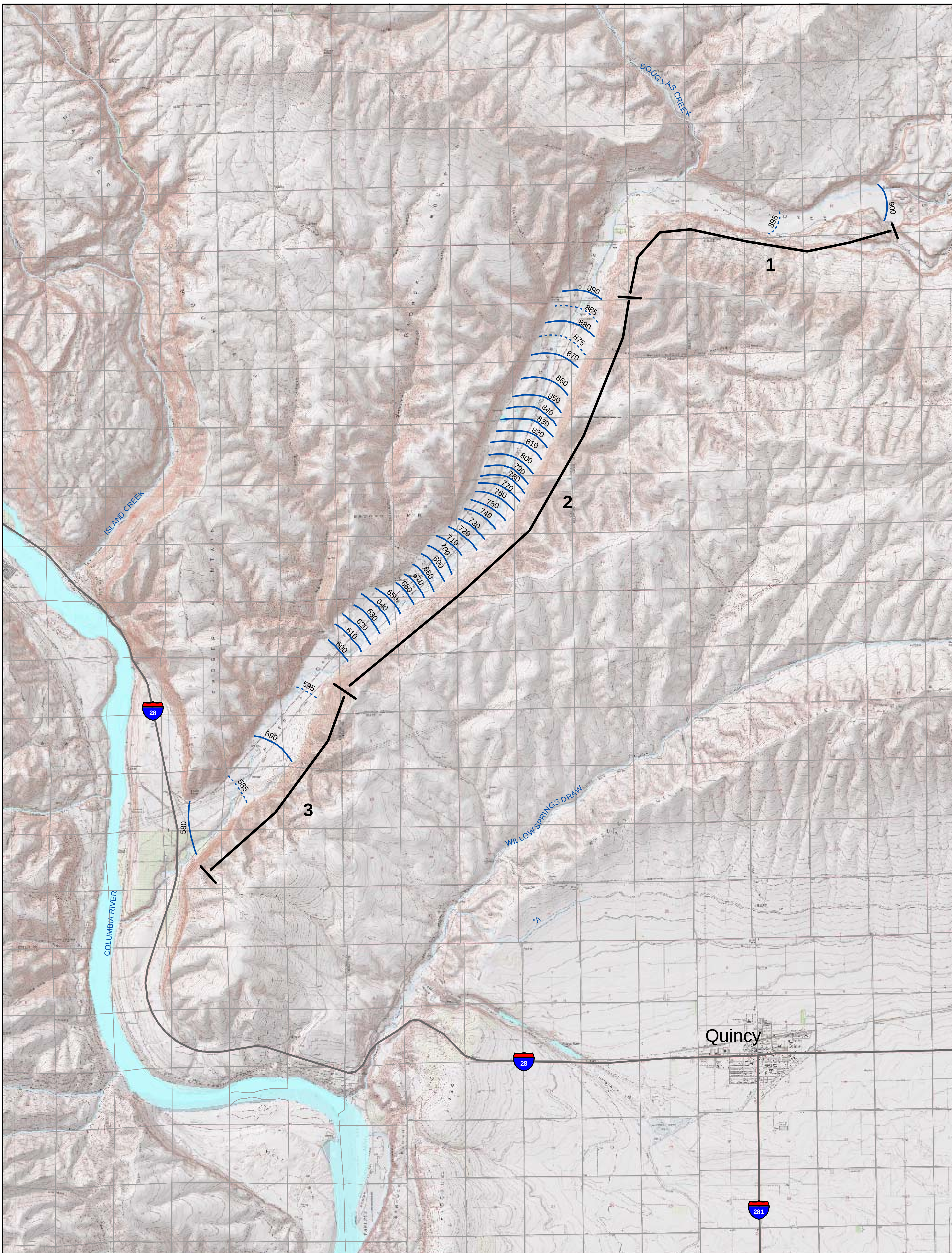


GROUNDWATER CONTOURS

- 5 ft. Contour Interval
- 10 ft. Contour Interval
- Gradient Zones
- State Routes
- Rivers & Streams
- Water Bodies

N
W E
S

1:100,177

0 0.5 1 Mile

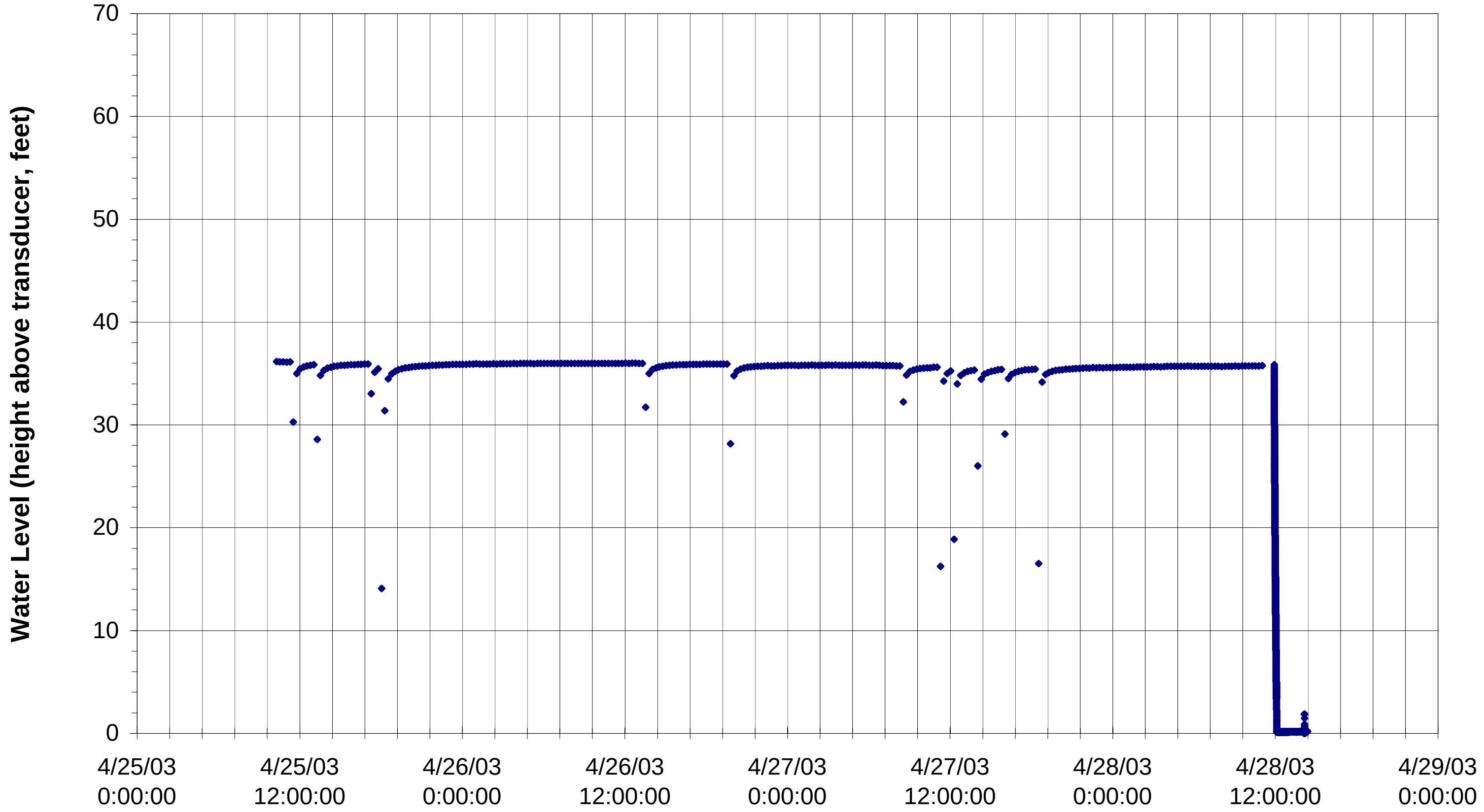
0 5,000 10,000 Feet

Figure 3
Moses Coulee Groundwater Elevations

Level 2
Hydrogeologic Assessment

PgG

K:\OTHERS\Steve\DouglasCounty\GIS\mxd_files\mc_gw_contours.mxd, 9/10/03



Legend

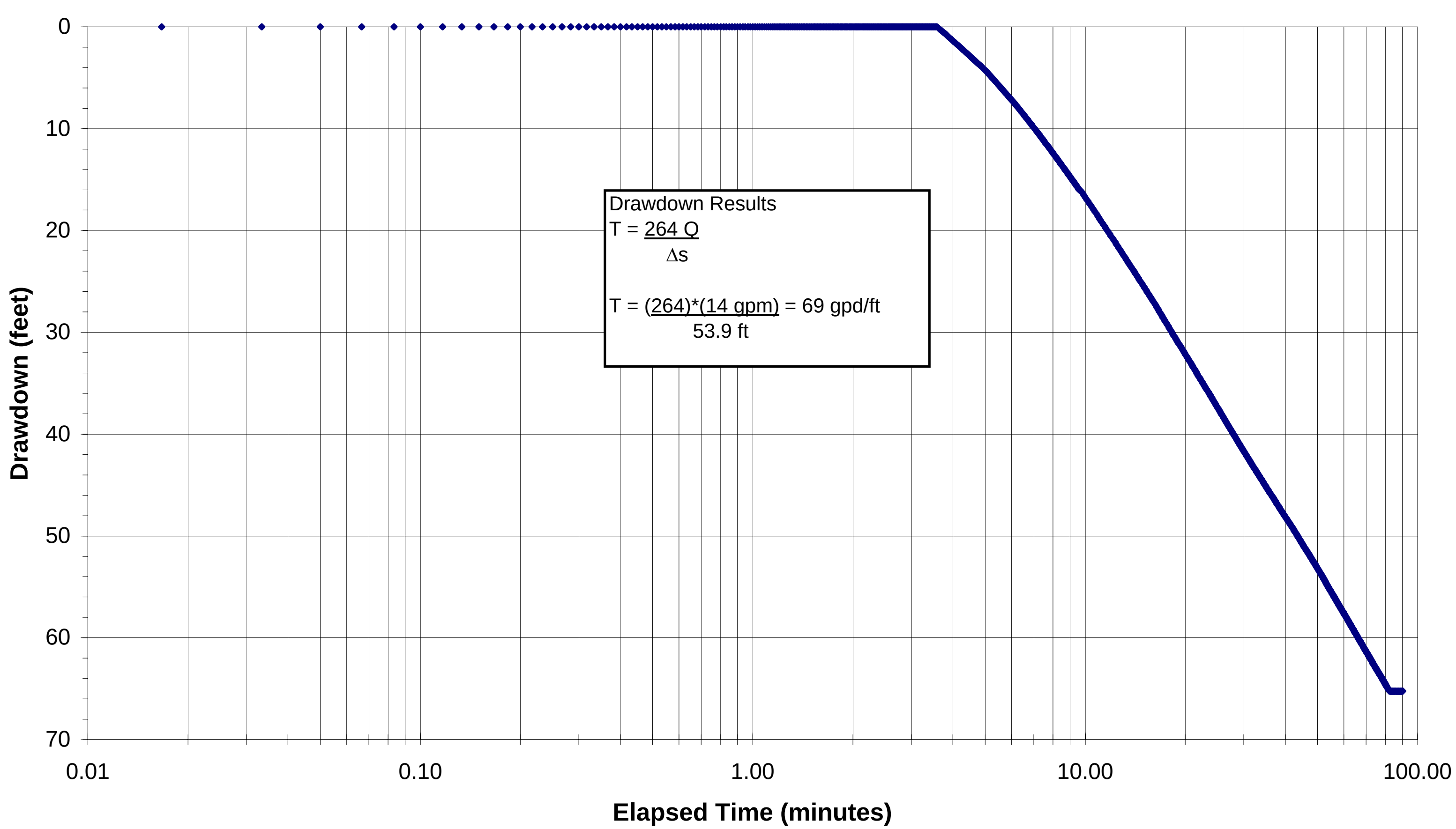
Pump started: 4/28/03 11:55
Pump stopped: 4/28/03 14:20
Pumping rate: 14 gpm

Test was aborted when water levels dropped below the transducer. The transducer was set lower and the test was repeated on 4/29/03.

Figure 4.
Hemmer Well Water Levels

WRIA 44/50
Level 2 Hydrogeologic Assessment

PgG



Legend

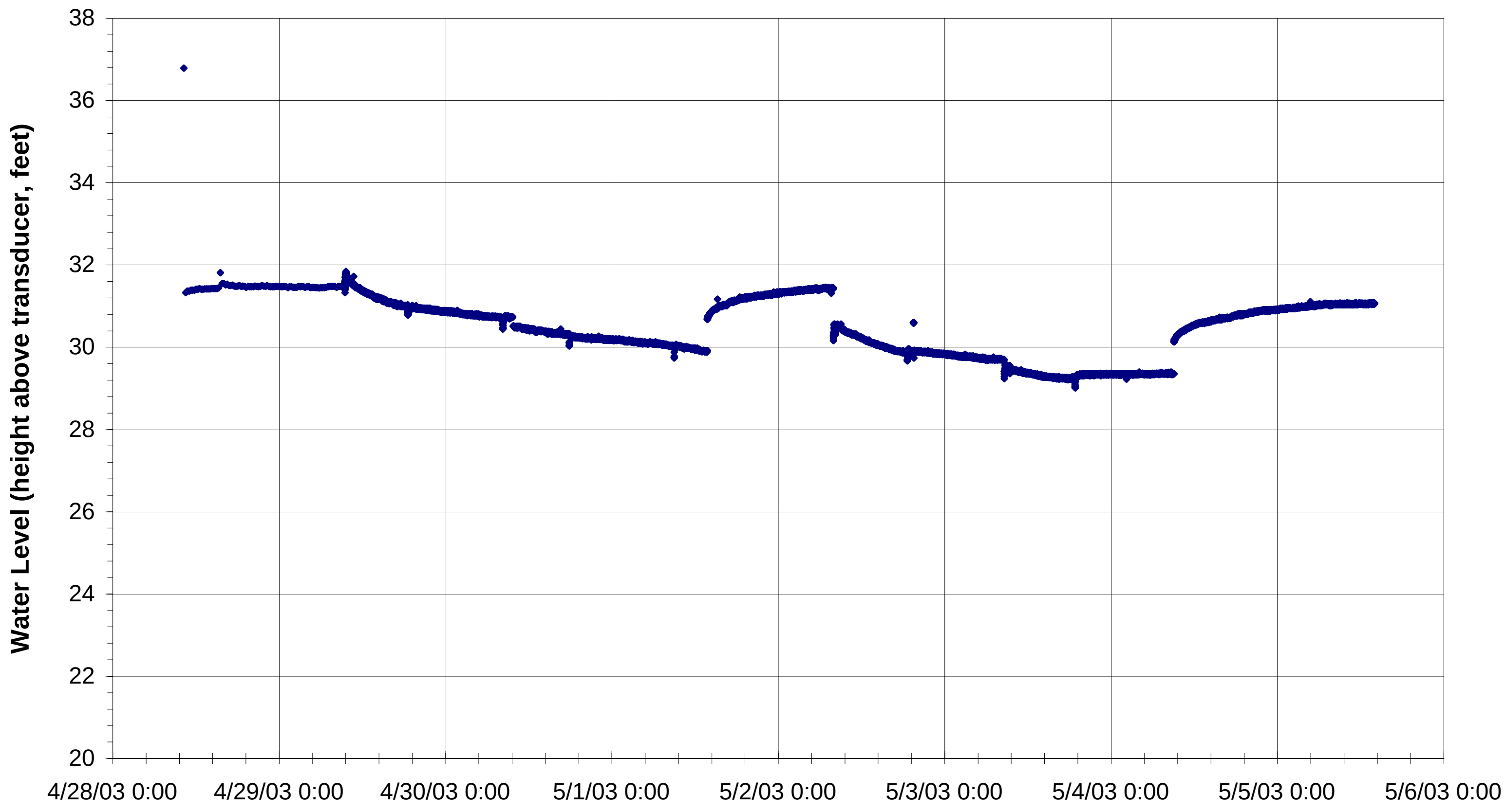
Pump started: 4/29/03 15:50
Pump stopped: 4/29/03 17:20
Pumping rate: 14 gpm

Pre-test data not collected. Because of short duration of test, data not barometrically compensated.

Figure 5.
Hemmer Well Drawdown

WRIA 44/50
Level 2 Hydrogeologic Assessment

PgG



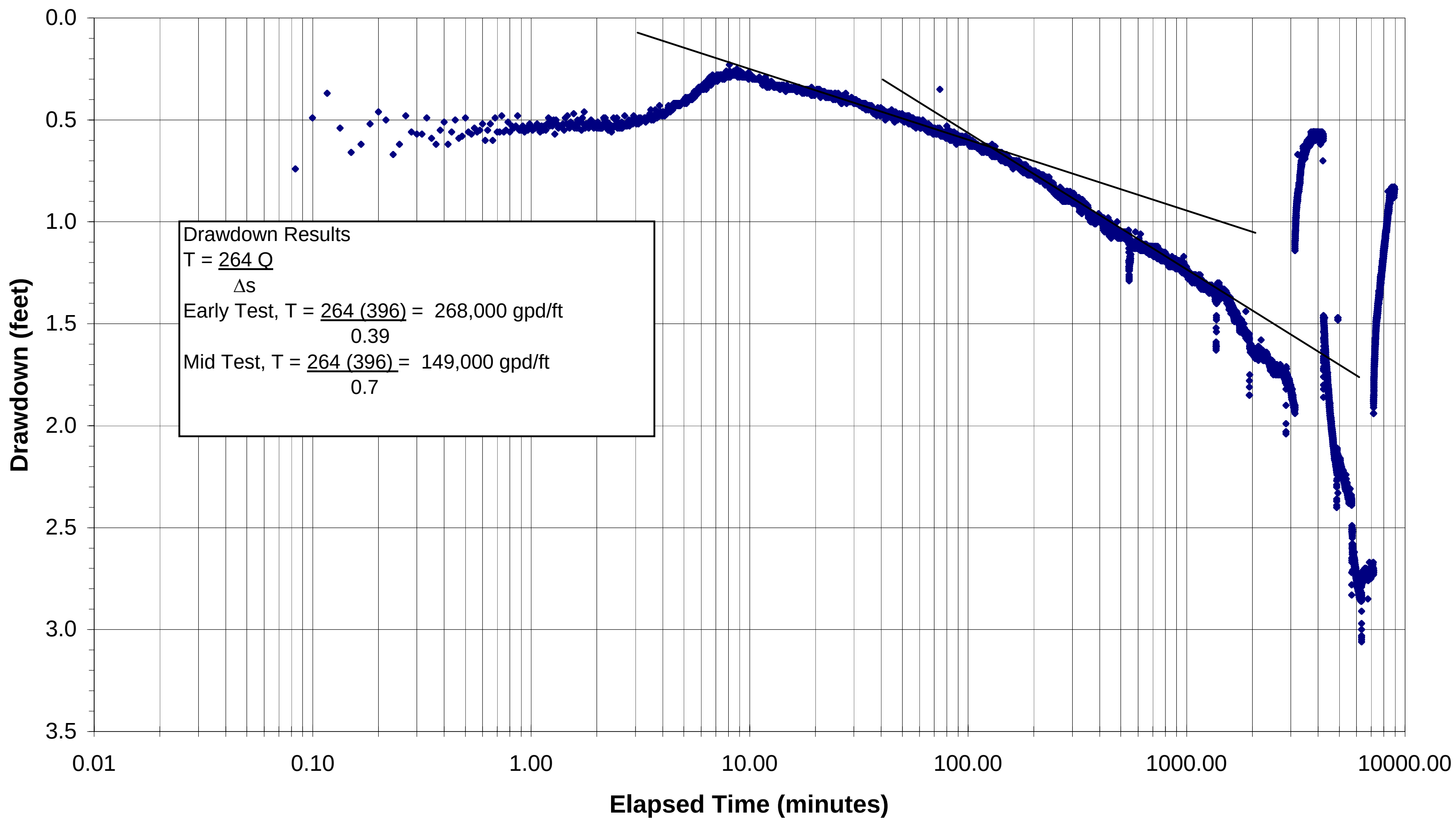
Legend
Pump started: 4/29/03 09:30   Pump Stopped: 5/1/03 13:45 (power fail)
Pumping rates: First 24 hours 396 gpm; beginning at 24 hours: 339 gpm

Note: Transducer equipment replaced between pre-test and test conditions. Pre-test data adjusted to reflect the transducer depth during the test.

Figure 6.
T29R25S35 Well Water Levels

WRIA 44/50
Level 2 Hydrogeologic Assessment

PgG



Legend

Pump started: 4/29/03 09:30 Pump stopped: 5/1/03 13:45 (power fail)

Pumping rates: First 24 hours 396 gpm; beginning at 24 hours: 339 gpm

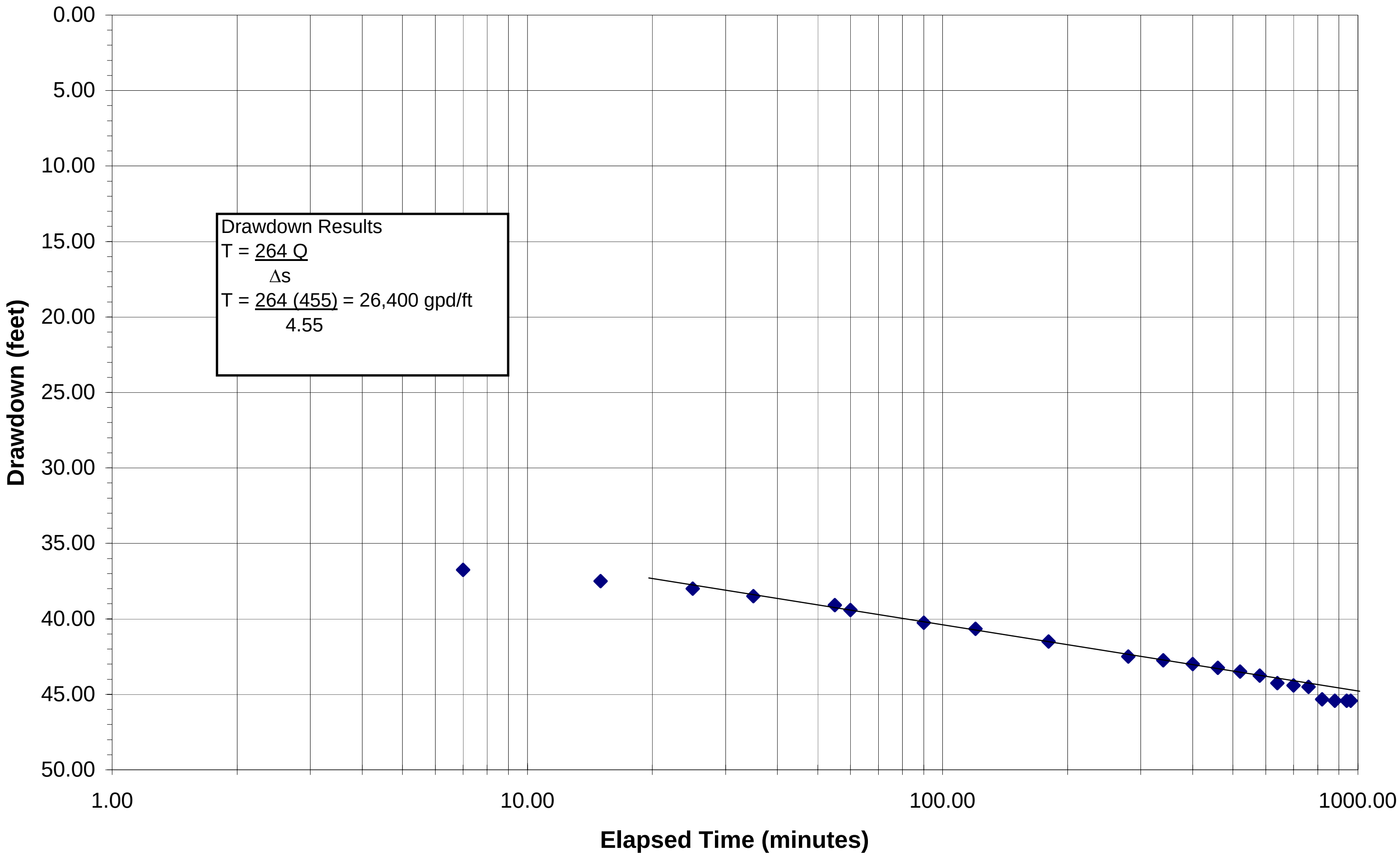
Early Test, duration of pumping between 10 and 200 minutes

Mid Test, duration of pumping between 200 and 1500 minutes

Figure 7.
T29R25S35 Well Drawdown

WRIA 44/50
Level 2 Hydrogeologic Assessment

PgG



Legend

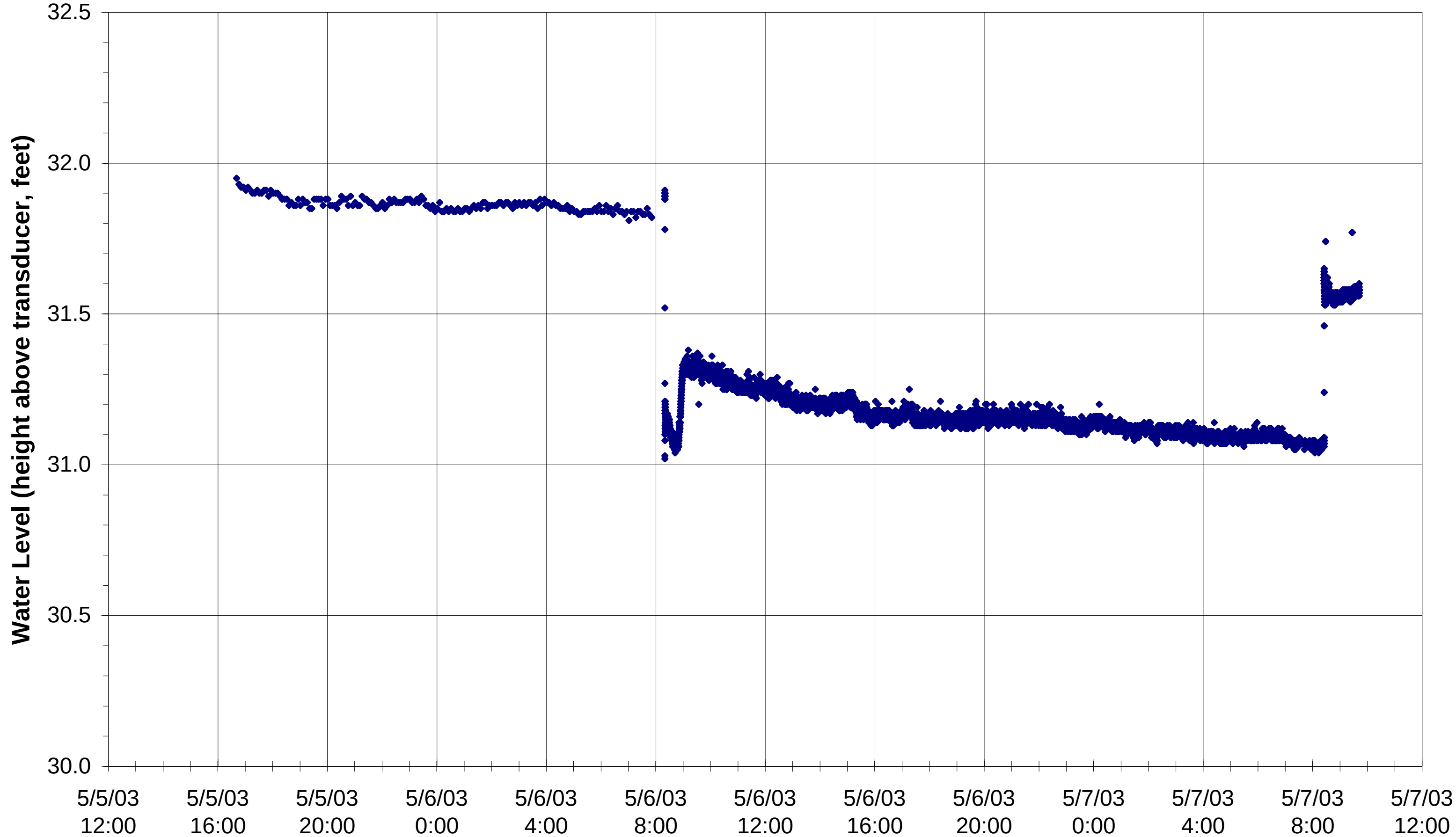
Pump started: 10/3/90 16:20
Pump stopped: 10/4/90 08:20
Pumping rate: 455 gpm

Test conducted by Okanogan Drilling & Development Co

Figure 8.
Town of Mansfield Well 3 Drawdown

WRIA 44/50
Level 2 Hydrogeologic Assessment

PGG



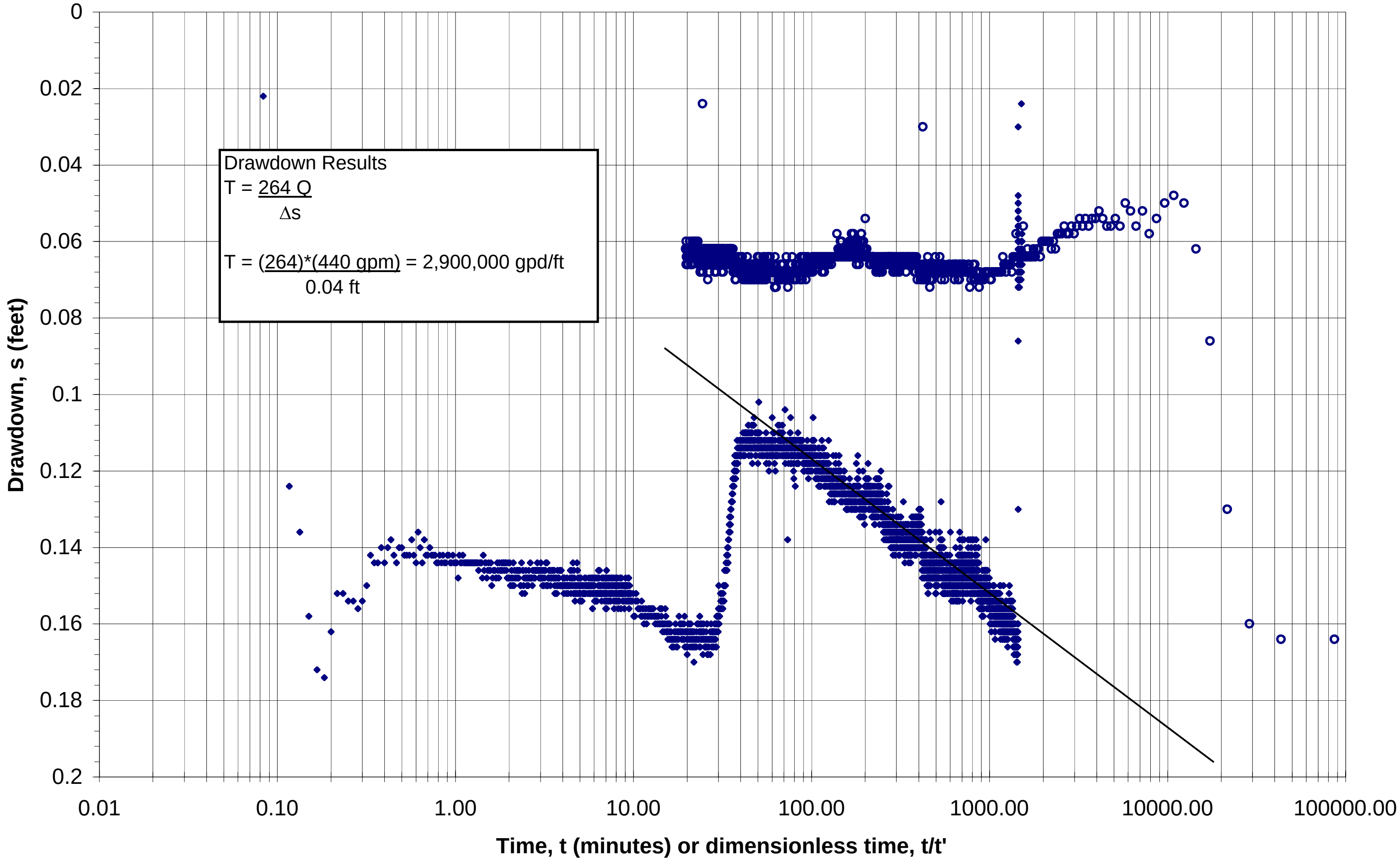
Legend

Pump started: 5/6/03 08:20
Pump stopped: 5/7/03 08:25
Pumping rate: 440 gpm

Figure 9.
Billingsley Well Water Levels

WRIA 44/50
Level 2 Hydrogeologic Assessment

PgG



Legend

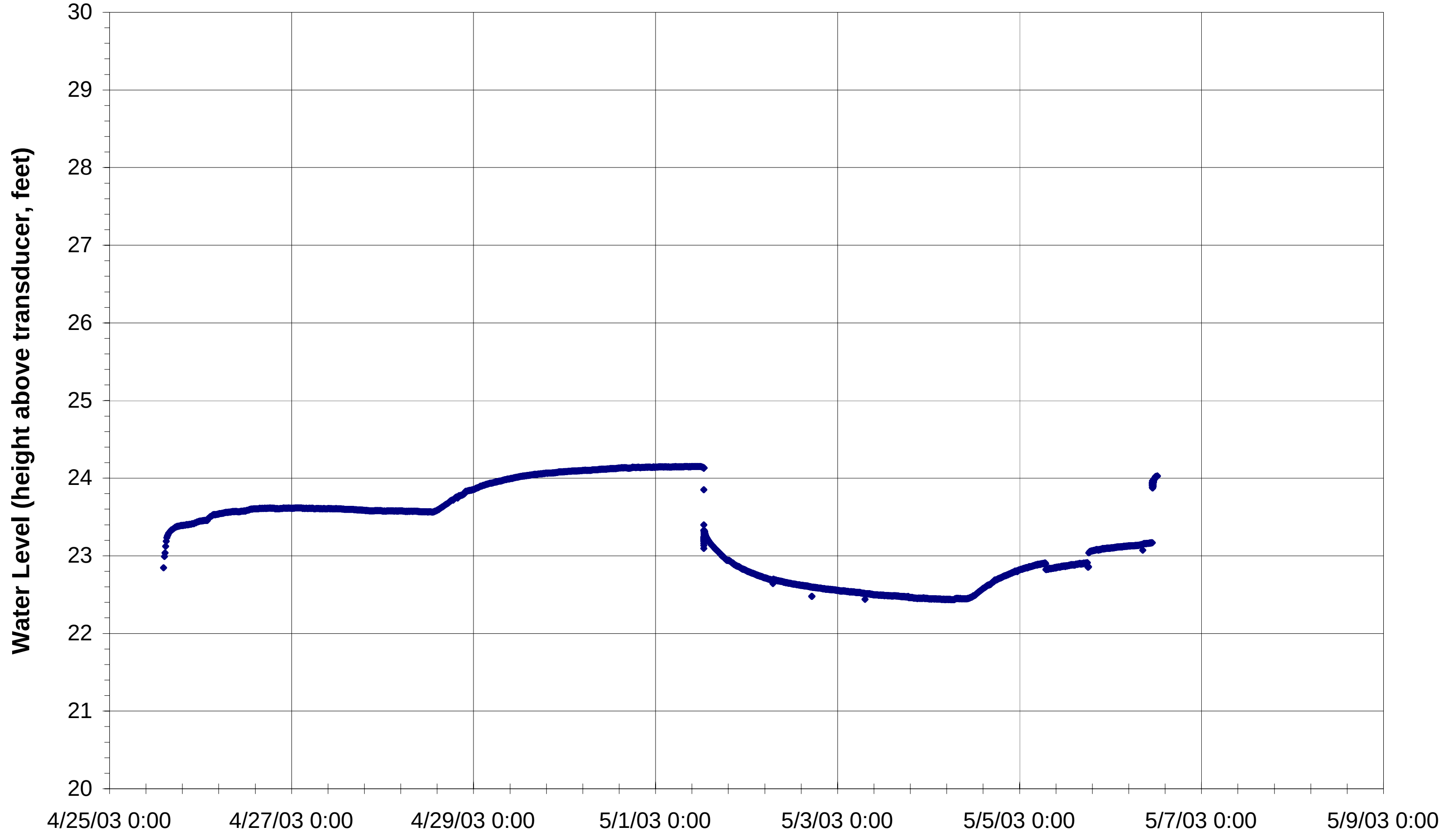
Pump started: 5/6/03 08:20
Pump stopped: 5/7/03 08:25
Pumping rate: 440 gpm (after approximately 40 min)
Data corrected for partial penetration

◆ Drawdown data
○ Recovery data

Figure 10.
Billingsley Well Drawdown and Recovery

WRIA 44/50
Level 2 Hydrogeologic Assessment

PGG



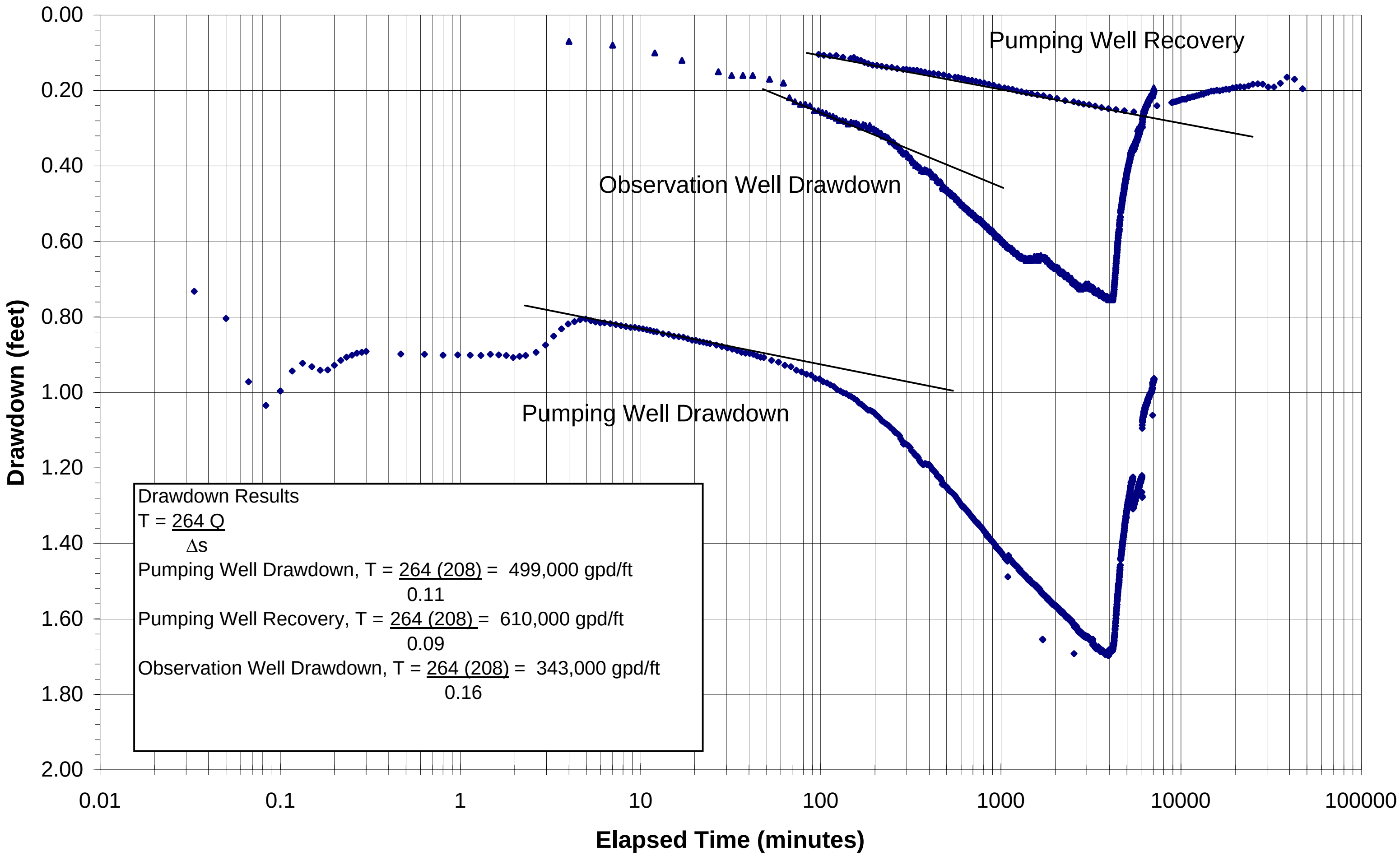
Legend

Pump started: 5/1/03 12:45
Pump stopped: 5/6/03 11:05
Pumping rate: First 24 hours, 208gpm. Second 24 hours, 190 gpm.

Figure 11.
Biram Pumping Well Water Levels

WRIA 44/50
Level 2 Hydrogeologic Assessment

PGG



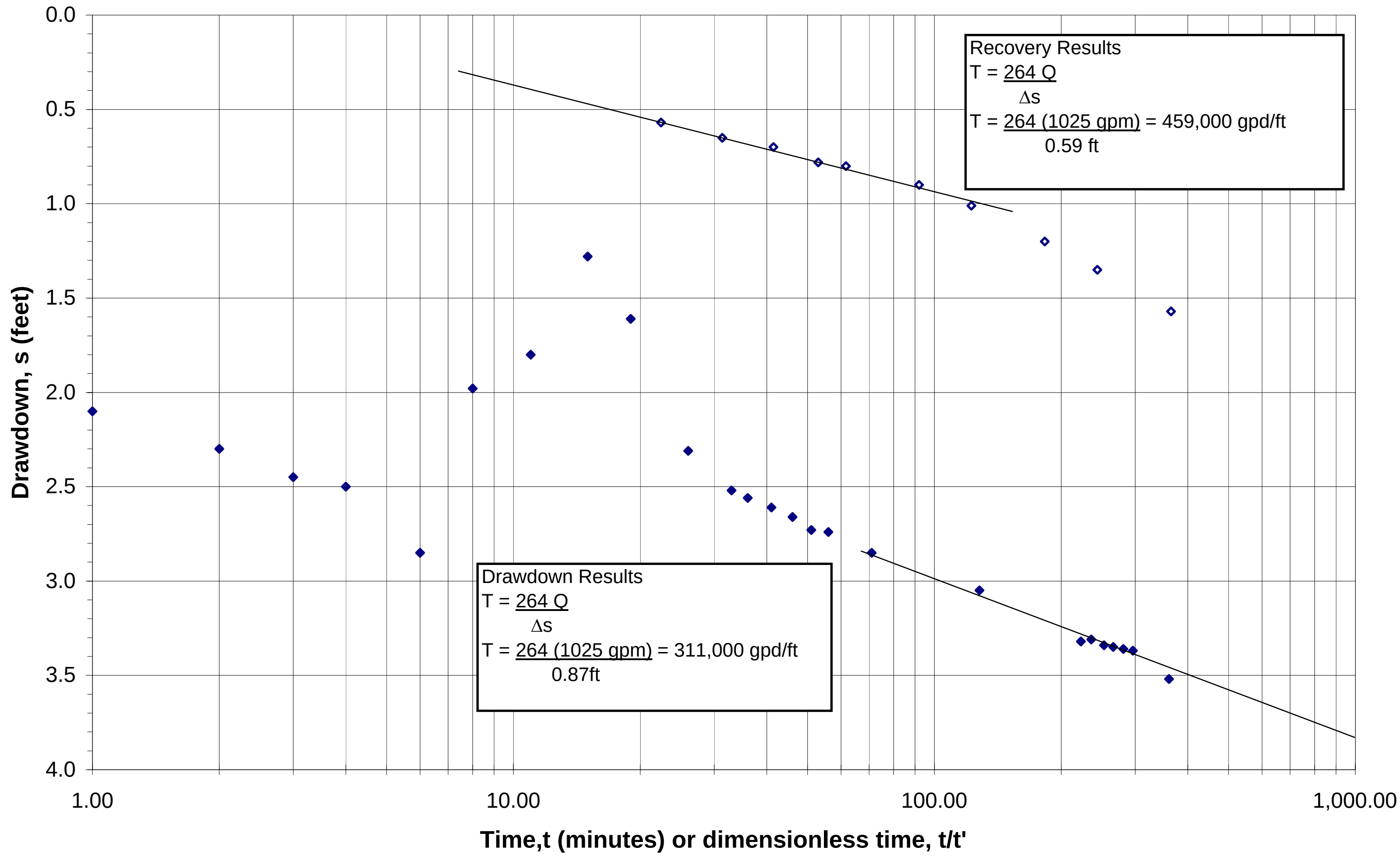
Legend

Pump started: 5/1/03 12:45
Pump stopped: 5/6/03 11:05
Pumping rate: First 24 hours, 208gpm. Second 24 hours, 190 gpm.

Figure 12.
Biram Pumping and Observation Wells Response to Pumping

WRIA 44/50
Level 2 Hydrogeologic Assessment

PGG



Legend

Pump started: 9/15/65 9:49 Pump stopped: 9/15/65 15:53

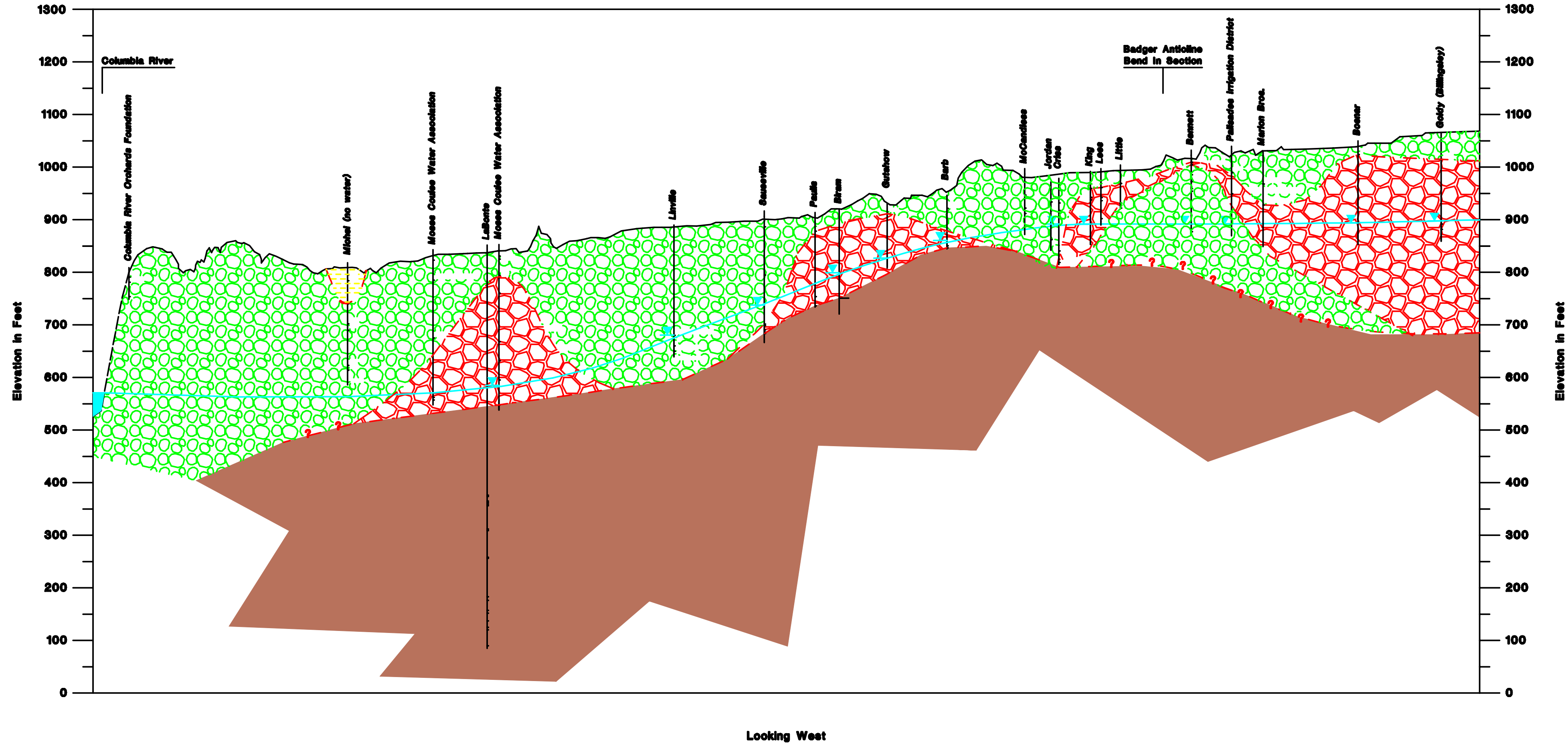
Pumping rate: 1025 gpm at end of test

◆ Drawdown Data ◇ Recovery Data

Test conducted by Department of Ecology (Smith, 1965)

Figure 13.
Roth Well Drawdown

WRIA 44/50
Level 2 Hydrogeologic Assessment



LEGEND

- Silt
- Coarse Alluvium
- Broken Basalt and Cobbles
- Solid Basalt

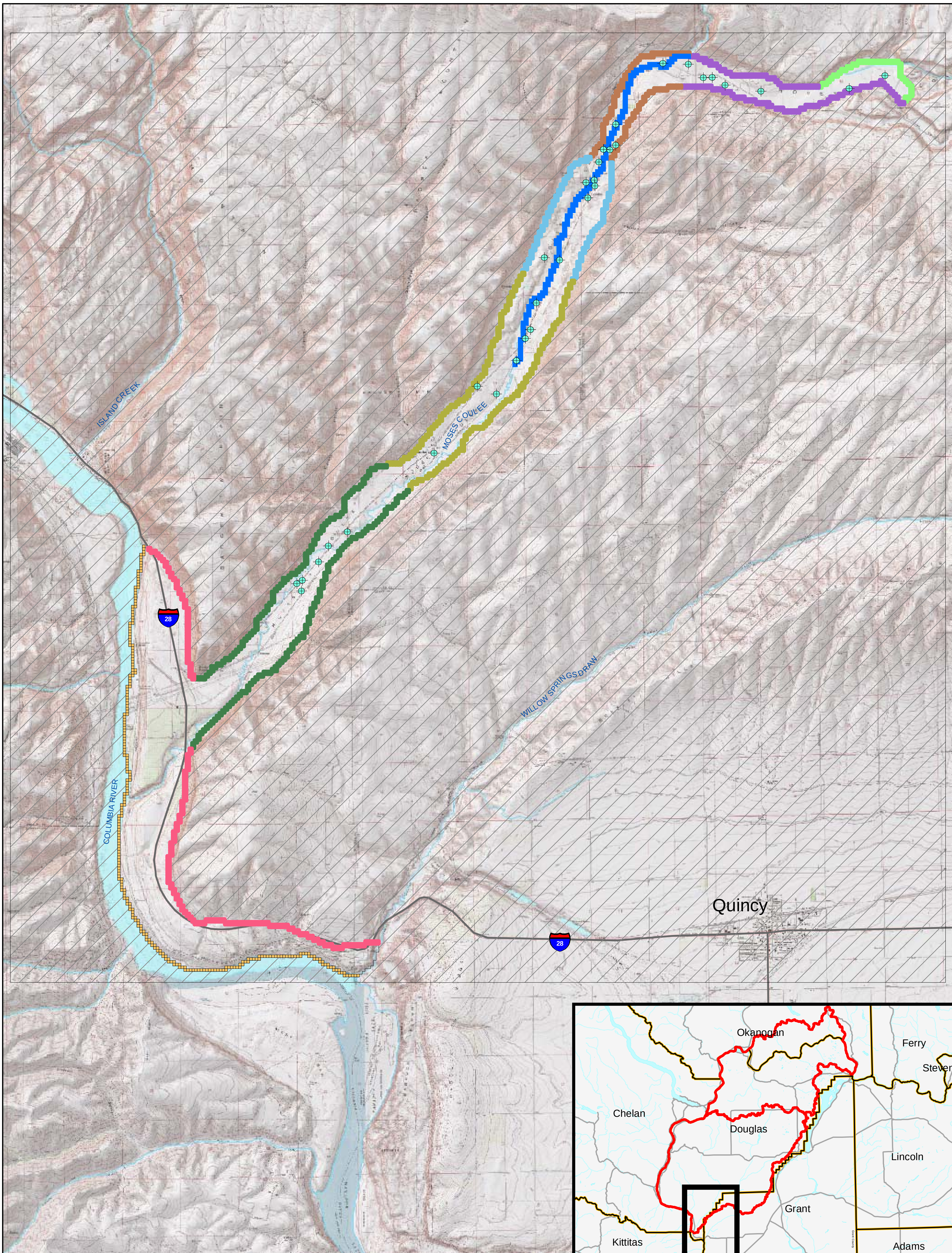
Well showing geologic contacts, screened or perforated interval, water level measured April 2003, and water table

Horizontal Scale in Feet: 0, 4000, 8000
Vertical Scale in Feet: 0, 100, 200

FIGURE 14
Moses Coulee Geologic Cross Section

Douglas County
Level 2 Hydrogeologic Assessment
MosesC.dwg

PgG



Modeled Pumping Wells
No Flow Cells
Specified Douglas Creek Flux
Constant Head
State Routes
Rivers & Streams
Water Bodies

SPECIFIED BASALT AQUIFER FLUX
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Reach 7
Reach 8

N W E S

1:100,233

0 0.75 1.5 Miles
0 5,000 10,000 Feet

Figure 15
Moses Coulee
Model Configuration

Level 2
Hydrogeologic Assessment

PGG

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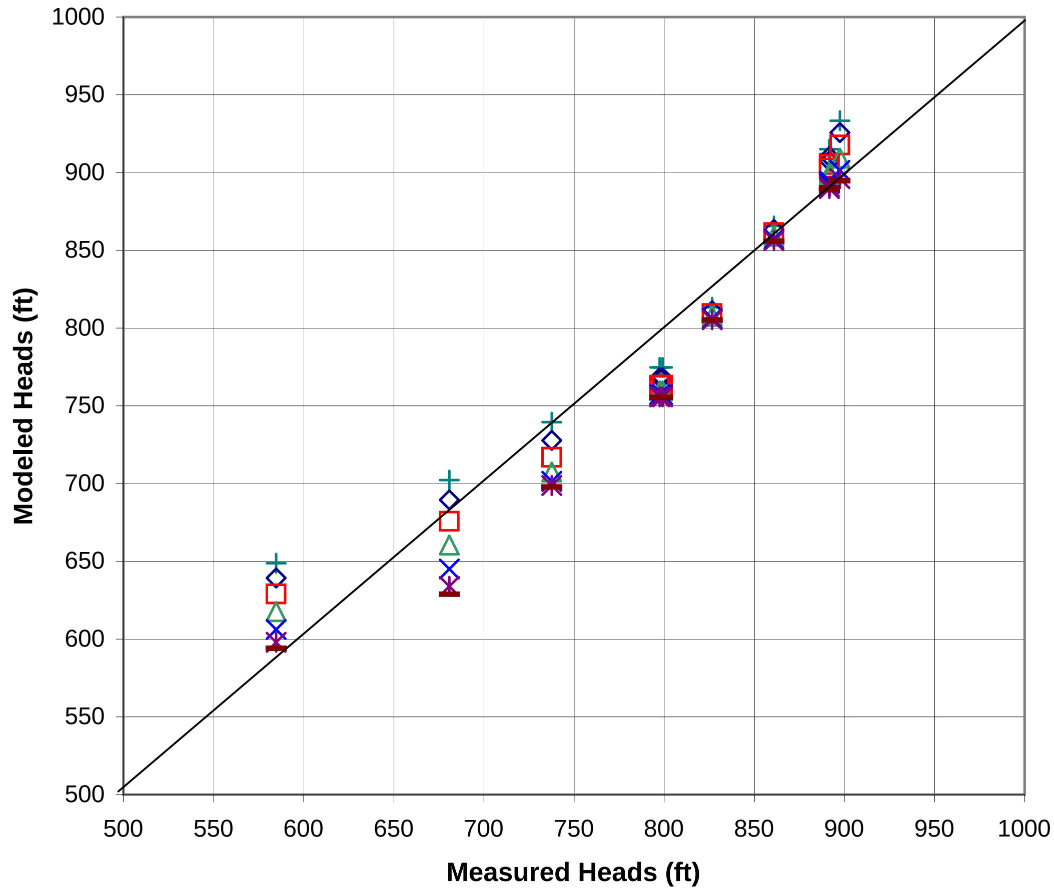

Legend

- Flux = 74 cfs, ARM = 23.21
- Flux = 61 cfs, ARM = 21.43
- Flux = 45 cfs, ARM = 20.32
- Flux = 30 cfs, ARM = 20.76
- Flux = 15 cfs, ARM = 20.82
- Flux = 6 cfs, ARM = 21.41
- Flux = 0 cfs, ARM = 22.07

Figure 16.
Modeled vs Measured Heads (K=4000 ft/day)

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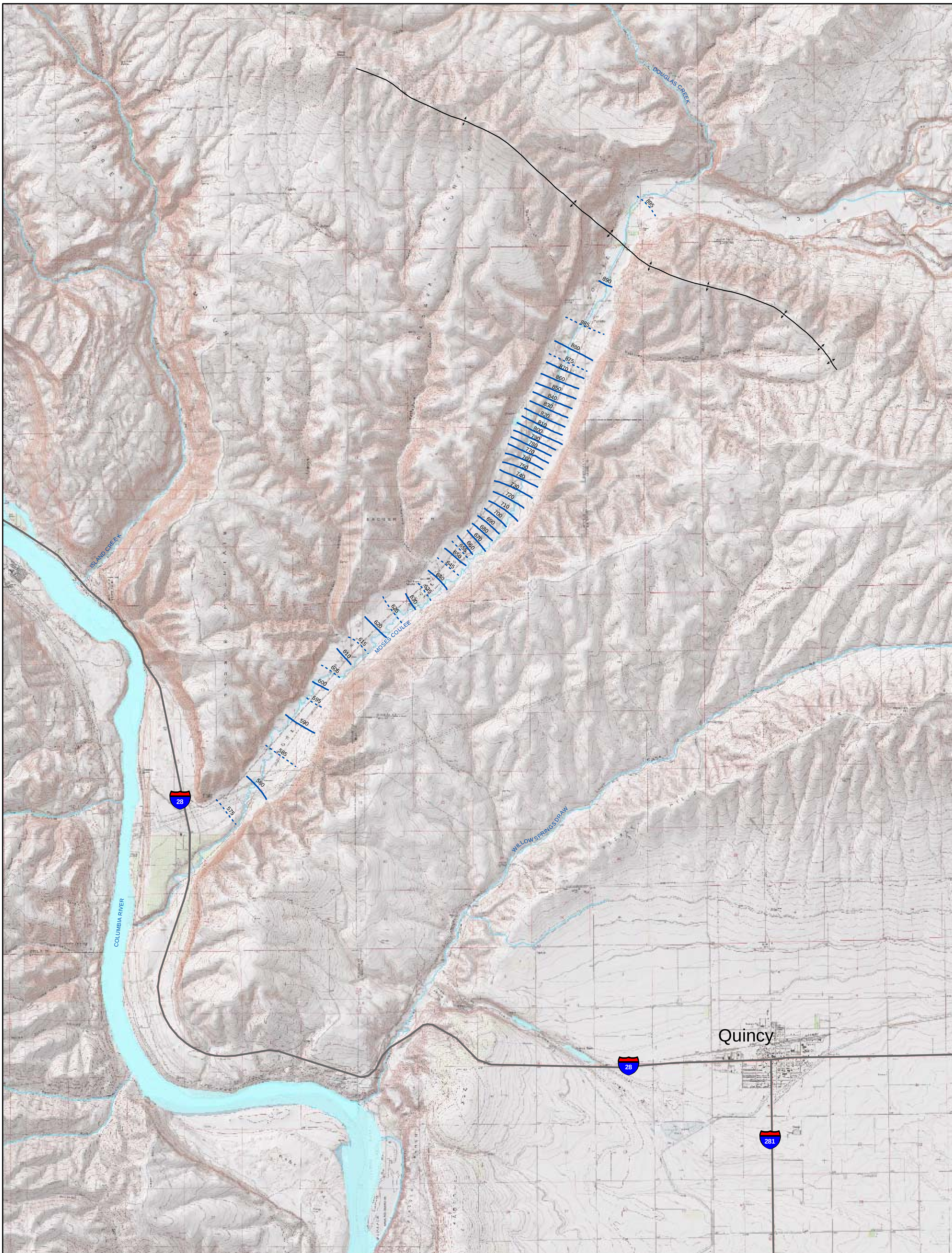

MODELED WATER LEVEL CONTOURS

5 ft. Contour Interval

10 ft. Contour Interval

Badger Mt. Anticline
(data source: WADNR, 2003)

Rivers & Streams

Water Bodies

State Routes

1:100,043

Miles: 0 | 0.75 | 1.5

Feet: 0 | 5,000 | 10,000

Figure 17

Moses Coulee Modeled Groundwater Elevations

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K:\OTHERS\Steve\DouglasCounty\GIS\mxd\mc_modeled_wt.mxd, 9/9/03

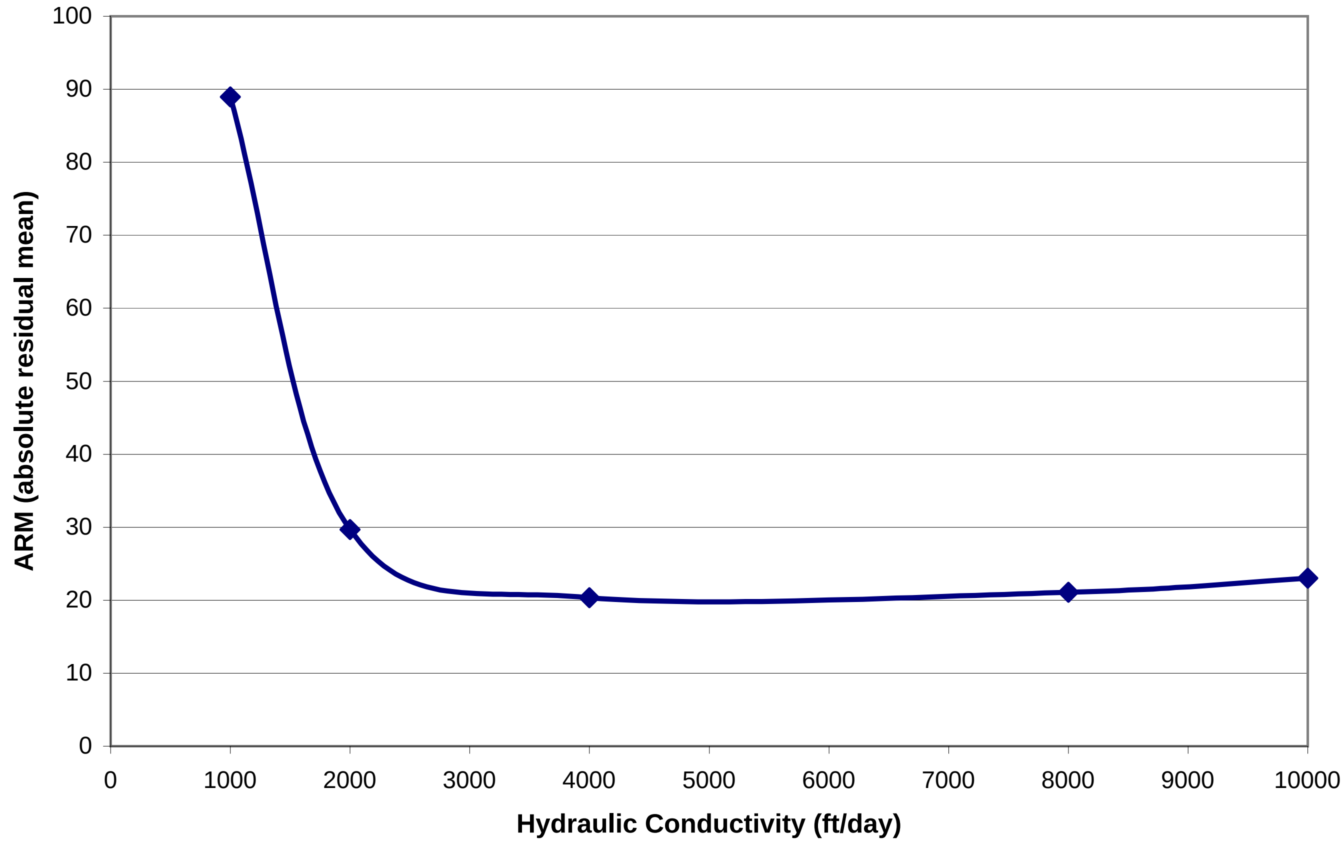


Figure 18.
Sensitivity of Head Solution to Hydraulic Conductivity

Appendix A
Foster Creek and Lower Moses Coulee
Well Logs

Appendix B
Foster Creek and Lower Moses Coulee Water Level Monitoring

FOSTER CREEK HYDROGRAPHS

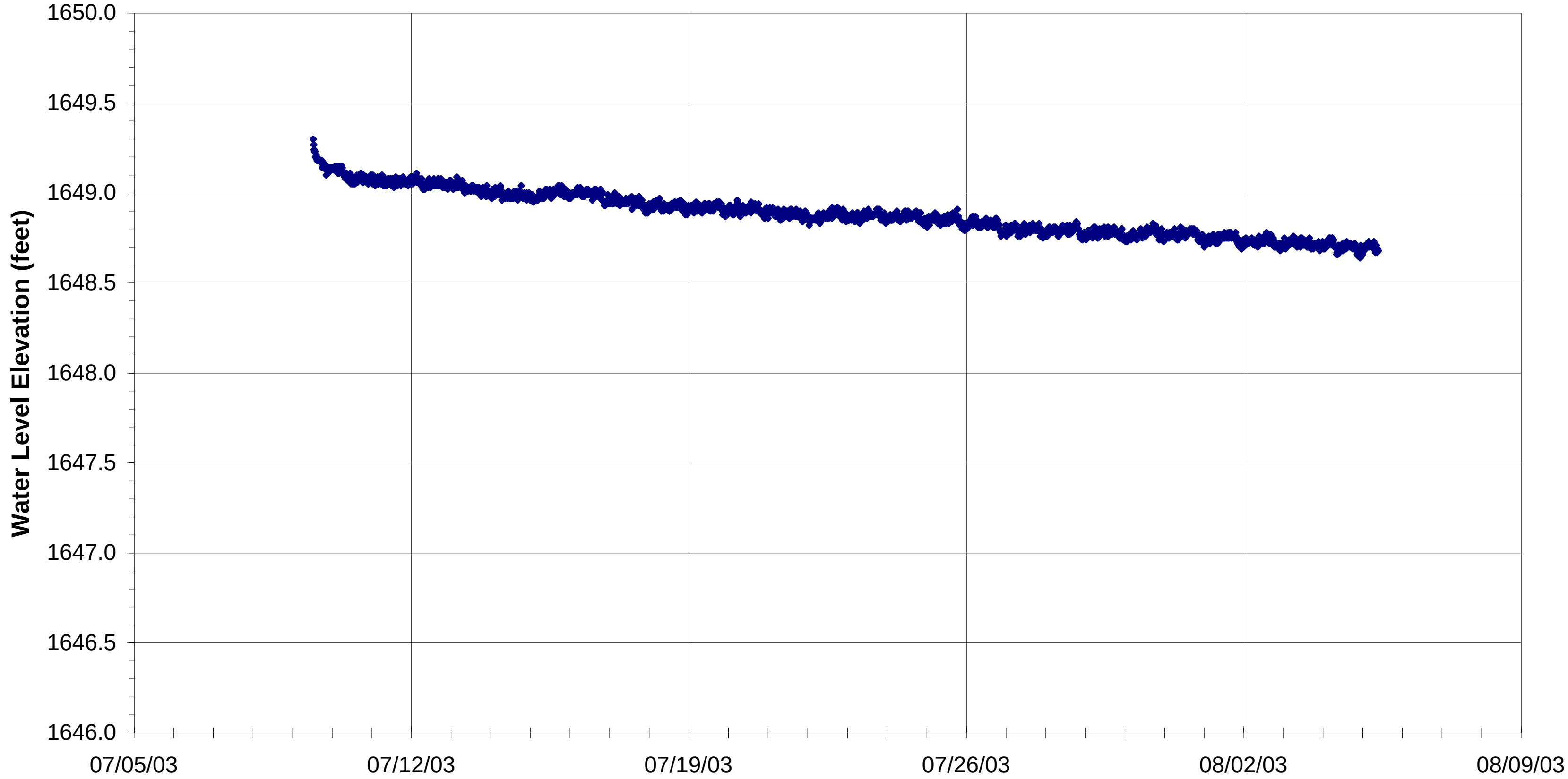
Hydrographs for instrumented wells in the Foster Creek area are presented in Figures B1 through B6. According to driller's well logs, the Malone, Hanford, and T29R25S35 wells are completed in the alluvial aquifer. The Hunt and Hemmer wells are completed in basalt and the Hammons well is completed in granite.

With the exception of the T29R25S35 well, hydrographs for the instrumented wells in the Foster Creek area indicate that water levels have generally been declining since the equipment was installed. This is consistent with the time of year and likely reflects seasonal variation. When a year or more of data have been collected, more rigorous analysis of groundwater trends may be completed.

T29R25S35 is an irrigation supply well. The hydrograph for this well reflects the intermittent pumping cycles. Throughout the non-irrigation season, data of the static conditions should be recorded. The Hemmer well hydrograph reflects pumping periods when the water level drew down at least 20 feet. The hydrographs for the Hammons and Hunt wells show similar responses although they are completed in different materials and are located approximately 17 miles apart.

MOSES COULEE HYDROGRAPHS

Hydrographs of continuous water level data collected from wells in Moses Coulee are presented in Figures B7 through B11. The hydrographs for the Moses Coulee wells indicate that water levels have generally been declining. This decline is likely the result of seasonal variation although at least a year of data would have to be collected to verivy that assessment. The break in the water level record of the King well on May 21, 2003 is due to a change in the suspension of the water level transducer. Water levels in the PID, King, and Linville North wells increased between May 29, 2003 and June 18, 2003. The magnitude of this increase ranged from 0.2 feet in the PID well to 0.6 feet in the Linville North well. The hydrographs for the Biram and Linville South wells indicate the greatest influence from nearby pumping wells.



Legend

Figure B1.
Malone Well Hydrograph

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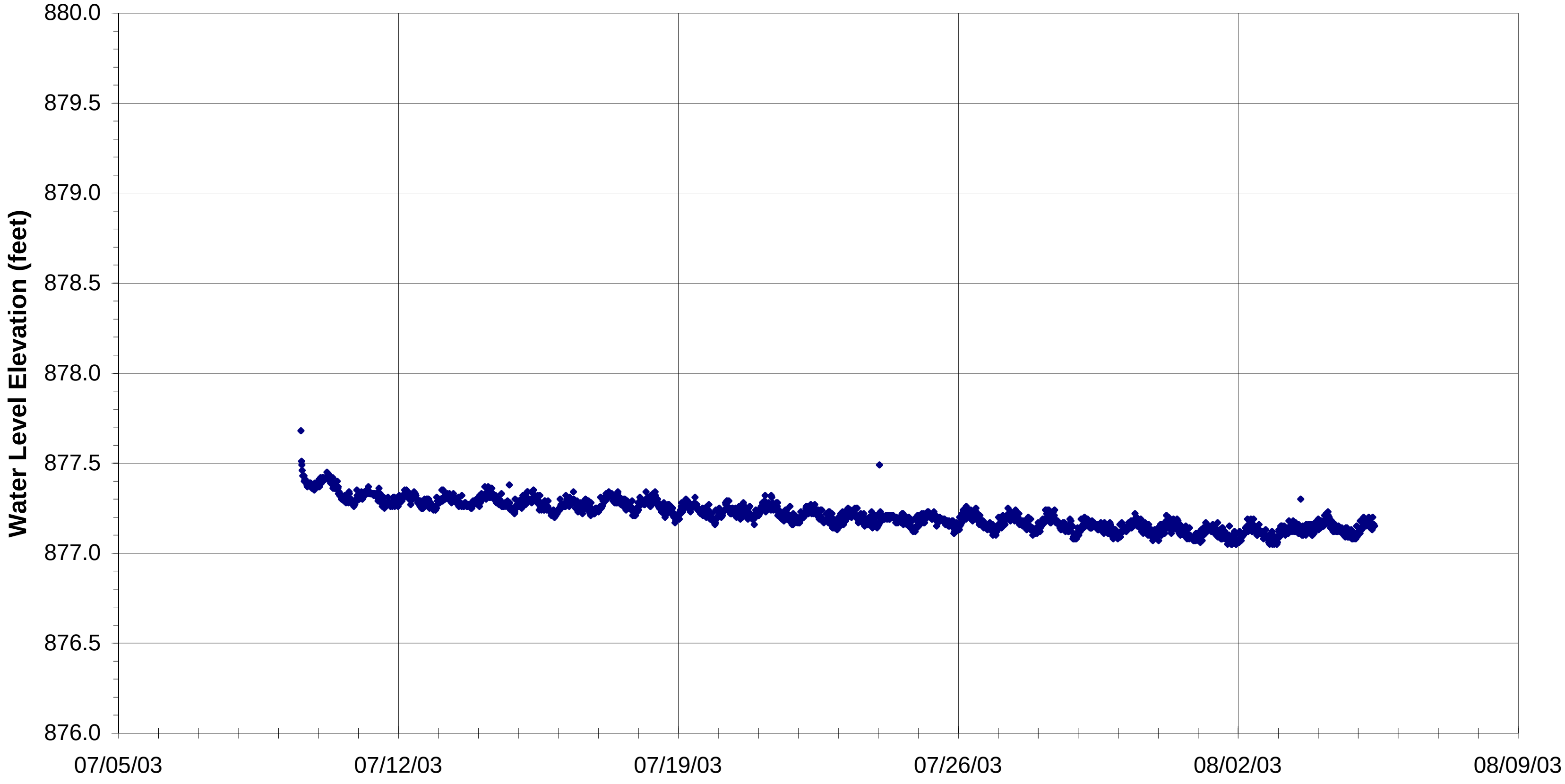

Legend

Figure B2.
Hanford Well Hydrograph

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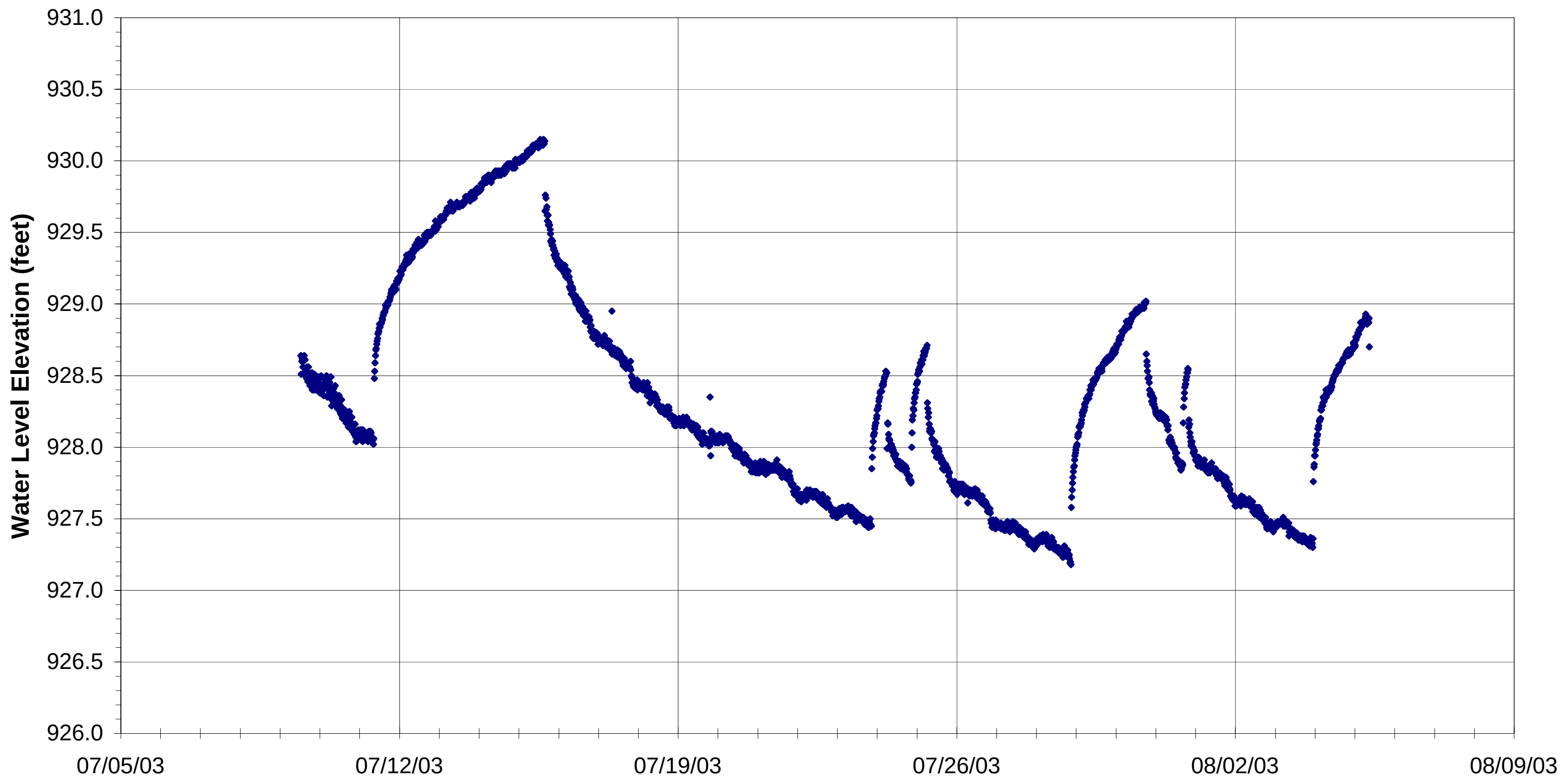

Legend

Figure B3.
T29R25S35 Well Hydrograph

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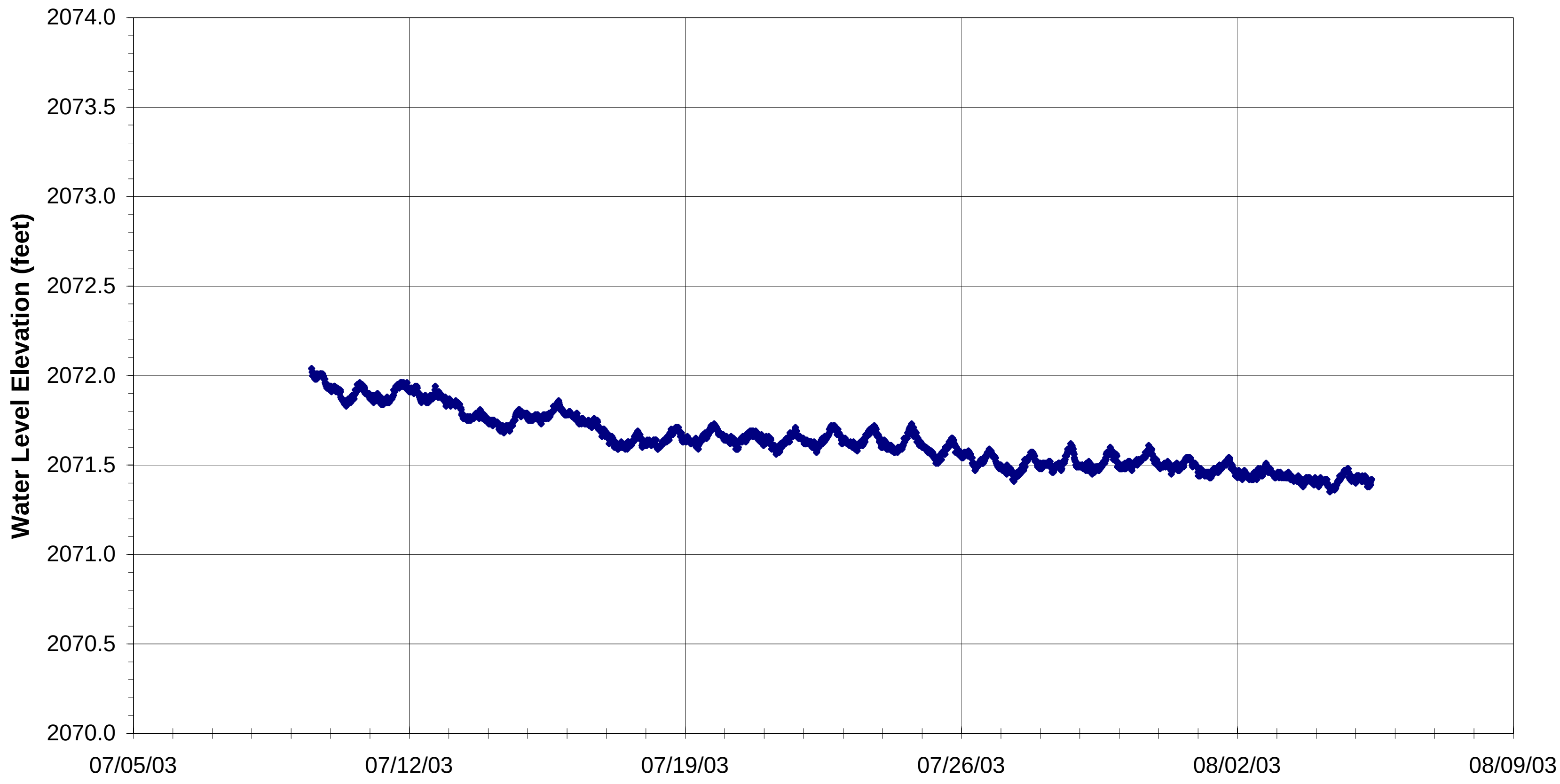

Legend

Figure B4.
Hunt Well Hydrograph

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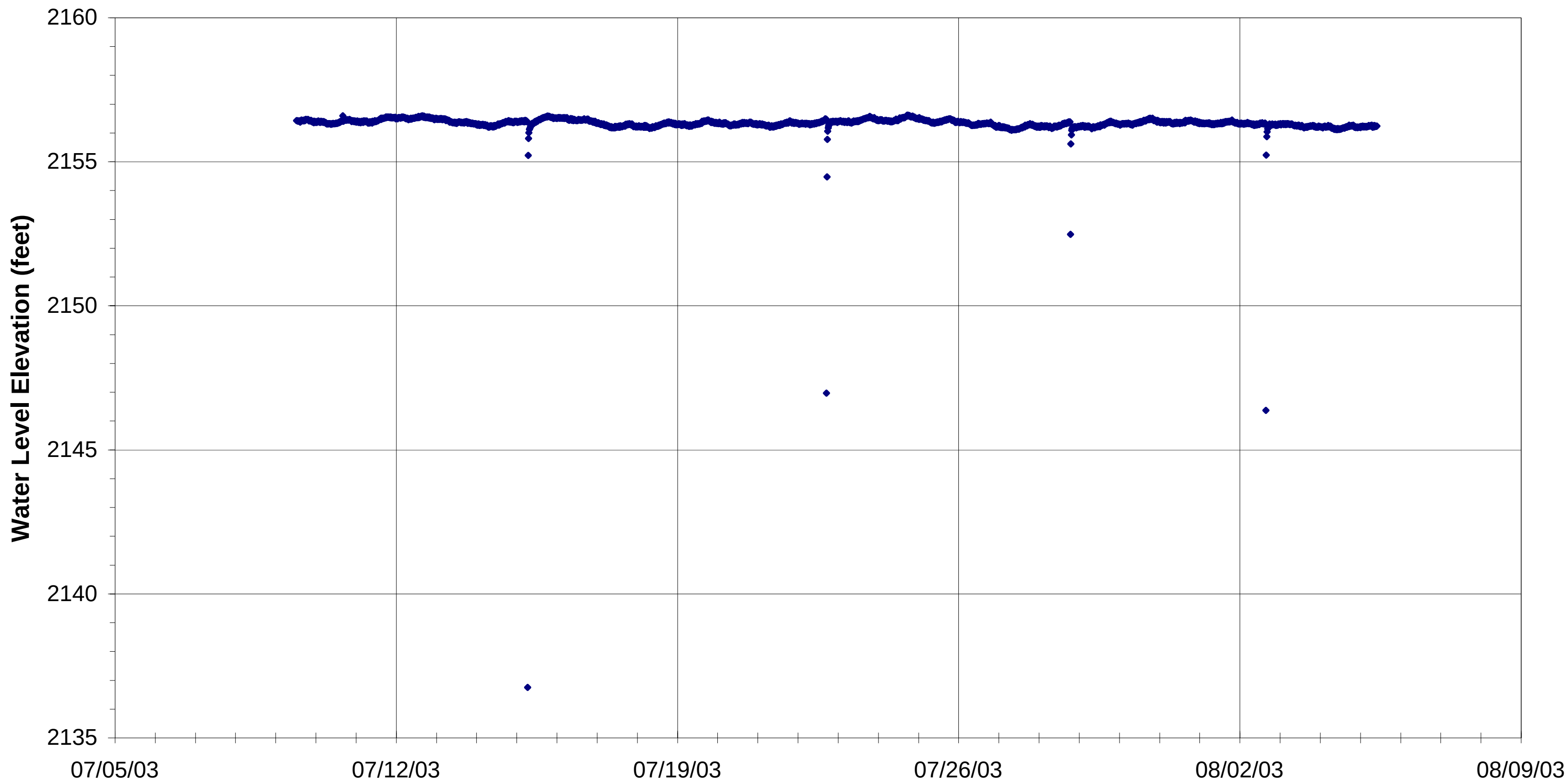

Legend

Figure B5.
Hemmer Well Hydrograph

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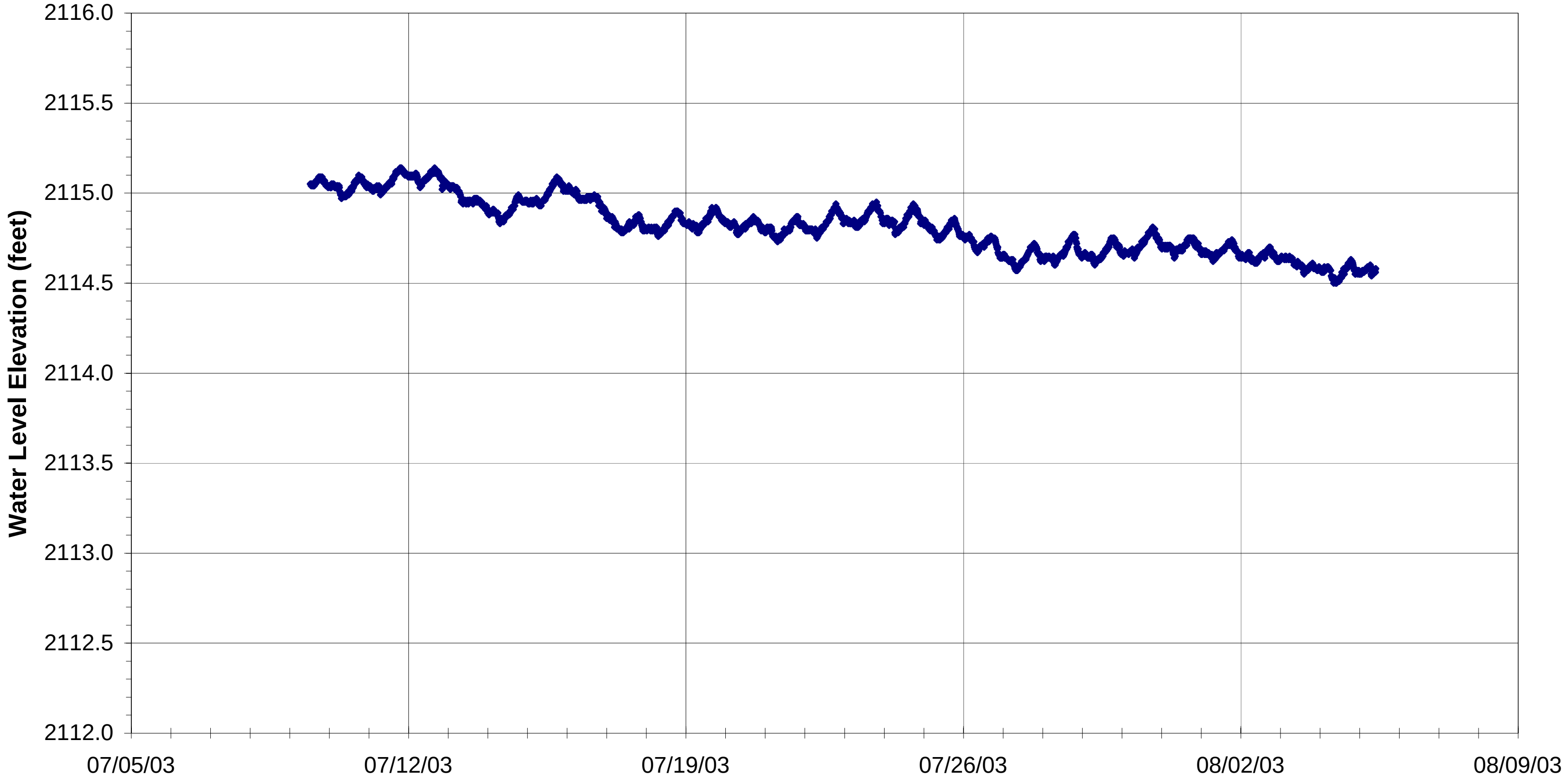

Legend

Figure B6.
Hammons Well Hydrograph

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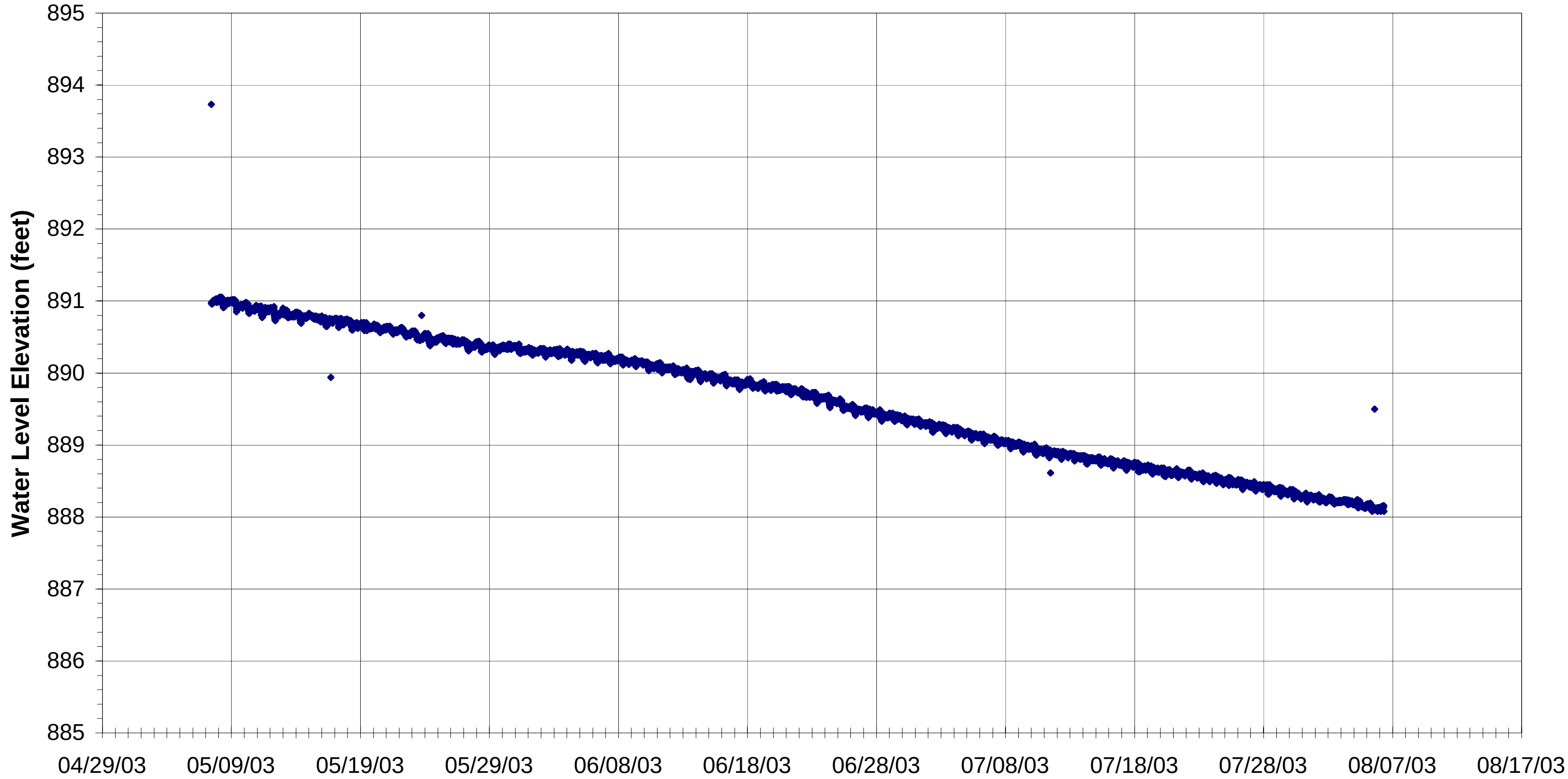

Legend

Figure B7.
Palisades Irrigation District Well Hydrograph

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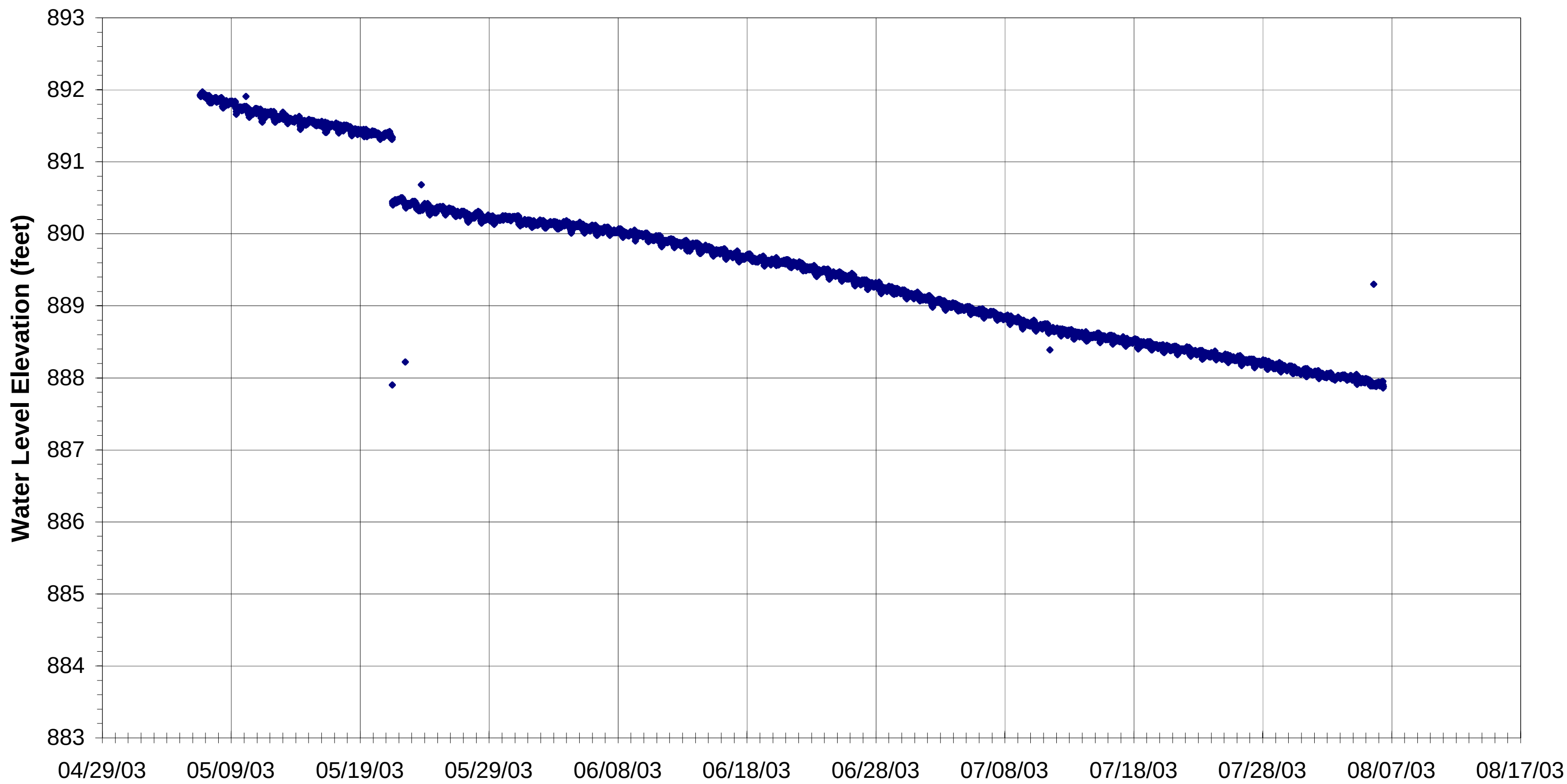

Legend

Measuring Point Altered on 5/21/03 11:45.

Figure B8.
King Well Hydrograph

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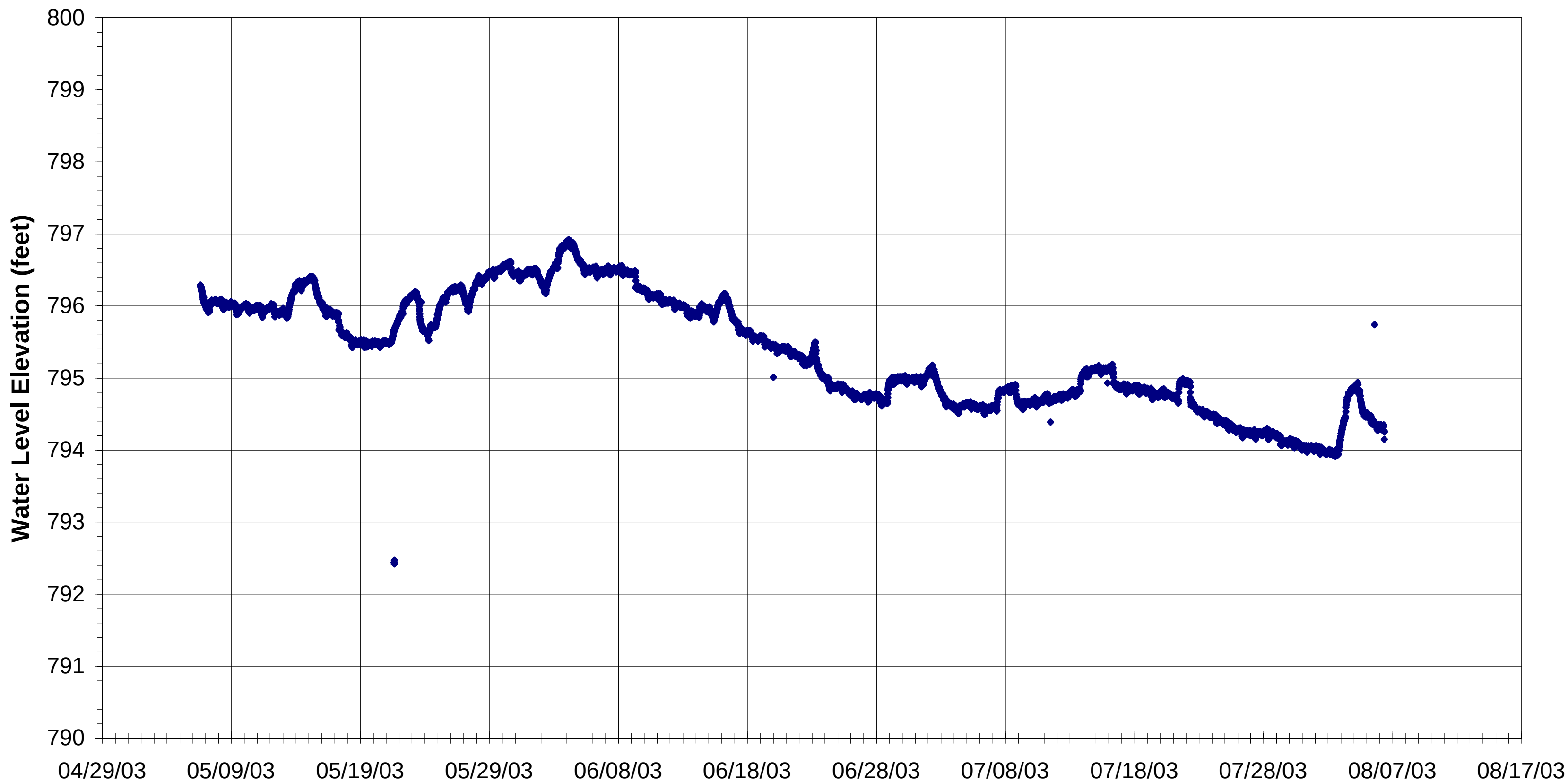

Legend

Figure B9.
Biram Observation Well Hydrograph

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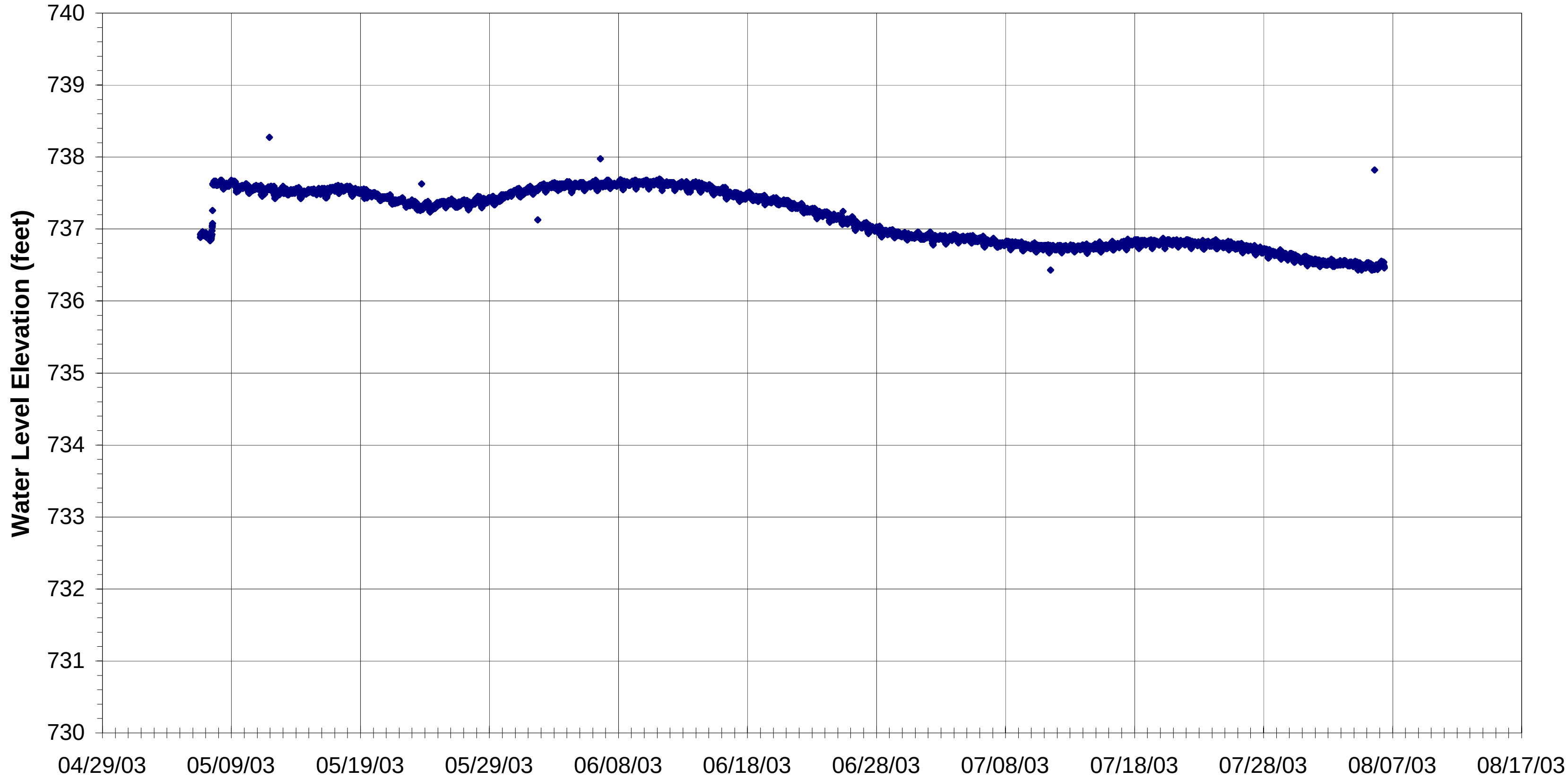

Legend

Figure B10.
Linville North Well Hydrograph

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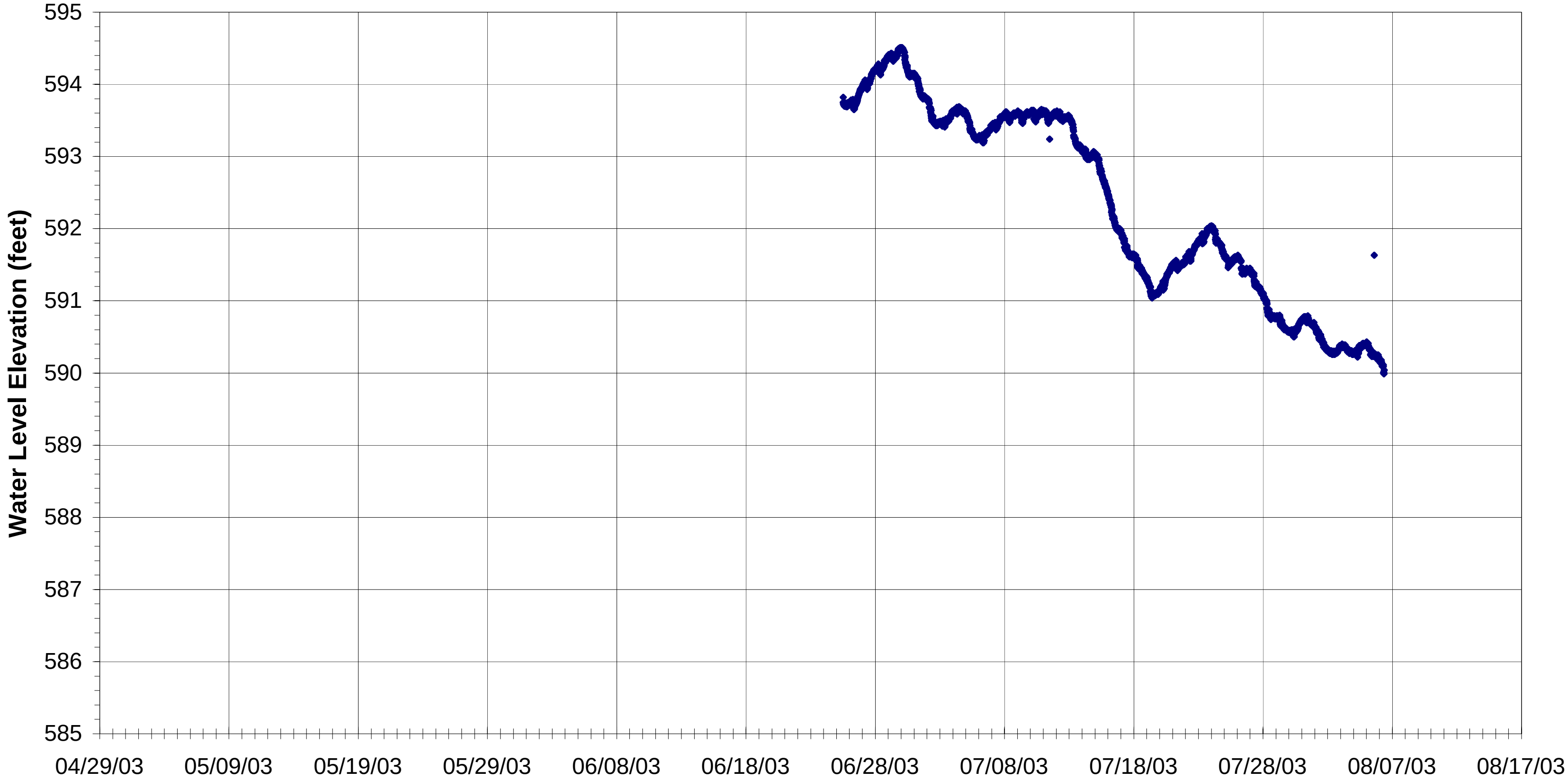

Legend

Figure B11.
Linville South Well Hydrograph

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