OBSERVATIONS OF RECHARGE TO THE WANAPUM AQUIFER SYSTEM IN THE MOSCOW AREA, LATAH COUNTY, IDAHO

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By

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Hannah P. Hernandez, submitted for the degree of Master of Science with a major in Hydrology and titled "Observations of Recharge to the Wanapum Aquifer System in the Moscow Area, Latah County, Idaho" has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

The Wanapum Aquifer system may provide a source of irrigation water for the Moscow area and help reduce water level declines in the Grande Ronde Aquifer system and subsequent groundwater mining. Continuous monitoring of water-table fluctuations in the Wanapum Aquifer system helps to differentiate areas experiencing recharge from those recovering from municipal pumping. Additionally, understanding the hydrogeologic connection between surface water resources and the Wanapum Aquifer system may help investigators quantify pumping-induced groundwater recharge in the Moscow area.

Several wells completed in the Wanapum Aquifer system were monitored throughout the year of 2006 to evaluate water level and temperature trends. Water levels and temperature data suggest that the Wanapum Aquifer system may be compartmentalized in the Moscow area.

Multiple well aquifer tests were conducted at the University of Idaho Groundwater Field Lab (UIGFL) to ascertain the hydrogeologic relationships between the Wanapum Aquifer system and Paradise Creek. The aquifer tests indicate that the wells completed in the shallow sediments overlying the Lolo basalt flow of the Priest Rapids Member respond immediately to pumping of wells completed in the Lolo basalt. Drawdown in the shallow sediments and in some wells completed in the Lolo basalt tended toward stabilization during the six-hour long aquifer tests due to the influx of water from Paradise Creek. Ground water temperature data support the movement of water between the shallow sediments and the basalt. The observed responses to the

aquifer tests suggest that the shallow sediments and Lolo basalt flow of Priest Rapids Member locally are parts of the same aquifer system.

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CHAPTER 1
INTRODUCTION

1.1 Overview

Two primary aquifer systems exist in the Moscow-Pullman area. The upper aquifer is referred to as the Wanapum Aquifer system and the lower one is referred to as the Grande Ronde Aquifer system. Prior to 1960, the Wanapum Aquifer system was the primary source of water for the city of Moscow; however, due to over pumping the water levels dropped alarmingly low. Consequently, subsequent production wells were installed in the Grande Ronde Aquifer system, which is now the primary source of water for the communities of Moscow, Idaho and Pullman, Colfax, and Palouse, Washington. Annual groundwater recharge to the Grande Ronde Aquifer system is not sufficient to replace the quantity being withdrawn annually. However, during the past 40 years, water levels in the Wanapum Aquifer system have recovered as annual pumping was reduced to more closely balance annual recharge.

Recharge to the Wanapum Aquifer system is known to occur on a seasonal time frame. Delineation of this recharge requires an understanding of water-table fluctuations, regional and local recharge mechanisms, areal distribution of recharge, and characterization of hydrogeologic interactions with surface water resources. The Wanapum Aquifer system has been monitored in detail for the past several years. Historical water level data, as well as current data, provide important information about water level fluctuations, and timing of potential recharge events. Aquifer tests may show that recharge from Paradise Creek can be induced by strategic pumping of the Wanapum Aquifer system.

1.2 Statement of the Problem

The Wanapum Aquifer system in the Moscow-Pullman area is tapped by city of Moscow wells and many domestic wells. Historically, water levels in the Wanapum Aquifer system fall by as much as 130 feet from the 1800's to the 1960's (Baines, 1992; Jones and Ross, 1969). However, water levels have recovered significantly since new municipal water supply wells have targeted the Grande Ronde Aquifer system rather than the Wanapum Aquifer system. The present need is to delineate the mechanisms that control groundwater recharge to the aquifer system, and identify the optimal locations for that recharge. This information may help maximize groundwater recharge by the strategic placement of new wells in specific areas capable of producing additional recharge.

1.3 Purpose and Objectives

The purpose of this study is to collect water level and temperature measured in wells completed in the Wanapum Aquifer system, and to assess the groundwater recharge and discharge relationships between the Wanapum Aquifer system and Paradise Creek. The general objective of the study is to examine and compare seasonal water level fluctuations, local well pumping stresses, and specific aquifer tests to identify the factors that control recharge to the Wanapum Aquifer system in the Moscow, Idaho area.

Specific objectives include:

1) Describe the climatic and geographic limitations on groundwater recharge within the Moscow-Pullman area.

2) Evaluate seasonal trends in groundwater levels and groundwater temperatures for the existing wells in the Wanapum Aquifer system monitoring network to help identify potential groundwater recharge areas.

3) Design and conduct a series of specific aquifer tests to evaluate groundwater and surface water interactions between Paradise Creek and the Wanapum Aquifer system.

1.4 Method of Study

The Palouse Basin Aquifer Committee (PBAC) maintains two groundwater-monitoring networks, one for the Grande Ronde Aquifer system and the other for the Wanapum Aquifer system. The monitoring network for the Wanapum Aquifer system was established in 2005 (Badon, 2007). In 2007, the monitoring network consists of 15 wells including: Tuck/Burns, Elliott, Shumway, Brandt, Palouse Clearwater Environmental Institute (PCEI), Stalnaker, Moscow Cemetery, Appaloosa Horse Club (A.H.C.), Carson, Whitman Co (County) Shop (WCS), McMurray, Sweet Avenue Site 1 (SAS1), Sweet Avenue Site 2 (SAS2) (Figure 1), INEL-D, and D19D (Figure 2). Monitoring of the Elk's Golf Course and Bond wells was discontinued in early 2006 at the request of the owners. The Whitman County Shop well and the Klemgard well are the only wells outside of the Moscow-Pullman area. Data for the Klemgard well (Figure 1) were not used in this investigation. The Klemgard well is maintained with the Grande Ronde Aquifer system database though it is completed in the Wanapum Aquifer system. Groundwater levels and groundwater temperatures were measured by submersible, programmable, Solinst Leveloggers™ (data loggers). All groundwater levels and groundwater temperatures measured for the Wanapum Aquifer system were qualitatively reviewed for seasonal trends for the monitoring period January 1, 2006 to December 31, 2006. Fluctuations in groundwater levels and temperatures between wells were also compared qualitatively.

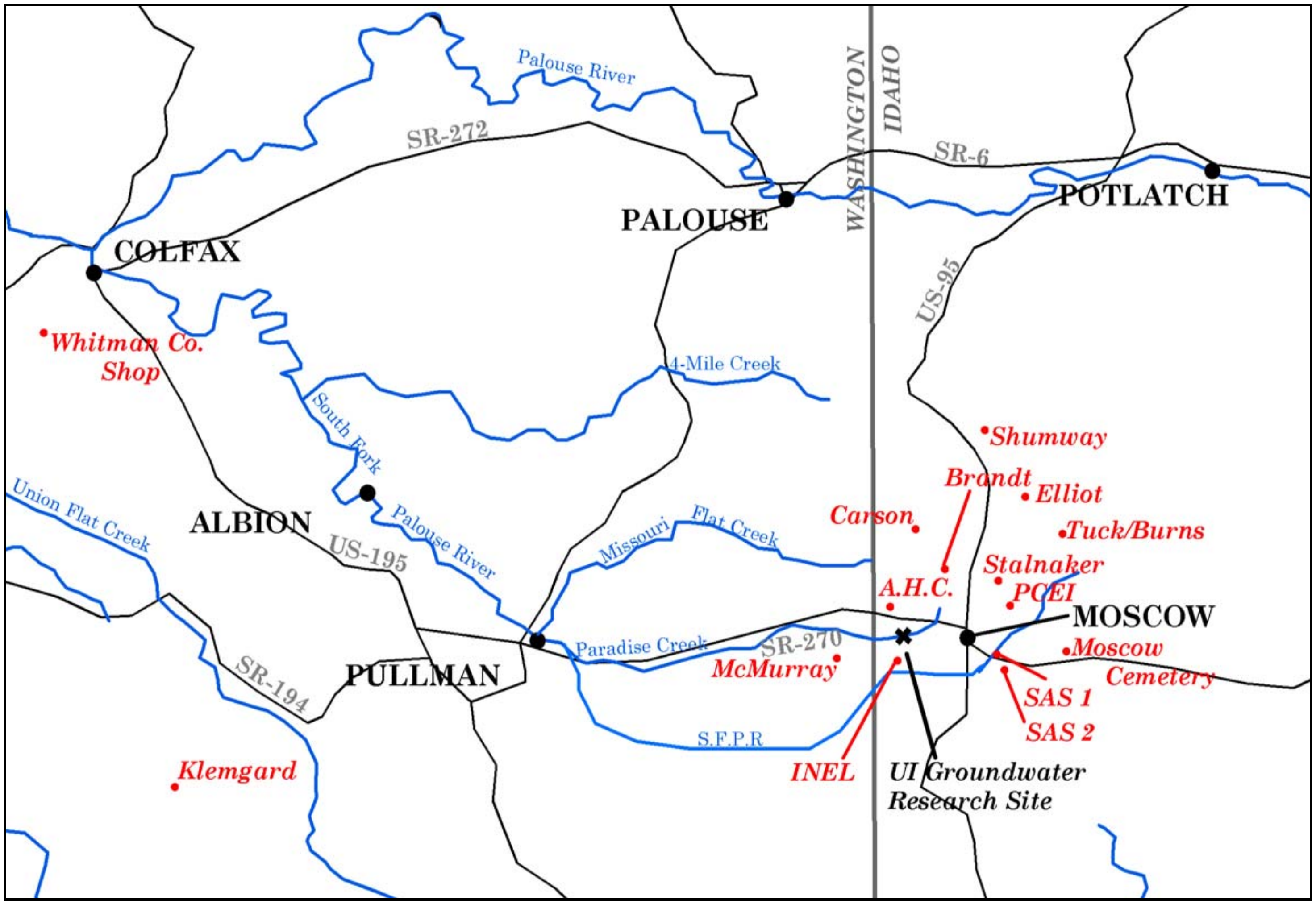


Figure 1. Wanapum Aquifer System Monitoring Well Locations (Douglas, 2006).
All wells at the UIGFL are shown in Figure 2.

Groundwater levels and groundwater temperatures were measured each minute for 11 wells at the UIGFL between June 7, 2006 and November 11, 2006; basalt wells included D19D, INEL-D, S12D2, Q17D, Q16S, T16D, and V16D. Shallow sediment wells included V16S, Bovill 1, Bovill 2, and Bovill 3 (Figure 2).

A GPS survey was conducted to provide coordinates of the UIGFL well locations (Appendix E). In addition, six pretests and three aquifer tests were conducted at the UIGFL for the purpose of evaluating groundwater/surface water interactions between Paradise Creek and the Wanapum Aquifer system. Data loggers were programmed to measure water levels and groundwater temperatures, initially at one-hour intervals between aquifer tests and at one-minute intervals during aquifer tests. The measurement frequency was changed for convenience to collect all aquifer data on one-minute intervals. Groundwater level data and groundwater temperature data were analyzed for trends for the entire sampling period. Wells exhibiting similar groundwater level trends and groundwater temperature trends were compared (Section 3.3). Drawdown and recovery data for Aquifer tests #1, #2, and #3 were analyzed using curve-matching techniques in AQTESOLV® (HydroSOLVE, 1996-2007). Drawdown curves were analyzed using the Theis (1935) equation modified for unconfined aquifer systems with the method of superposition for multiple wells (one image well). Qualitative analyses of groundwater temperature changes measured during the aquifer tests also were performed.

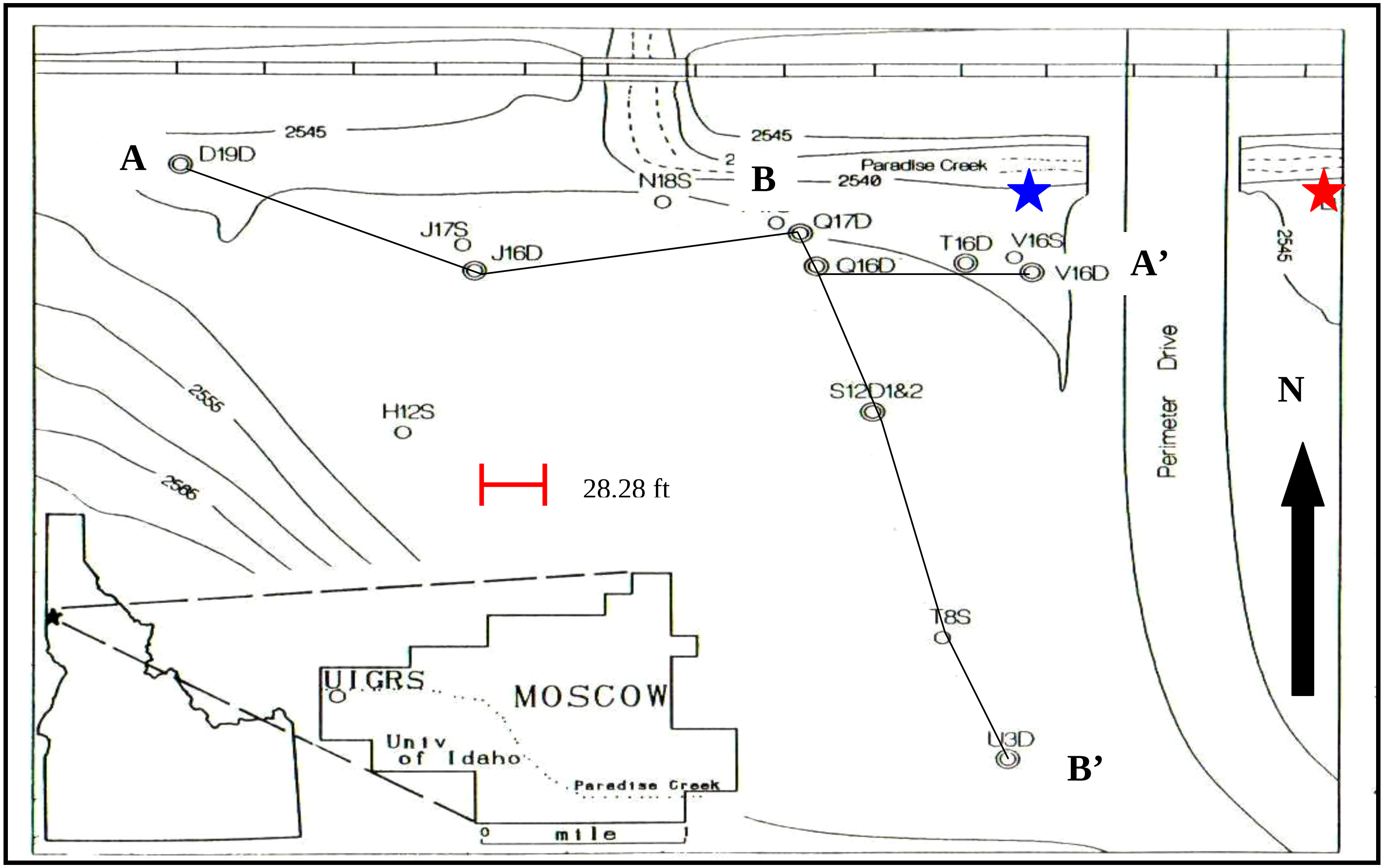


Figure 2. UIGFL Well Locations (modified after Li, 1991).
Sediments of Bovill wells 1, 2, and 3, and USGS Paradise Creek gage station are represented by blue and red stars, respectively. The Lines A-A' and B-B' show the locations of the cross-sections shown in Figure 8 and Figure 9, respectively.

1.5 Previous Investigations

Groundwater and surface water research pertaining to the Wanapum Aquifer system has been conducted for many years. Pardo (1993) analyzed the relation between groundwater and surface water at the UIGFL. Pardo analyzed the recharge and discharge patterns between the shallow sediments and Wanapum basalt aquifers, and Paradise Creek. She concluded: 1) Paradise Creek recharges the shallow sediments, and the E-fracture aquifers at the UIGFL during the summer and early fall, as well as frequently during maximum stream flow events; 2) the stream stage for Paradise Creek, and the groundwater levels in the shallow sediment wells, and in the E-fracture aquifer wells follow the same fluctuation patterns; 3) the water levels in Paradise Creek and in the aquifers are lower during the summer and early fall; seasonal decline is greatest in the shallow aquifer wells, and least in Paradise Creek; 4) well V16S has a higher water level elevation than that of V16D during rainfall events; therefore, during high stream flow periods, the flow could be downward from the shallow sediments to the E-Fracture at this location; and 5) the fluctuation pattern of the W-fracture aquifer wells is different from the shallow sediments or the E-fracture.

` Heinemann (1994) analyzed the relationship between groundwater and surface water in the Moscow-Pullman area. He identified and described stream reaches where groundwater recharge or discharge occurs. Heinemann concluded: 1) streams in the Moscow-Pullman area flow primarily on the Wanapum Formation; and 2) the upper reach of the North Fork of the Palouse River, and the central portion of Union Flat Creek receive significant groundwater discharge from the Wanapum Aquifer system while Four

Mile Creek and Paradise Creek receive less groundwater from the Wanapum Aquifer system.

Larson (1997) used stable isotopes to define the ages of groundwater in the Grande Ronde Aquifer system and the Wanapum Aquifer system, and possible recharge scenarios to those systems in the Moscow-Pullman area. She concluded: 1) groundwater in the Wanapum Aquifer system and in the upper Grande Ronde Aquifer system dated to the Holocene, and groundwater in the deeper Grande Ronde Aquifer system dated to the Pleistocene; and 2) precipitation infiltrating through the loess could not be distinguished from precipitation infiltrating at the base of Moscow Mountain.

Hopster (2003) conducted a recession analysis of springs and streams in the Moscow-Pullman area to evaluate the mechanisms of groundwater discharge and recharge. She concluded: 1) flow from springs along Union Flat Creek and the South Fork of the Palouse River originates from perched water tables within the Palouse Formation; 2) many flow systems that discharge into Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek appear to be contained within the loess; and 3) the Palouse Formation is sufficiently thick to contain water tables that exist throughout the summer.

Douglas (2004) used radiocarbon dating to assess groundwater age and aquifer residence time in the Wanapum Aquifer system; however, the primary focus was on the Grande Ronde Aquifer. She concluded: 1) groundwater in the lower Grande Ronde Aquifer system is the oldest; 2) the groundwater age dates for the lower Grande Ronde Aquifer system range from 12,993 to 26,406 years (B.P.), for the upper Grande Ronde Aquifer system groundwater age dates range between 4,420 and 11,832 years (B.P.), and for the Wanapum Aquifer system groundwater age dates range from present to 14,605 years (B.P.); and 3) stratification of groundwater age indicates vertical travel of areally distributed recharge.

Badon (2007) established a groundwater-monitoring system for the Wanapum Aquifer system, and conducted aquifer tests to evaluate the seasonality of recharge and whether compartmentalized aquifer conditions exist, respectively. She concluded: 1) the Wanapum Aquifer system is poorly connected hydraulically, and appears to be compartmentalized in the Moscow area; 2) the Wanapum Formation is heterogeneous, and probably anisotropic with respect to aquifer transmissivity; and 3) the Wanapum Aquifer system is probably unconfined near Moscow well 2.

Several research projects pertaining to the UIGFL area have been conducted. Li (1991) characterized the hydrogeology of the UIGFL. He developed a conceptual model of groundwater flow in fractured basalt, and characterized the site hydraulic properties by analyzing data from hydraulic tests. On the basis of his findings he concluded that: 1) a multiple aquifer system with three aquifers, consisting of a shallow alluvial aquifer, E-fracture aquifer, and W-fracture aquifer exist at the UIGFL; 2) the E-fracture aquifer behaves like a porous medium during multiple well aquifer tests; and 3) the W-fracture aquifer exhibits double-porosity behavior during multiple well aquifer tests.

Kopp (1994) characterized the hydrogeology of the Wanapum Aquifer system in the vicinity of the UI Aquaculture Lab. He analyzed geologic, stratigraphic, and aquifer test data for the area. Kopp concluded: 1) the Wanapum Aquifer system consists of both the Lolo basalt flow of the Wanapum Formation, and the underlying Latah Formation sediment interbed; 2) the shallow alluvial aquifer and the E-fracture aquifer are hydraulically connected and receive recharge mostly from infiltration of precipitation and flow from Paradise Creek; and 3) aquifers in the sediment interbed and the W-fracture, and the basal zones in the basalt are hydraulically separate from the near-surface zones.

Provant (1995) conducted a geologic and hydrogeologic investigation of the Viola and Moscow West Quadrangles. Provant's objective was to refine the concepts of shallow groundwater movement in the Moscow-Pullman area. He concluded: 1) the sediments of Bovill are important in influencing the quantity and locations of groundwater recharge in the eastern portion of the Moscow-Pullman area; 2) cross-sections through University of Idaho well #3 and Moscow City well #8 indicate the existence of a paleo-stream channel or faulted section of basalt which could influence groundwater movement; 3) water levels in the eastern portion of the Moscow-Pullman area show a significant water-level change from August to January; and 4) five mechanisms of recharge were hypothesized: percolation through Palouse loess, percolation through Palouse loess and sediments of Bovill, percolation through coarse-grained sediments along the basin margins, aquifer gain from stream loss, and percolation through the crystalline basement rocks.

Nimmer (1998) used groundwater tracer tests to study transport characteristics within a single fracture zone at the UIGFL. She concluded: 1) the E-fracture aquifer is hydraulically continuous within the area of wells V16D, T16D, Q16DS, Q17D; 2) particles and conservative tracers in the same tracer experiment help identify the existence of preferential flow paths in a fractured rock environment as seen by the early arrival of the microbeads relative to the conservative tracers; and 3) fractures with apertures greater than 6 μm connect the wells in the E-fracture based on the breakthrough of the microbeads (6 μm diameter).

Three research projects pertaining to the Sweet Avenue site on the UI campus have been conducted. The Sweet Avenue site is a former location for commercial storage and distribution of agrichemicals and hydrocarbons that contained contaminated soils and shallow groundwater. The site was cleared and decontaminated prior to being purchased by the UI. The site is located on the eastern side of the UI campus and currently contains a UI parking lot. Wright (1996) conducted a hydrogeological and groundwater contaminant assessment of the Sweet Avenue site, Moscow, Idaho. Wright compiled information from previous studies pertaining to groundwater chemistry data and groundwater elevation data, and conducted several single well and multiple well aquifer tests. He concluded: 1) shallow groundwater flows toward and probably discharges into Paradise Creek; 2) groundwater gradients are downward in the western and northern portions of the site; and 3) groundwater gradients are upward adjacent to Paradise Creek in the southeastern portion of the site..

Namlick (1998) assessed the impacts to Paradise Creek from fertilizer-contaminated groundwater, and stormwater drains at the Sweet Avenue site. Namlick collected water samples from stormwater drains discharging to Paradise Creek at the Sweet Avenue site area, and groundwater samples from monitoring wells at the site to evaluate the impacts of groundwater discharge to Paradise Creek. He concluded: 1) residual groundwater contamination and water from stormwater drains contribute to ammonia and nitrate loading of Paradise Creek; 2) shallow groundwater discharge to Paradise Creek along the reach bordering the Sweet Avenue site is of limited extent; and

3) groundwater discharge from the site to Paradise Creek was less than five L/min per meter over the entire study area.

Johnson (2002) conducted a geostatistical analysis of a NO^-_3-N plume at the Sweet Avenue site. Johnson collected seasonal NO^-_3-N data from a network of piezometers along the Paradise Creek restored riparian zone (RRZ). He concluded: 1) a NO^-_3-N plume at the Sweet Avenue site was migrating into the Paradise Creek RRZ; 2) piezometers showing upward vertical hydraulic gradients suggest that groundwater NO^-_3-N concentrations decrease as the plume flows through the RRZ and discharges into Paradise Creek; and 3) seasonal variations in NO^-_3-N concentrations within the riparian zone are not a function solely of changes in water elevation (dilution), but also depend on assimilation and denitrification processes.

Fairley, J.P., M.D. Solomon, J.J. Hinds, G.W. Grader, J.H. Bush, and A.L. Rand, (2006) conducted the "Latah County Hydrologic Characterization Project." This study evaluated sediment types in relation to the potential for shallow groundwater recharge to the upper aquifer in the Moscow area (the "Wanapum aquifer") through sediments along the granite/basalt contact on the east side of Moscow. Fairley et al., (2006) concluded: 1) surface water infiltrates into the near surface sediments throughout a broad area along the margin of Moscow Mountain; 2) near surface sediments generally have high infiltration capacity; 3) the majority of infiltrated water is probably prevented from becoming deep percolation by the relatively impermeable granite or low-permeability clays that underlie the coarser near-surface sediment; and 4) much of the shallow groundwater probably returns to the land surface as spring discharge, or by intersecting an incised channel and becoming stream flow.

1.6 Geography and Climate

The Palouse Groundwater Basin (hereinafter referred to as the Palouse Basin) encompasses an area of approximately 235 mi^2 in eastern Washington and northwestern Idaho. The Moscow-Pullman area is located in the eastern portion of the Palouse Basin. The Moscow-Pullman area is delimited to the south by Paradise Ridge and Baco Butte, and to the north by the North Fork of the Palouse River. The Palouse Range marks the eastern boundary of the Palouse Basin. The Moscow-Pullman area is characterized by rolling hills composed of deep loess (Figure 3). Major tributaries in the Moscow-Pullman area include the South Fork of the Palouse River, Four Mile Creek, Missouri Flat Creek, and Paradise Creek (Figure 1).

Figure 3. Palouse Hills From McMurray Road, Whitman County, Washington.

The Palouse is considered part of the geographic Palouse bio-region (Sisk, 1998). The Palouse Bio-region (Bailey, 1995) covers 16,000 km^2 in west central Idaho, southeastern Washington, and northeastern Oregon between the western edge of the Rocky Mountains and the Columbia River basin. The region is characterized by a moderate climate and loess soils deposited on plateaus dissected by rivers deeply incised through layers of basalt (Sisk, 1998). The Palouse bio-region is considered semi-arid. The region is characterized by a moderate climate, mild wet winters, cool damp springs, and hot dry summers. The average maximum temperature is 58.0 F, the average minimum temperature is 36.6 F, the average total precipitation is 23.59 inches, and the average total snowfall is 49 inches (Sisk, 1998).

1.7 Organization of Thesis

This thesis is divided into six (6) chapters. Chapter 1 presents the introduction, statement of the problem, purpose and objectives, method of study, and previous investigations. Chapter 2 describes the geology and hydrogeology of the Moscow-Pullman area and the University of Idaho Groundwater Field Lab. Analysis of water data for the Wanapum Aquifer system for 2006 is presented in Chapter 3. Chapter 4 describes the aquifer tests, data collection, and analysis. Chapter 5 describes a conceptual model for groundwater and surface water interactions in the Moscow-Pullman area. Conclusions and recommendations are presented in Chapter 6.

CHAPTER 2
GEOLOGY AND HYDROGEOLOGY OF THE MOSCOW-PULLMAN AREA

2.1 Introduction

Monitoring of the Wanapum Aquifer system is concentrated in the Moscow, Idaho area although one outlying well in the Colfax, Washington area is included in the monitoring system. Figures 1 and 2 show all the wells monitored as part of the Wanapum Aquifer system monitoring program. The majority of the wells are completed in the Wanapum Formation of the Columbia River Basalt Group (CRBG); however, the INEL-D well is completed in the Latah Formation sediments below the Wanapum Formation and the Shumway well is completed in granitic basement rock. In general, the geology of the Moscow-Pullman area consists mostly of basalt, overlain by loess and lacustrine/fluvial sediments. The Wanapum Aquifer system in the Moscow, Idaho area comprises the Latah Formation sediments and the Lolo flow of the Priest Rapids Member of the Wanapum Formation.

2.2 Regional Geologic and Hydrogeologic Setting

The Palouse Basin is on the eastern margin of the Columbia River Basalt plateau (Figure 4). The basement rock of the Palouse Basin is believed to consist of Precambrian Belt Supergroup metamorphic rocks, Cambrian metamorphic rocks, and Cretaceous granite associated with the Idaho Batholith. These crystalline rocks are overlain by Miocene basalt flows that are interbedded with sedimentary deposits of the Latah Formation. The basalts are overlain by Latah Formation sediments and loess. The basin is bounded to the north and the northwest by metasediments of Smoot Hill and Kamiak Butte, to the east by Idaho Batholith granite of the Palouse Range (Moscow Mountain), and to the south by granite and metasediments along the western edge of Paradise Ridge, Tomer Butte, and Bald Butte (Nimmer, 1998) (Figure 4). The western boundary of the Palouse Basin is undefined.

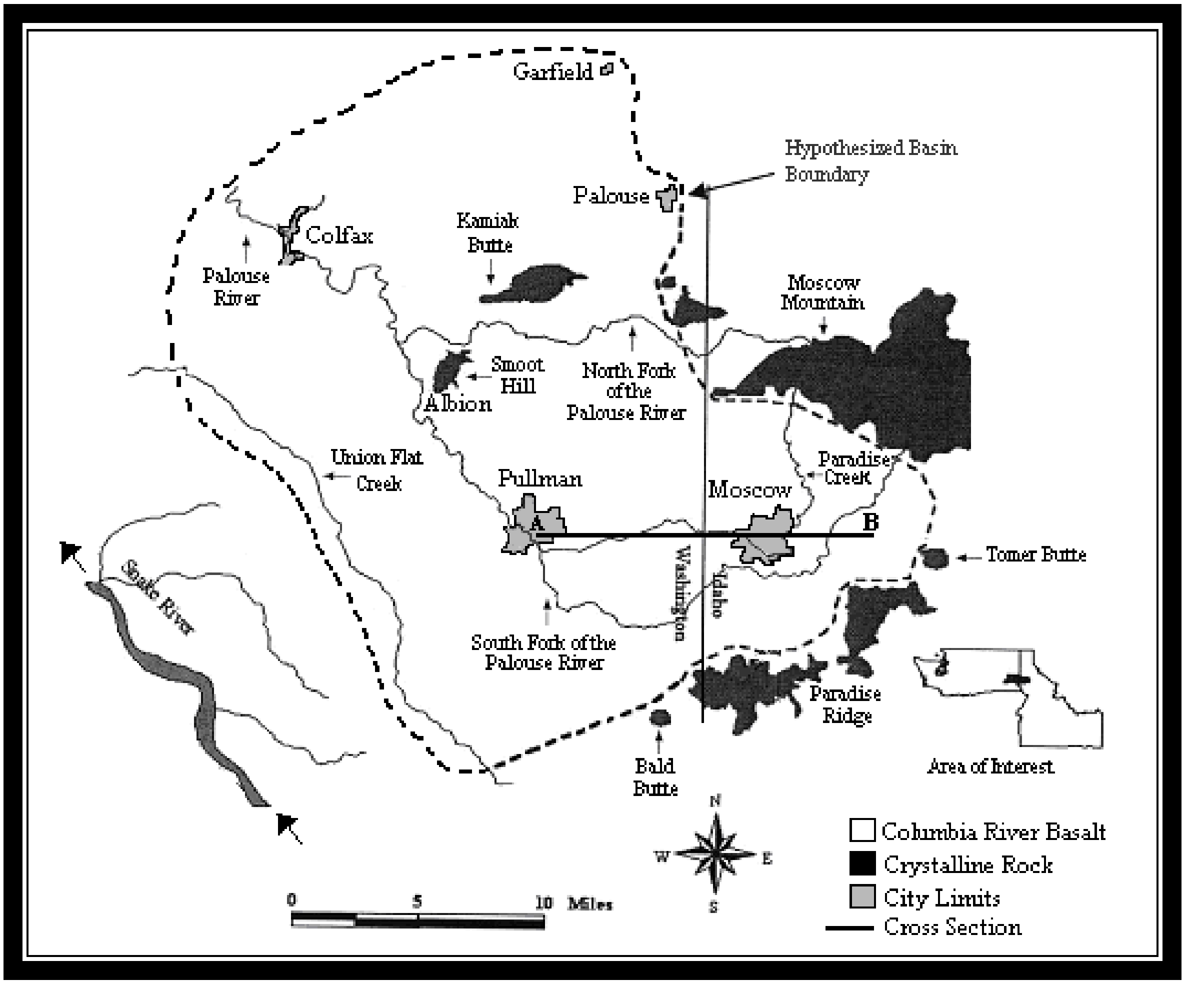


Figure 4. Bedrock-geologic and Hydrographic Map of the Palouse Basin (Hopster, 2003). Line A-B represents the approximate location of the west-east cross section shown in Figure 5.

The aquifer systems in the Moscow-Pullman area include the Wanapum Aquifer system, the Grande Ronde Aquifer system, a crystalline rock aquifer system, and a surficial loess aquifer system (Badon, 2007). Badon suggested that the Wanapum Aquifer system in the Moscow area may be compartmentalized.

2.2.1 Geology of the Moscow-Pullman Area

The Moscow-Pullman area can be divided into four distinct geologic units, the crystalline basement rocks, Columbia River basalts, interbedded sediments, and surficial loess. The basement rocks comprise Precambrian and Cambrian metasediments, and Cretaceous granite intrusions. These rocks crop out throughout the basin and exist at a depth of several thousand feet in the western portion of the basin. This basement complex is overlain by Miocene basalt flows of the Columbia River Basalt Group (CRBG) and associated sediment interbeds. The basalts in the Moscow-Pullman area are part of the Yakima Basalt Subgroup that is separated into four formations. The Imnaha Formation is the oldest and deepest basalt formation in the basin; the Grande Ronde Formation overlies the Imnaha and is overlain by the Wanapum Formation. The Wanapum is overlain in places by remnants of the Saddle Mountains Formation (Figure 5). Latah Formation sediments exist below the deepest basalt flows, as interbeds between basalt flows, as sediments that drape the edges of individual flows, and as fluvial sediments that overlie the uppermost basalt flow in much of the Moscow area (Badon, 2007). The uppermost stratigraphic unit is referred to as the Palouse Formation and is composed of windblown loess (Nimmer, 1998).

The Grande Ronde Formation is composed of numerous individual flows, in places separated by thin layers of interbedded sediments of the Latah Formation (Kopp, 1994). The Grande Ronde Formation is thicker in the west than in the east. The Grande Ronde Formation is dated 15.6 to 17.0 million years old (Provant, 1995). Up to 60 percent of the stratigraphic column in the Moscow area is composed of interbedded sediments of the Latah Formation (Lin, 1967; Jones and Ross, 1972).

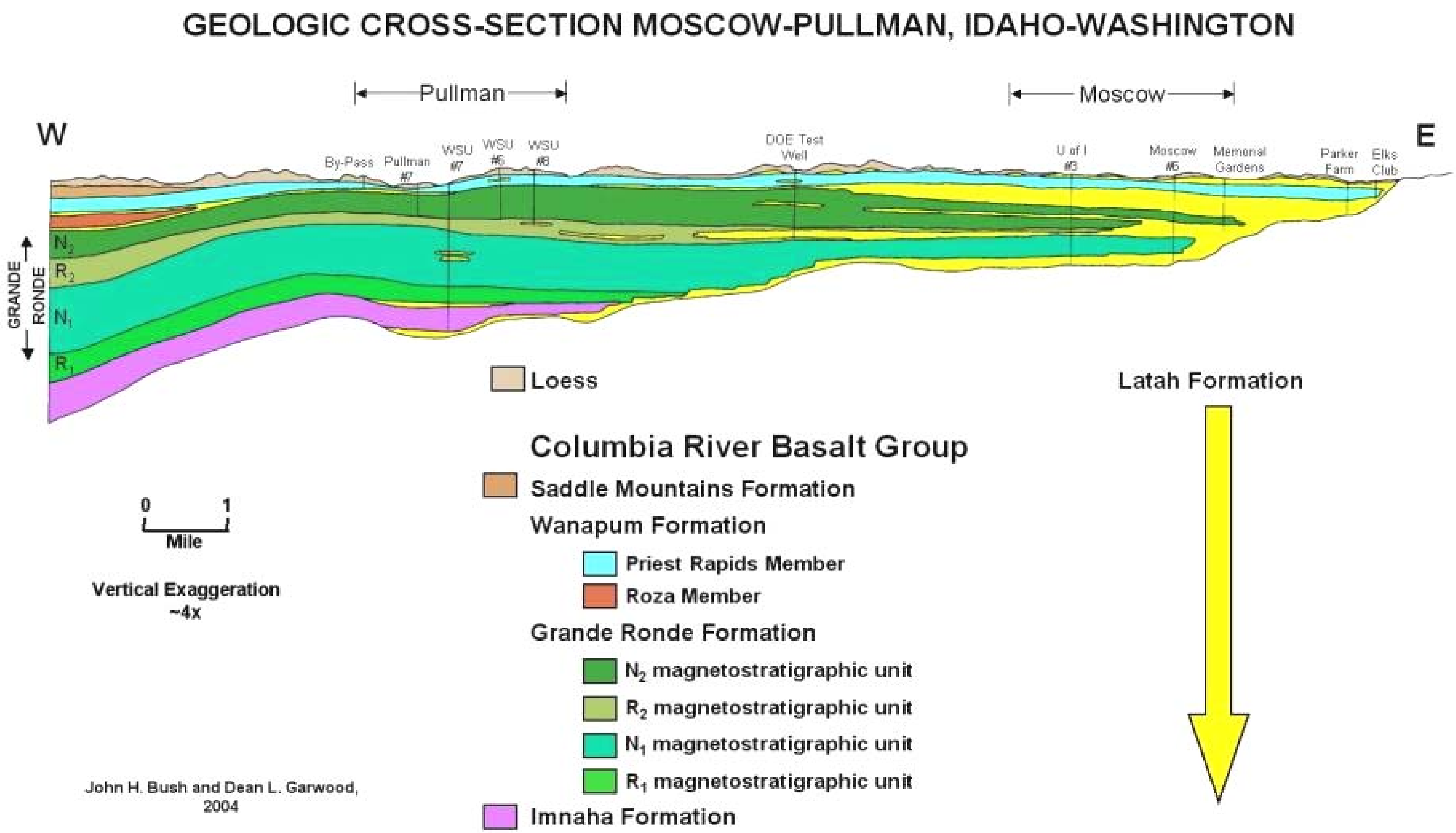


Figure 5. Geologic Cross-Section Near Line A-B in Figure 4 (after Bush and Garwood, 2004).

The Latah Formation comprises fluvial and lacustrine derived sediments, primarily clay and silt with lesser amounts of sand and gravel (Bush, 2005; Provant, 1995). The Latah Formation sediments that separate the Wanapum Formation from the Grande Ronde Formation are informally referred to as the Vantage equivalent interbed (Siems et al. 1974, and Swanson et al. 1980, as cited in Kopp, 1994). Although these sediments have no physical relation to the Vantage Member of the Miocene Ellensburg Formation in central Washington, they are considered to be a lateral equivalent (Kopp, 1994; Provant, 1995), and are referred to in this thesis as “the Vantage.”

The Wanapum Formation in the Moscow-Pullman area is represented by the Lolo flow of the Priest Rapids Member. The Wanapum Formation exists over the entire basin except where removed by erosion in the deepest river valleys. In the Moscow area, the Lolo flow is approximately 200 feet thick. It is dated to 14.5 million years old and is distinguished from the Grande Ronde Formation by higher concentrations of phosphorus and titanium and lower magnesium content (Wright, T.L., M.J. Grolier, and D.A. Swanson, 1973).

The uppermost stratigraphic unit of the Moscow-Pullman area comprises mostly of sediments of the Latah Formation and Palouse Formation. The uppermost part of the Latah Formation is composed of fluvial deposits, and is informally referred to as the sediments of Bovill (Bush and Provant, 1998a, 1998b; Bush, 2005). The sediments of Bovill are the result of physical and chemical weathering of the granites and metasediments, and consist of clays, silts, sands, and gravels thought to have been deposited in fluvial environments (Bush, 2005). The sediments of Bovill thin from east to west. In most areas the Palouse Formation overlies the sediments of Bovill. The

Palouse Formation is composed of 2 to 4 million-year old wind blown loess and clay. The Palouse Formation varies from zero up to several hundred feet thick (Kopp, 1994), and thins from west to east.

Structural deformation in the Moscow-Pullman area is minimal and few structural features exist (Kopp, 1994). The only basin wide feature in the basalts is a slight northwest dip of several degrees. The Lolo basalt flow has a vesicular flow top underlain by blocky basalt containing horizontal platy fractures. An alternating entablature marks the center of the flow, and the bottom of the flow consists of colonnade with large diameter columns; colonnade features grade upwards into hackly entablature (Li, 1991).

2.2.2 Aquifers in the Moscow-Pullman Area

The Moscow-Pullman area contains two primary aquifer systems. A deep system exists in the Grande Ronde Formation and associated sedimentary interbeds, and a shallow system exists in the Vantage, the Wanapum Formation and overlying Latah Formation sediments. Most municipal and university wells in the cities of Moscow, Pullman, and Palouse are completed in the Grande Ronde Aquifer system. Well depths are between about 400 and 1800 feet, and the depth to water varies from about 250 to 375 feet depending on topography. Many domestic and a few municipal and university wells are completed in the Wanapum Aquifer system. Well depths range from 100 to 400 feet, and the depth to water varies from about 10 to 140 feet depending on topography.

2.2.3 Groundwater Flow Systems in the Moscow-Pullman Area

Prior to the 1960s, the Wanapum Aquifer system was the primary source of municipal water for Moscow, Idaho. Due to use exceeding the rate of recharge, the Wanapum Aquifer system was nearly depleted by the 1960s. Consequently, deeper municipal wells were drilled into the Grande Ronde Aquifer system beginning in the early 1960s to reduce the pumping stresses on the Wanapum Aquifer system. Since then water levels in the Wanapum Aquifer system have recovered (Heinemann, 1994). The Wanapum Aquifer system has not been re-exploited for municipal water use due to its relatively low productivity. Producing zones in the Wanapum Aquifer system are limited to the Vantage and fractures in the Lolo basalt flow (Figure 6).

Figure 6. Horizontal Cooling Fracture in Lolo Basalt Leaking Water at a Road Cut Along the Moscow-Pullman Highway about 4 Miles West of Moscow, Idaho.

Natural groundwater flow in the Moscow-Pullman area is thought to generally move east to west, but current groundwater flow is believed to be towards the major pumping centers in Moscow, Idaho and Pullman, Washington (Osiensky, 2006). Groundwater flow in the Grande Ronde Formation occurs predominantly between basalt flows, and horizontally and vertically through cooling fractures within the basalt. Groundwater flow in the Wanapum Formation occurs in vertical (Figure 7) and horizontal (Figure 6) basalt cooling fractures, the Vantage interbed, and the sediments of Bovill. Lower head in the Grande Ronde Aquifer system (Lum et al., 1990) indicates groundwater flows slowly downward from the Wanapum Aquifer system to the Grande Ronde Aquifer system.

Figure 7. Vertical Fractures in the Lolo Basalt at a Quarry Along the Moscow-Pullman Highway about 4 Miles West of Moscow, Idaho (photo from Nimmer, 1998).

Streams in the Moscow-Pullman area generally flow on the surficial loess layer in the upper reaches, and gradually incise into the basalts as they flow westward across the basin (Heinemann, 1994). Heinemann (1994) characterized reaches of Missouri Flat Creek, Paradise Creek, and the South Fork of the Palouse River as either groundwater recharge or discharge areas. Heinemann (1994) found that groundwater discharge to Missouri Flat Creek occurs in the form of springs in the upper reach, but ground water discharge is minimal in the middle and lower reaches. Groundwater discharge to Paradise Creek was not noted in the upper reach, but small amounts were observed in the lower reaches. Groundwater discharge to the South Fork of the Palouse River from the Wanapum Formation (lower Priest Rapids Member and the lower portion of the Roza Member) is significant between Pullman and Colfax (Heinemann, 1994).

Three general hypotheses pertaining to recharge in the Moscow-Pullman area have been proposed: 1) precipitation infiltrates through the loess and percolates into the Wanapum Aquifer system (Barker, 1979); 2) precipitation in the mountains east of the basin infiltrates into sediments of the Latah Formation along the crystalline rock/sediment contact and moves laterally into the basalt (Bush, 1996); 3) water originating from losing reaches of streams in the Moscow area recharge the sediments of Bovill and the Wanapum basalt (Pardo, 1993).

2.3 Geologic and Hydrogeologic Setting of the UIGFL

The UIGFL is located in a cow pasture along Perimeter Drive at the western edge of the University of Idaho campus (Figures 1 and 2). Research conducted at the UIGFL was focused on the Lolo basalt and the overlying sediments of Bovill.

2.3.1 Local Geologic Features

The Wanapum Formation at the UIGFL is represented by the Lolo flow of the Priest Rapids Member (Li, 1991). The upper surface of the Lolo flow exists at a depth of about 15 feet below land surface. The majority of the Lolo basalt is dense; however, Li (1991) described two, locally distinct, intraflow cooling structures in the Lolo basalt based on outcrops along the Moscow-Pullman Highway (Figure 7). The structures are: 1) thick columnar sections with alternating entablature and colonnade in the lower section, and hackly entablature in the upper section; and 2) dense, massive dark-gray basalt lacking a distinct flow top and vesicular zone (Kopp, 1994). The upper third of the Lolo flow is characterized by an oxidized flow top with large blocks and sub-horizontal conchoidal fractures confirmed by drill-hole cuttings analyzed by Kopp (1994). The majority of the wells at the UIGFL are completed in the upper third of the Lolo; only INEL-D and D19D are completed below a depth of 100 feet (Figure 2).

The upper stratigraphic unit at the UIGFL is comprised of the sediments of Bovill and reworked loess. The thickness of this unit varies from about four to 18 feet. There are several shallow wells completed in this unit including Bovill 1, Bovill 2, Bovill 3, and V16S.

2.3.2 Aquifers at the UIGFL

The UIGFL is underlain by the Wanapum Aquifer system composed from top to bottom of sediments of Bovill, basalt of the Lolo flow, and the Vantage. There are two distinct, water transmitting, basalt fracture zones (the E-fracture and the W-fracture in Figure 8) at the UIGFL (Li, 1991). These fractures are sub-horizontal cooling features much like the one shown in Figure 6. Li (1991) distinguished the E-fracture zone as dipping less than 10 degrees to the west and located in the northeast portion of the field lab. The E-fracture aquifer is approximately 0.5 to 3 feet thick, most likely filled with clay, located at a depth of 64 to 79 feet below land surface, and is tapped by five wells; V16D, T16D, Q17D, Q16D, and S12D1 (Figure 2). Li (1991) characterized the “E-fracture aquifer" as being a confined system that yields between about one to 30 gallons per minute (gpm) depending on the pumping well.

The W-fracture zone, the stratigraphic equivalent to the E-fracture zone, is located in the western and southern area of the UIGFL. The "W-fracture aquifer" is tapped by four wells: D19D, J16D, U3D, and S12D2 (Figure 2). The aquifer exists at a depth of about 70 feet and has a thickness of 0.5 to 1.0 feet (Li, 1991). Li (1991) characterized the "W-fracture aquifer" as a confined system that yields about one to 60 gpm. Wells UI #7 and UI #5 at the Aquaculture Research Site penetrate what is thought to be the W-fracture. Additionally, rapid water level declines were noted in several W-fracture wells at the UIGFL during the drilling and development of wells UI #6 and UI #7 (Kopp, 1994). The horizontal and vertical orientations of the "E-fracture aquifer" and the "W-fracture aquifer" are illustrated in Figure 8 and Figure 9. Wells Q16D and Q17D are completed in both the "E-fracture aquifer" and the "W-fracture aquifer (Figure 9)."

These two fracture zones are differentiated by water level elevations, hydraulic responses, microbiology, and water chemistry (Li, 1991; Zheng, 1992). Zheng (1992) distinguished different microbial communities and geochemical composition between the two aquifers; microbes in the "E-fracture aquifer" utilized more substrate than those in the "W-fracture aquifer." In addition, the ammonia and nitrate ratios differed between aquifers.

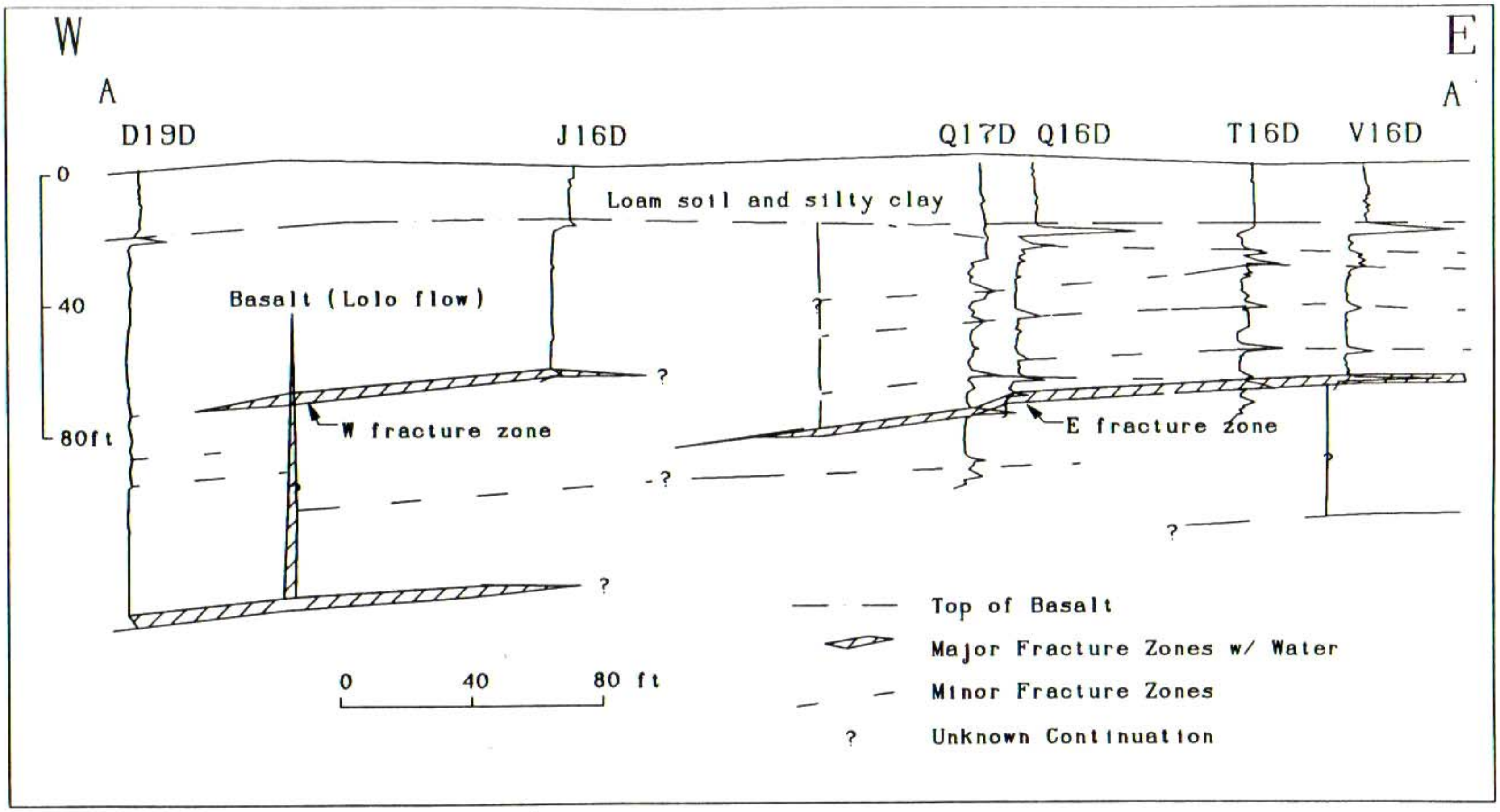


Figure 8. Geologic Cross-Section Between Wells D19D and V16D at the UIGFL (after Li, 1991).
See Figure 2 for location of the cross-section.

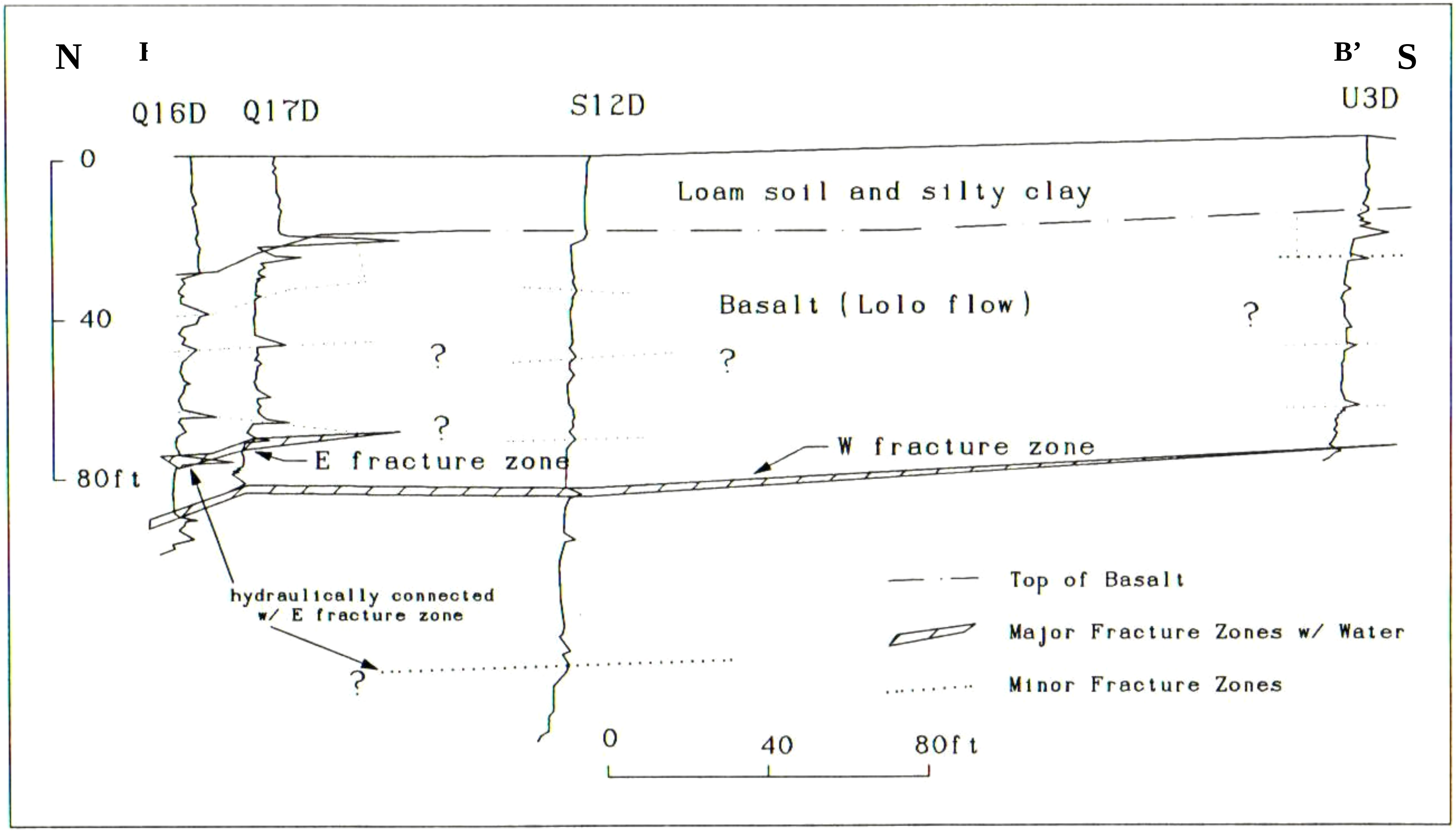


Figure 9. Geologic Cross-Section Between Wells Q16D, Q17D, S12D2 and U3D at the UIGFL (after Li, 1991). See Figure 2 for location of the cross-section.

Li (1991) and Pardo (1993) observed a distinct hydraulic connection between the sediments of Bovill, the E-fracture, and Paradise Creek. Leakage into the E-fracture aquifer is primarily through vertical joints and fractures in the basalt (Kopp, 1994). Water levels in the E-fracture respond to fluctuations in Paradise Creek; however, the W-fracture zone and Paradise Creek appear to be poorly connected. A slight hydraulic connection between the W-fracture aquifer and the Vantage was observed during pumping of Aquaculture Research Facility wells (Kopp, 1994). Leakage between the W-fracture aquifer and the Vantage occurs through vertical fractures and columnar joints (Kopp, 1994). Table 1 illustrates the completion schedules for the wells monitored during this investigation.

Table 1. Well Completion Schedules for Wells Monitored During Aquifer Tests at the UIGFL (Li, 1991).

Well	Depth	Well Screen
V16D	70 ft	65-67.5 ft
V16S	10 ft	10 ft
T16D	80 ft	65-69 ft
Q17D	100 ft	76-79 ft
Q16S	40 ft	26-27 ft
INEL-D	205 ft	192-202 ft
D19D	140 ft	137-139 ft
S12D2	146 ft	65-74 ft
Bovill 1	8.5 ft	1 ft *
Bovill 2	8.5 ft	1 ft *
Bovill 3	8.5 ft	1 ft *

* Hacksaw slots approximately every inch.

CHAPTER 3
ANALYSIS OF WATER DATA FOR THE WANAPUM AQUIFER SYSTEM FOR THE YEAR 2006

3.1 Introduction

Groundwater levels and groundwater temperatures are recorded by submersible, programmable, Solinst Leveloggers™ [data loggers] (Figure 10). The Solinst Leveloggers™ used for this investigation had a depth range of 15 ft to 30 ft, depth accuracy of 0.1% net FS, and a depth resolution of 0.02 % FS as well as a temperature range of –20 degrees Celsius to +80 degrees Celsius, temperature accuracy of ± 0.1 degree Celsius, and a temperature resolution of 0.01 degree Celsius. Data collection was on one (1) hour intervals and required four (4) downloads per year.

Figure 10. Solinst Levelogger™ Gold Model 3001. Leveloggers used in this investigation were one generation older than the one shown here and were silver in color.

All data collected for Wanapum Aquifer system monitoring wells in 2006 are presented as graphs in the following sections. Qualitative descriptions are presented for groundwater levels and groundwater temperatures separately for each well. Wells exhibiting similar seasonal fluctuations in groundwater levels and groundwater temperatures are then compared (section 3.3). All groundwater levels presented in this thesis are raw uncorrected values. Raw data and groundwater levels corrected for barometric effects are presented in Appendix A.

3.2 Data Fluctuations and Discrepancies

Data discrepancies including breaks and shifts in the data structure are visible in the plots of groundwater levels and groundwater temperatures. These discrepancies are attributed to downloading errors, timing of depth-to-water (dtw) measurements relative to the data-logger readings, and the pumping schedule for each well relative to downloading and resetting the data logger for subsequent depth-to-water measurements. Data loggers were downloaded and reprogrammed to start at the top of the next hour. Water levels in the wells can change dramatically due to pumping over the one-hour period between water level measurements. Data logger measurements recorded up to one hour after the last hand measurement (Figure 11) prior to data logger deployment may result in an offset in the plotted data. Similarly the depth-to-water measurements (hand measurements) may have been recorded up to one hour after the last data-logger recording. Timing of water level measurements relative to rapid drawdown and/or recovery in each well also may contribute to data discrepancies.

The majority of Wanapum Aquifer system monitoring wells display seasonal water elevation fluctuations; higher water levels exist in the winter and spring, and lower water levels exist in the summer and fall. Wells with distinct seasonal fluctuations include the Whitman County Shop (WCS), TuckBurns, Shumway, Sweet Avenue Site 2 (SAS2), Sweet Avenue Site 1 (SAS1), McMurray, Carson, Brandt, Appaloosa Horse Club (A.H.C), INEL-D and D19D.

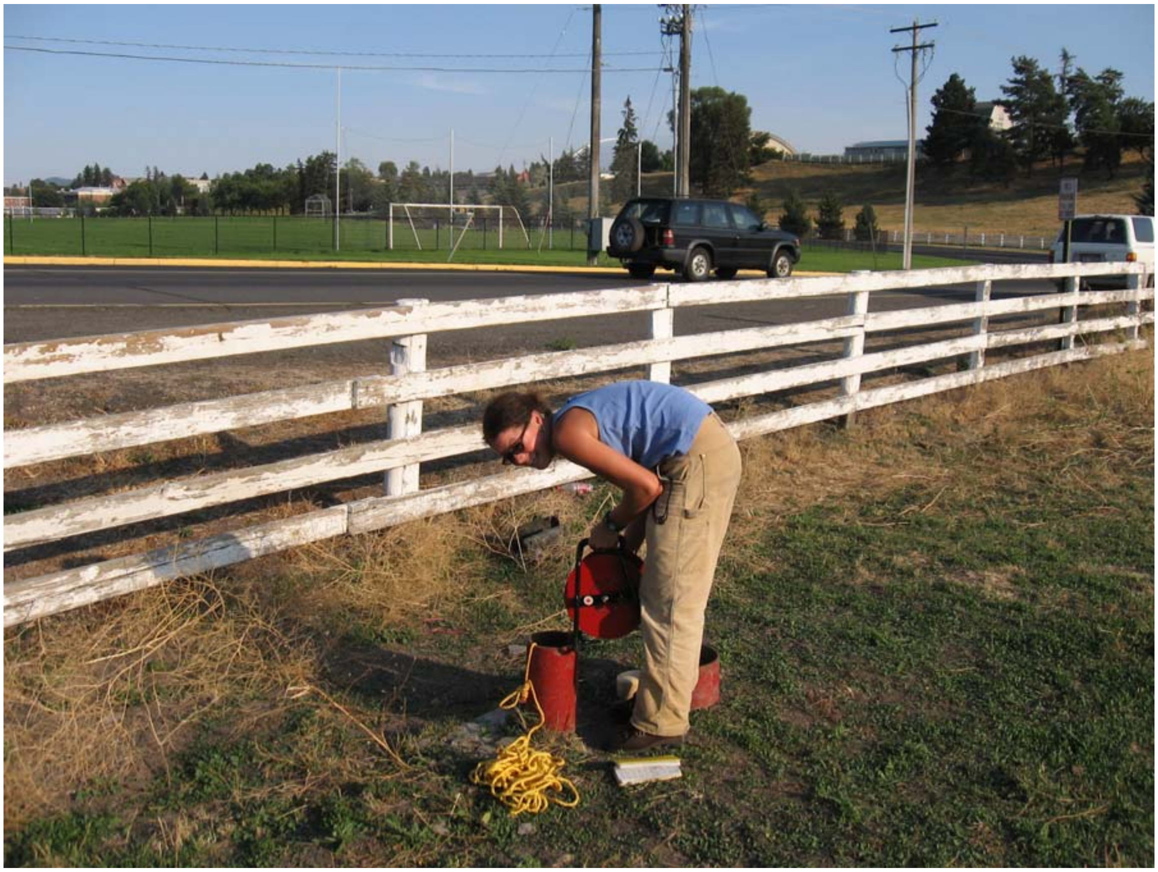


Figure 11. Hand Measurement of Depth to Water in well V16D at the UIGFL with an electronic water level tape measure (etape).

Much of the water level record for the Elliott well is corrupted because the data logger was consistently submerged deeper than its measurement capabilities. The Stalnaker, Palouse Clearwater Environmental Institute (PCEI), and Moscow Cemetery wells exhibit more attenuated seasonal fluctuations compared to the other wells. Water levels in the Bond well were very dynamic during the seven-month monitoring period. The Bond well is known to respond to pumping of Moscow Well #2 (Badon, 2007).

Water temperature measurements were recorded in 12 of the Wanapum Aquifer system monitoring wells. Wells with water temperature data include the TuckBurns, D19D, INEL-D, Shumway, SAS1, SAS2, McMurray, Carson, Brandt, Bond, Elliott, and

Moscow Cemetery. Wells exhibiting seasonal water temperature fluctuations include the TuckBurns, Shumway, SAS1, SAS2, McMurray, Carson, and Elliott. Wells with very little to no seasonal water temperature fluctuations include D19D, INEL-D, Brandt, Bond, and Moscow Cemetery. Water temperature data were evaluated for seasonal trends.

Considerable noise exists in the records of groundwater levels and groundwater temperatures, and the magnitude of fluctuations varies substantially between wells. The noise may be attributed to proximity to major pumping wells, the number of times the pump in the monitored well was turned on and off, potential for the pump in the monitoring well to heat up, barometric effects, tidal effects, or seasonal fluxes. The large amount of noise in the data records limits the use of direct cross-correlation for inter-well analyses. Additionally, the noise requires significant filtering. Wells with considerable noise include Elliott, Stalnaker, Whitman County Shop, TuckBurns, Shumway, Carson, and Appaloosa Horse Club. Wells exhibiting minimal noise include D19D, INEL-D, Moscow Cemetery, PCEI, SAS1, SAS2, McMurray, Brandt, and Bond. All groundwater level elevation data, raw and corrected, and groundwater temperature data for monitoring wells in the Wanapum Aquifer system are presented in Appendix A.

3.3 Wanapum Aquifer System Groundwater Level and Groundwater Temperature Database

3.3.1 Whitman County Shop Well

Figure 12 presents an arithmetic plot of water level elevations versus measurement date for the Whitman County Shop well. The plot illustrates the seasonal and intra-seasonal groundwater level fluctuations observed in the Whitman County Shop well. Groundwater elevations were higher in the winter and spring, lower in the summer and fall.

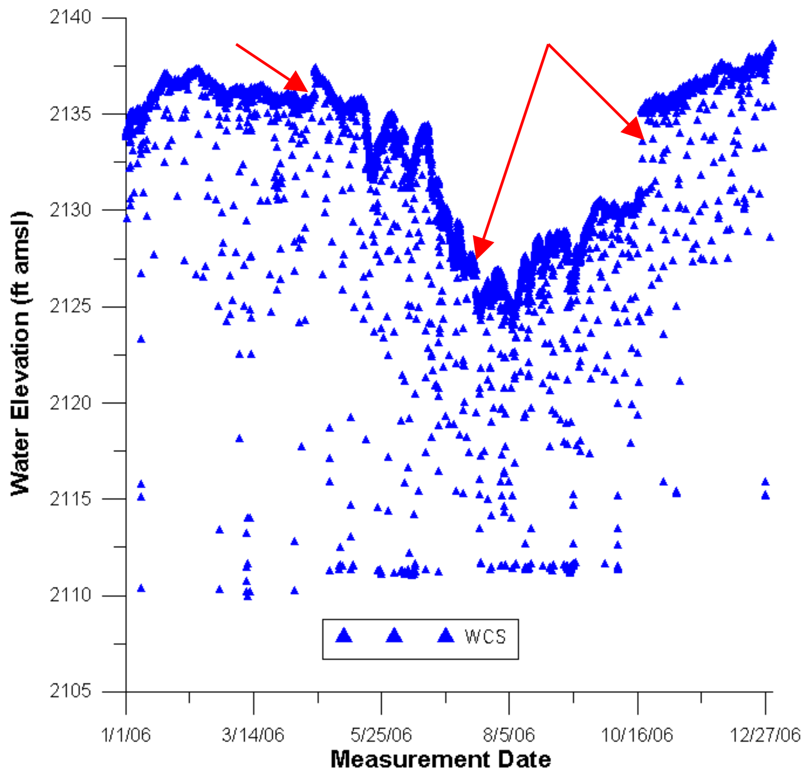


Figure 12. Groundwater Level Elevations for the Whitman County Shop Well.

The three distinct breaks in data structure (delineated by the red arrows) are attributed to downloading errors when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not thought to be real and the data should be shifted downward relative to the baseline data for 1/1/2006 to 4/17/2006. Data logger 05070, used for the year 2006, was replaced on 1/24/2007 with data logger 33753, a newer data logger that records water temperature as well as water level. No well log could be found for the WCS well. Table 2 presents the depth to water measurements and groundwater level elevations during downloading periods for the Whitman County Shop well.

Table 2. Depth to Water and Water Level Elevations During Downloading Periods for the Whitman County Shop Well.				
Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/18/2006	Download 1/24/2007
Whitman County Shop	DTW 44.95 ft BTOC	DTW 54.12 ft BTOC	DTW 50.14 ft BTOC	DTW 46.26 ft BTOC
Water Level Elevation	2136.12 ft amsl	2126.95 ft amsl	2130.93 ft amsl	2134.81 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.2 TuckBurnsWell

Figure 13 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the TuckBurns well. Groundwater elevations were higher in the winter and spring, lower in the summer and fall. Smaller intra-seasonal water level fluctuations are also noticeable. Groundwater level fluctuations observed in the TuckBurns well were similar to those in the Shumway well and may reflect a possible hydraulic connection. The groundwater temperatures in the TuckBurns well rose gradually over the monitoring period. Smaller temperature fluctuations are visible and are attributed to the pump in the well. The groundwater temperatures ranged from 10.7 °C to 11.51 °C. The four distinct breaks in data structure (delineated by red arrows) are attributed to downloading errors when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not thought to be real and the data should be shifted upwards relative to the background data from 1/1/2006 to 4/17/2006. The TuckBurns data logger number is 54708.

The TuckBurns well was completed in 1995 to a depth of 160 ft in Wanapum basalt. The well has an 8 in diameter steel casing from 2 ft above ground surface (ags) to

130 ft below ground surface (bgs). The well is a open hole from 130 ft bgs to 160 ft bgs. At the time of drilling, the yield was approximately 35 gpm and the static water level was at 80 ft bgs. An interesting fact is that the TuckBurns well was completed in basalt to a depth of 160 feet whereas the Shumway well was completed in granite to a depth of 129 ft. The similar groundwater level trends in the two wells and higher head in the Shumway well suggests that water may flow from the granite to the basalt. Table 3 presents the depth to water measurements and water level elevations during downloading periods for the TuckBurns well.

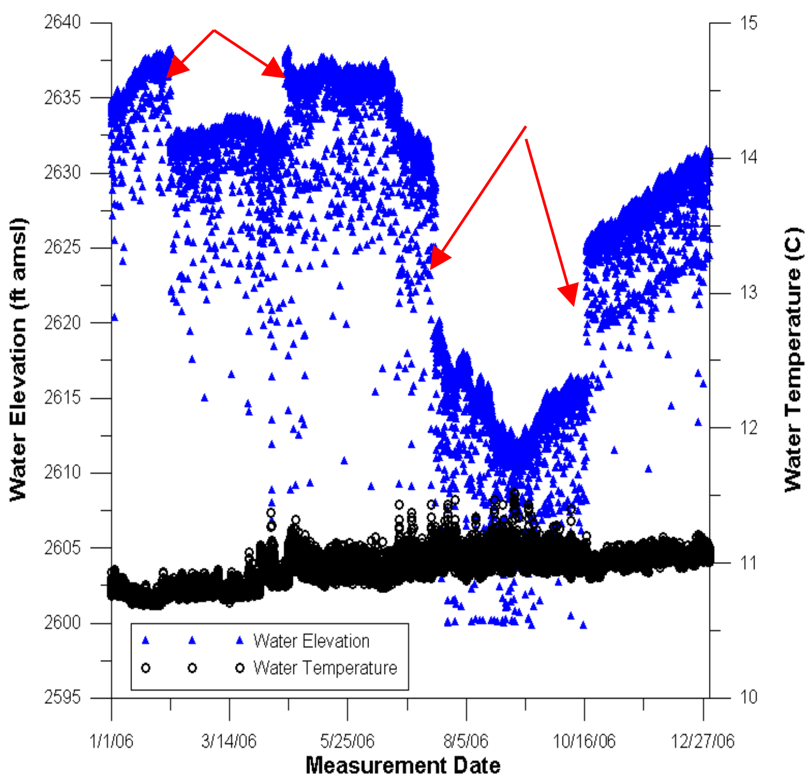


Figure 13. Groundwater Elevations and Temperatures for the TuckBurns Well.

Table 3. Depth to Water and Water Level Elevations During Downloading Periods for the TuckBurns Well.				
Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/26/2007
TuckBurns	DTW 37.1 ft BTOC	DTW 42.64 ft BTOC	DTW 53.62 ft BTOC	DTW 36.7 ft BTOC
Water Level Elevation	2632.8 ft amsl	2627.26 ft amsl	2616.28 ft amsl	2633.2 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.3 Shumway Well

Figure 14 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the Shumway well. Groundwater elevations were higher in the winter and spring, lower in the summer and fall. Smaller intra-seasonal groundwater level fluctuations are also noticeable. The groundwater temperatures ranged from 9.3 °C to 10.47 °C. The groundwater temperatures declined from 1/1/2006 to 6/23/2006 and then began to rise. The four distinct breaks in data structure (delineated by red arrows) are attributed to downloading errors when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not thought to be real and the data should be shifted upward relative to the baseline data from 1/1/2006 to 4/17/2006. The Shumway data logger number is 54686.

The Shumway well was completed in 1988 to a depth of 129 ft in granite. The well has 8 in diameter steel casing from 1 ft ags to 20 ft bgs. The well is a open hole from 20 ft bgs to 129 ft bgs. At the time of drilling, the yield was approximately 4 gpm with a static water level at 20 ft bgs. Table 4 presents the depth to water measurements and groundwater level elevations during downloading periods for the Shumway well.

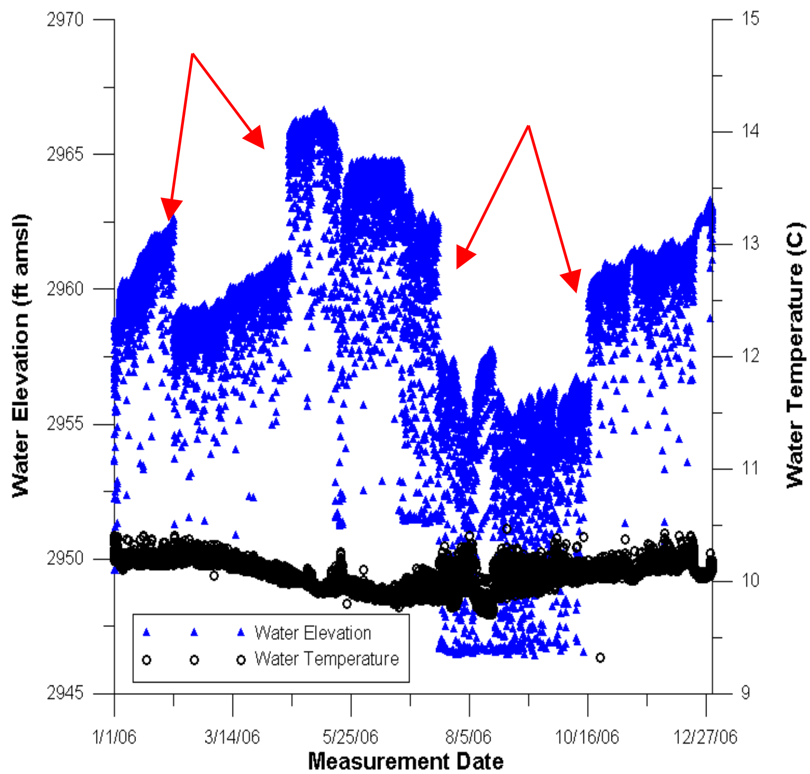


Figure 14. Groundwater Level Elevations and Temperatures for the Shumway Well.

Table 4. Depth to Water and Groundwater Level Elevations During Downloading Periods for the Shumway Well.				
Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/26/2007
Shumway	DTW 31.74 ft BTOC	DTW 30.82 ft BTOC	DTW 37.1 ft BTOC	DTW 27.2 ft BTOC
Water Level Elevation	2958.96 ft amsl	2959.88 ft amsl	2953.6 ft amsl	2963.5 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.4 SAS1 Well

Figure 15 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the SAS1 well. The plot illustrates the seasonal and intra-seasonal groundwater levels and seasonal groundwater temperatures observed in the SAS1 well. Groundwater temperatures in the SAS1 well ranged from 11.33 °C to 12.36 °C. The groundwater temperatures declined from 1/1/2006 to 9/29/2006 and then began to rise. A 31 ft head difference over a vertical distance of 23 ft (well completion depth difference) between SAS1 and SAS2 suggests that an unsaturated zone existed between the two wells. Water moves from Paradise Creek downward into the Lolo basalt at the Sweet Avenue Site. Visible breaks in the dataset structure (delineated by red arrows) are due to downloading errors when the data logger was removed from the well and reset. The offsets are not thought to be real and the data should be shifted downwards relative to the background data from 4/13/2006 to 5/1/2006. Table 5 presents the depth to water measurements and water level elevations during downloading periods for the SAS1 well.

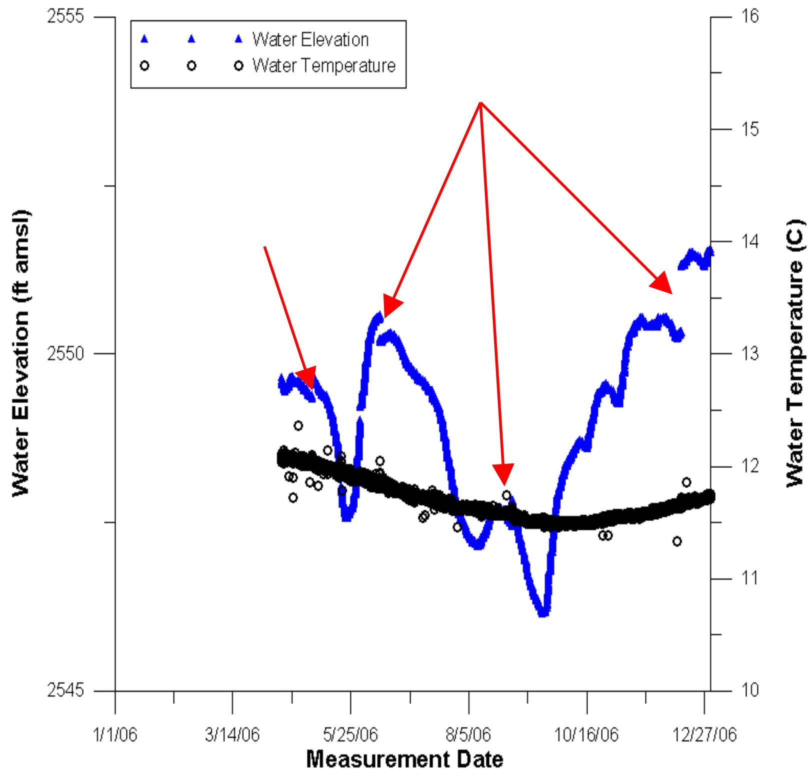


Figure 15. Groundwater Level Elevations and Temperatures for the SAS1 Well.

Table 5. Depth to Water and Water Level Elevations During Downloading for SAS1 Well.

Site ID	Download 4/13/2006	Download 5/1/2006	Download 5/19/2006	Download 5/31/2006	Download 6/12/2006
SAS1	DTW 23.2 ft BTOC	DTW 23.65 ft BTOC	DTW 24.8 ft BTOC	DTW 24 ft BTOC	DTW 22.45 ft BTOC
Water Level Elevation	2549.8 ft amsl	2549.3 ft amsl	2548.2 ft amsl	2549 ft amsl	2550.5 ft amsl
Site ID	Download 7/14/2006	Download 8/31/2006	Download 12/13/2006	Download 3/30/2007	
SAS1	DTW 23.6 ft BTOC	DTW 25.56 ft BTOC	DTW 22.67 ft BTOC	DTW 21.34 ft BTOC	
Water Level Elevation	2549.4 ft amsl	2547.4 ft amsl	2550.3 ft amsl	2551.6 ft amsl	

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.5 SAS2 Well

Figure 16 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the SAS2 well. The plot illustrates the seasonal and intra-seasonal groundwater levels and seasonal groundwater temperatures recorded in the SAS2 well. Groundwater level fluctuations in the SAS2 well were similar to those in the SAS1 well and may reflect hydraulic connection between the two wells. The SAS1 well is completed to a depth of 38 ft in basalt, and the SAS2 well is completed to a depth of 15.5 ft in clayey silt; well SAS2 is located in the Paradise Creek channel. The groundwater temperatures in SAS2 ranged from 6.44 °C to 14.42 °C. Groundwater temperatures in the SAS2 well rose considerably from 1/1/2006 to 8/13/2006 and then began to decline. Visible breaks in the dataset structure (delineated by red arrows) are due to downloading errors when the data logger was removed from the well and reset.

The offsets are not thought to be real and the data should be shifted upwards relative to the background data for the period 4/13/2006 to 5/1/2006. Table 6 presents the depth to water measurements and groundwater level elevations during downloading periods for the SAS2 well.

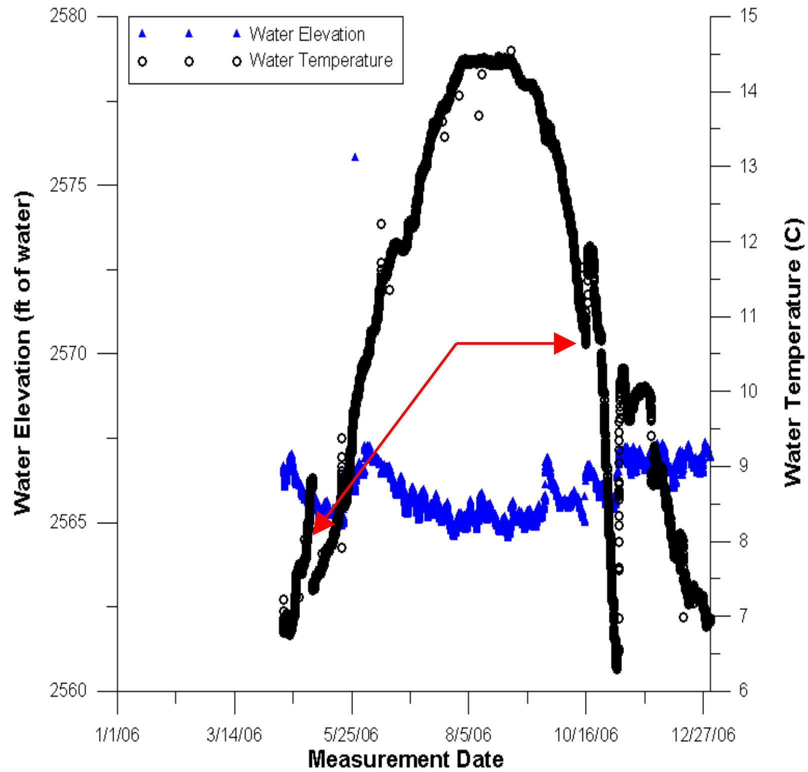


Figure 16. Groundwater Level Elevations and Temperatures for the SAS2 Well.

Table 6. Depth to Water and Water Level Elevations During Downloading for SAS2 Well.

Site ID	Download 4/13/2006	Download 5/1/2006	Download 5/19/2006	Download 5/31/2006	Download 6/12/2006
SAS2	DTW 1.3 ft BTOC	DTW 2.65 ft BTOC	DTW 2.87 ft BTOC	DTW 1.62 ft BTOC	DTW 1.3 ft BTOC
Water Level Elevation	2566.7 ft amsl	2565.3 ft amsl	2565.1 ft amsl	2566.3 ft amsl	2566.7 ft amsl
Site ID	Download 7/14/2006	Download 8/31/2006	Download 12/13/2006	Download 3/30/2007	
SAS2	DTW 2.65 ft BTOC	DTW 3.12 ft BTOC	DTW 0.91 ft BTOC	DTW 1.81 ft BTOC	
Water Level Elevation	2565.3 ft amsl	2564.8 ft amsl	2567 ft amsl	2566.1 ft amsl	

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.6 McMurray Well

Figure 17 provides an arithmetic plot of groundwater level elevations and temperatures versus measurement date for the McMurray well. The plot illustrates the groundwater levels and groundwater temperatures recorded during the winter and summer seasons, and smaller intra-seasonal fluctuations in groundwater levels and groundwater temperatures observed in the McMurray well. The water level peaked in February and declined to a low in September. The water temperatures in the McMurray well ranged from 10.1 °C to 11.2 °C. The water temperatures rose slightly from 1/1/2006 to 6/6/2006 before beginning to decline. No major breaks exist in the dataset structure. The McMurray data logger number is 33699. No well log for the McMurray well could be found. Table 7 presents the depth to water measurements and water level elevations during downloading periods for the McMurray well.

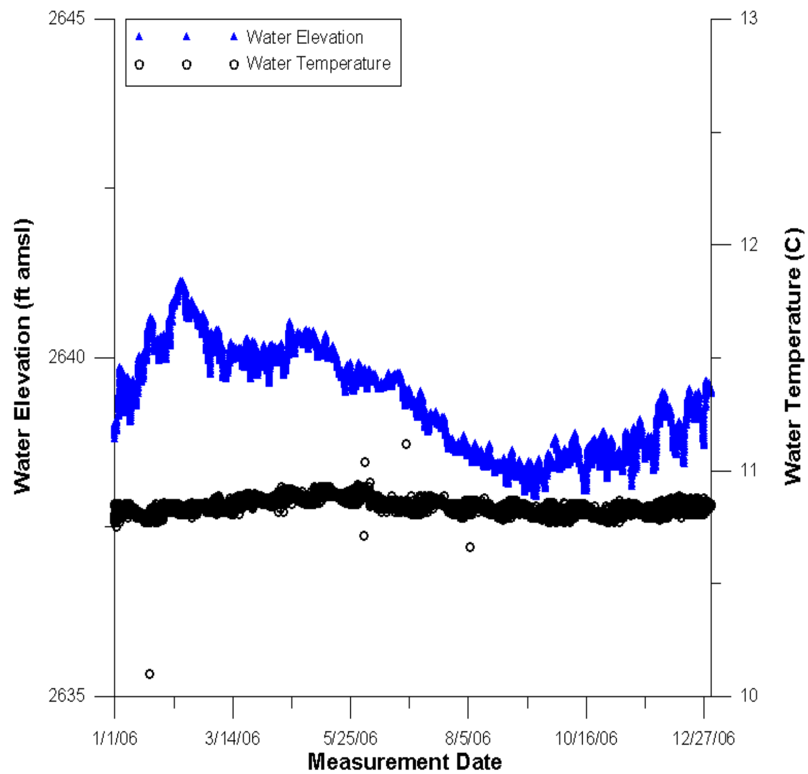


Figure 17. Groundwater Level Elevations and Temperatures for the McMurray Well.

Table 7. Depth to Water and Water Level Elevation During Downloading for the McMurray Well				
Site ID	Download 3/6/2006	Download 6/6/2006	Download 9/26/2006	Download 1/10/2007
McMurray	DTW 29.5 ft BTOC	DTW 29.9 ft BTOC	DTW 31.3 ft BTOC	DTW 30.2 ft BTOC
Water Level Elevation	2640.2 ft amsl	2639.8 ft amsl	2638.4 ft amsl	2639.5 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.7 Carson Well

Figure 18 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the Carson well. The plot illustrates the seasonal and intra-seasonal groundwater level and groundwater temperature fluctuations recorded in the Carson well. The groundwater levels rose from 1/1/2006 to 3/13/2006, declined dramatically at the end of June, then began to rise until the end of November before declining. The groundwater temperature in the Carson well ranged from 9.8 °C to 10.94 °C. No major breaks exist in the dataset structure. The Carson data logger number is 33724. No well log exists for the Carson well. However, according to owner Alan Carson, the well is completed in basalt to a depth of 120 ft. The well is cased with 8 in. diameter steel casing 0.7 ft ags to unknown depth below ground surface. At the time of drilling, basalt was located from 55 ft bgs to 120 ft bgs. The well is artesian and water overflows from the well the majority of the time. When water levels are greater than the casing collar (2609.4 ft amsl) water is overflowing from the well. Table 8 presents the depth to water measurements and groundwater level elevations during downloading periods for the Carson well.

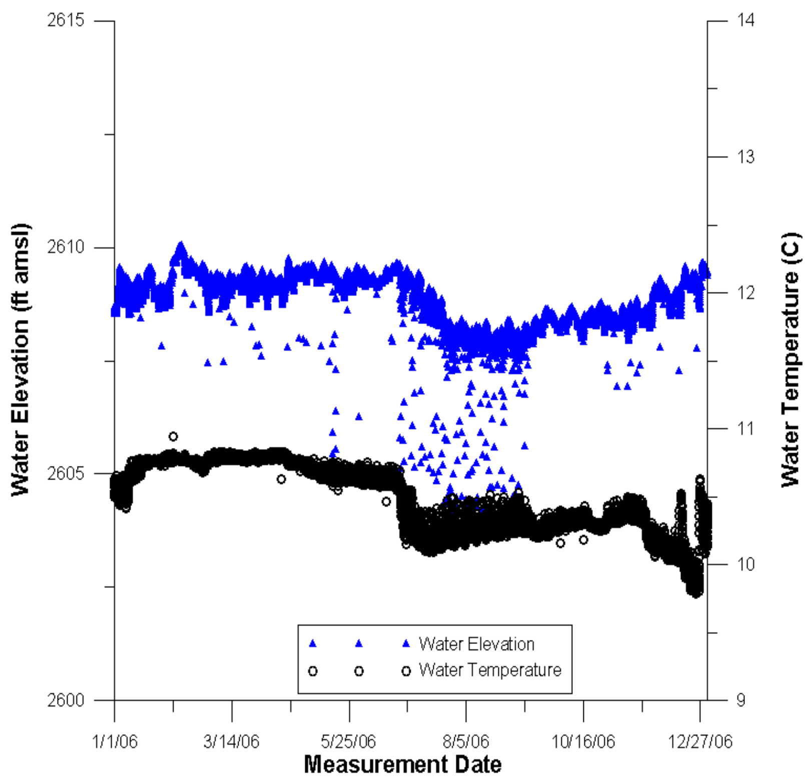


Figure 18. Groundwater Level Elevations and Temperatures for the Carson Well.

Table 8. Depth to Water and Water Level Elevation During Downloading for the Carson Well. Note the elevation of the casing collar is 2609.4 ft amsl. Therefore, water levels above this elevation are meaningless because the well is flowing during these times.				
Site ID	Download 4/17/2006	Download 7/18/2006	Download 10/18/2006	Download 1/22/2006
Carson	Water Flow Above TOC	DTW 0.6 ft BTOC	DTW 0.9 ft BTOC	Water Flow Above TOC
Water Level Elevation	2609.4 ft amsl	2608.8 ft amsl	2608.5 ft amsl	2609.4 ft amsl

DTW = Depth to water BTOC = below top of casing TOC = Top of Casing amsl = above mean sea level

3.3.8 Brandt Well

Figure 19 presents an arithmetic plot of water level elevation and temperature versus measurement date for the Brandt well. The plot clearly shows seasonal and intra-seasonal water level and seasonal temperature fluctuations observed.

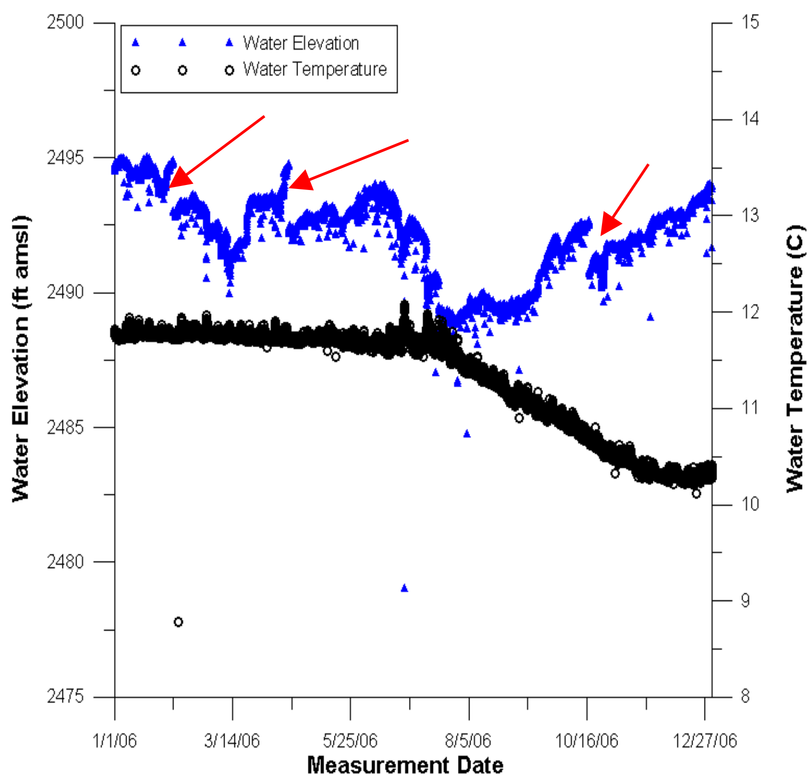


Figure 19. Groundwater Level Elevations and Temperatures for the Brandt Well.

The three distinct breaks in the data structure (delineated by red arrows) are due to downloading when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not thought to be real and the data should be shifted upwards relative to the baseline data. The Brandt data logger number is 39105.

The Brandt well was completed in 1990 to 153 ft in Wanapum basalt. The well was cased with 8 in. diameter steel casing from 1 ft ags to 119 ft bgs. The well is a open hole from 119 ft bgs to 153 ft bgs. At the time of drilling, the yield was 5 gpm with static water at 128 ft bgs. In 1994, the well was deepened to 279 ft. The well is now open hole from 119 ft bgs to 279 ft bgs. At the time of deepening in 1994, the yield was 25 gpm and the static water level was 135 ft bgs. Table 9 presents the depth to water measurements and groundwater level elevations during downloading periods for the Brandt well.

Table 9. Depth to Water and Groundwater Elevation During Downloading for the Brandt Well.

Site ID	Download 4/17/2006	Download 7/18/2006	Download 10/17/2006	Download 1/22/2006
Brandt	DTW 149.14 ft BTOC	DTW 153.45 ft BTOC	DTW 151.22 ft BTOC	DTW 150.57 ft BTOC
Water Level Elevation	2494.7 ft amsl	2490.4 ft amsl	2492.6 ft amsl	2493.32 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.9 Bond Well

Figure 20 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the Bond well. The plot illustrates the seasonal and intra-seasonal groundwater level fluctuations recorded. This well is potentially very important because it is near Paradise Creek and responds to pumping of Moscow 2; however, the data logger was removed on 7/12/2006 because the owner did not want to continue a relationship with the University of Idaho. Consequently, very little data exist to compare with records for wells SAS1 and SAS2. The two distinct breaks in water level data structure (distinguished by red arrows) are due to downloading errors when the data logger was removed from the well and reset. The offsets are not thought to be real and the data should be shifted downward relative to the background data. The Bond data logger number is 54736. No well log exists for the Bond well.

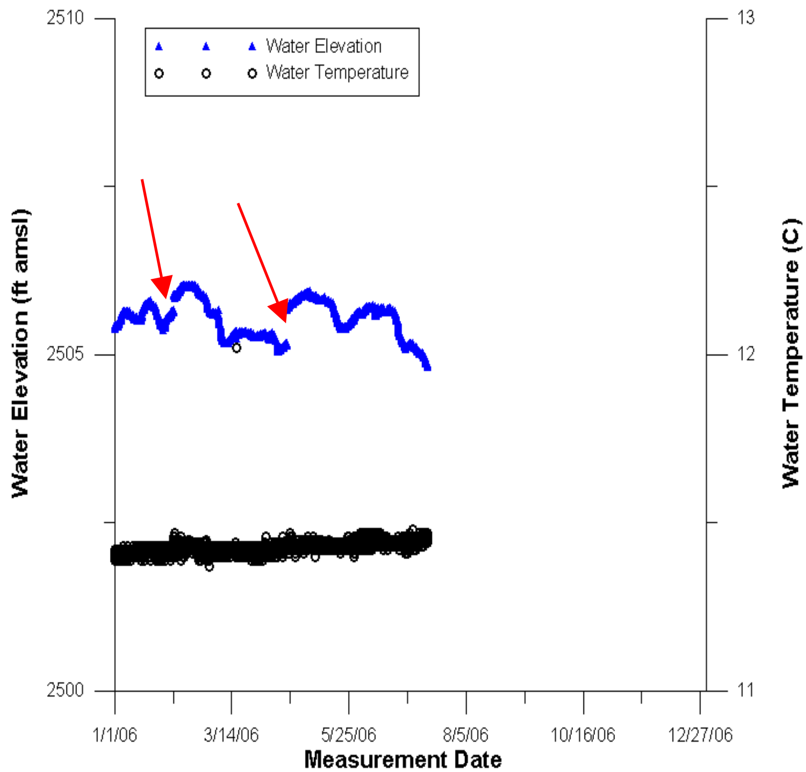


Figure 20. Groundwater Level Elevations and Temperatures for the Bond Well.

However, a video log shows the well to be a open hole in Wanapum basalt to a depth of at least 180 ft bgs Osiensky (2006). The top and bottom of the formation cannot be distinguished from the well video log and an obstruction prevented lowering of the camera beyond 180 ft bgs. Table 10 presents the depth to water measurements and groundwater level elevations during downloading periods for the Bond well.

Table 10. Depth to Water and Groundwater Level Elevations During Downloading for the Bond Well. Note the data logger was pulled on 7/12/2006.

Site ID	Download 4/17/2006	Download/Remove 7/12/2006
Bond	DTW 69.64 ft BTOC	DTW 69.98 ft BTOC
Water Level Elevation	2505.16 ft amsl	2504.82 ft amsl

DTW = Depth to water BTOC = below top of casing
amsl = above mean sea level

3.3.10 Appaloosa Horse Club (AHC) Well

Figure 21 presents an arithmetic plot of groundwater level elevations versus measurement date for the AHC well. The plot depicts seasonal and intra-seasonal groundwater level fluctuations observed in the AHC well. Fluctuations in groundwater level recorded in the AHC well were similar to those observed in the well D19D and well INEL-D. The three distinct breaks in the data structure (delineated by red arrows) are due to downloading errors when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not believed to be real and the data should be shifted downward relative to the baseline data. Data logger 04697, used for the year 2006, was replaced with data logger 64065 which records water temperature as well as water level on 1/24/2007.

The AHC well was completed to 214 ft bgs in Wanapum basalt. The well is cased with 8 in. diameter steel casing from 1 ft ags to 55 ft bgs. The well is a open hole from 55 ft bgs to 214 ft bgs. No information is available on the year of completion, yield, and static water level at the time of drilling. Table 11 presents the depth to water measurements and groundwater level elevations during downloading periods for the AHC well.

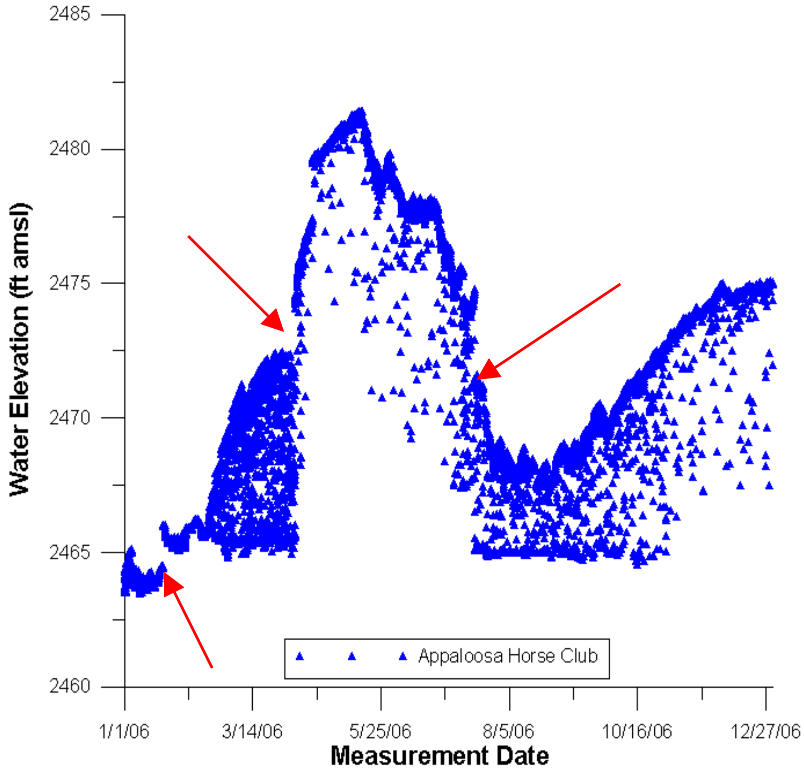


Figure 21. Groundwater Level Elevations for the AHC Well.

Table 11. Depth to Water and Water Level Elevations During Downloading for the AHC Well.

Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/24/2006
AHC	DTW 83.4 ft BTOC	DTW 89.6 ft BTOC	DTW 87.81 ft BTOC	DTW 83.72 ft BTOC
Water Level Elevation	2475.9 ft amsl	2469.7 ft amsl	2471.5 ft amsl	2475.6 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.11 Well INEL-D

Figure 22 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the well INEL-D. The plot depicts distinct seasonal and intra-seasonal groundwater level fluctuations observed in the INEL-D well. Groundwater temperatures in the well INEL-D were relatively constant during the monitoring period.

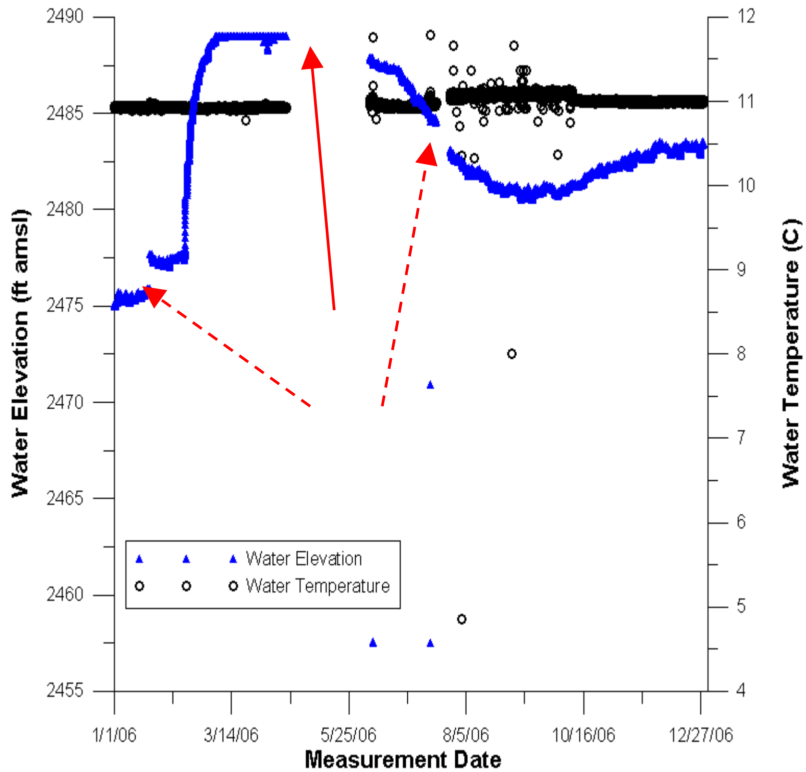


Figure 22. Groundwater Level Elevations and Temperatures for the Well INEL-D.

The groundwater temperatures ranged from 4.86 °C to 11.79 °C. The "flat" groundwater level elevations in the INEL-D dataset from 3/4/2006 to 4/17/2006 were caused by the data logger being submerged beyond recording capability. The INEL-D dataset from 4/17/2006 to 6/7/2006 is missing data due to accidental erasure (delineated by the solid red arrow). The two breaks in the dataset are attributed to downloading and resetting the data logger (delineated by dashed red arrows). The INEL-D data logger number is 54706.

The INEL-D well was completed in 1992 to a depth of 205 ft in sediments of the Vantage. Two casing liners exist in the borehole. INEL-D, the borehole monitored for this study, is completed 202 ft bgs. The well is cased with 8 in. diameter steel outer casing from 1.4 ft ags to 19 ft bgs, and 2 in. PVC liner from 1.4 ft ags to 192 ft bgs. The well is screened in eight feet of Wanapum basalt and two feet of the Vantage (screened interval from 192 ft bgs to 202 ft bgs). At the time of drilling, the yield was approximately 5 gpm, and the static water level was 55 ft bgs. Table 12 presents the depth to water measurements and groundwater level elevations during downloading periods for the well INEL-D.

Table 12. Depth to Water and Water Level Elevations During Downloading for the Well INEL-D.

Site ID	Download 4/17/2006	Download 6/7/2006	Download 6/9/2006	Download 7/12/2006	Download 7/18/2006	Download 7/26/2006
INEL-D	DTW 57.75 ft BTOC	DTW 58.85 ft BTOC	DTW 59.03 ft BTOC	DTW 61.7 ft BTOC	DTW 62.18 ft BTOC	DTW 63.49 ft BTOC
Water Level Elevation	2490.6 ft amsl	2489.5 ft amsl	2489.3 ft amsl	2486.67 ft amsl	2486.1 ft amsl	2484.8 ft amsl
Site ID	Download 8/9/2006	Download 8/23/2006	Download 9/5/2006	Download 9/22/2006	Download 10/9/2006	
INEL-D	DTW 64.83 ft BTOC	DTW 65.55 ft BTOC	DTW 65.7 ft BTOC	DTW 65.49 ft BTOC	DTW 65.34 ft BTOC	
Water Level Elevation	2483.5 ft amsl	2482.8 ft amsl	2482.6 ft amsl	2482.8 ft amsl	2483.03 ft amsl	

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.12 Well D19D

Figure 23 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the well D19D. The plot depicts seasonal and intra-seasonal water level fluctuations observed in the well D19D. The water temperatures in the D19D well ranged from 4.37 °C to 12.16 °C. No major breaks exist in the dataset structure. The D19D data logger number is 33750.

The well D19D was completed to a depth of 140 ft in Wanapum basalt. The well is cased with 6 in. diameter steel outer casing and a 4 in. diameter PVC inner casing from 2 ft ags to 135 bgs. The well is screened in Wanapum basalt from 135 ft bgs to 140 ft bgs. At the time of drilling, the yield was approximately 50 gpm. The well log does not indicate the year completed or a static water level. Table 13 presents the depth to water measurements and groundwater level elevations during downloading periods for the well D19D.

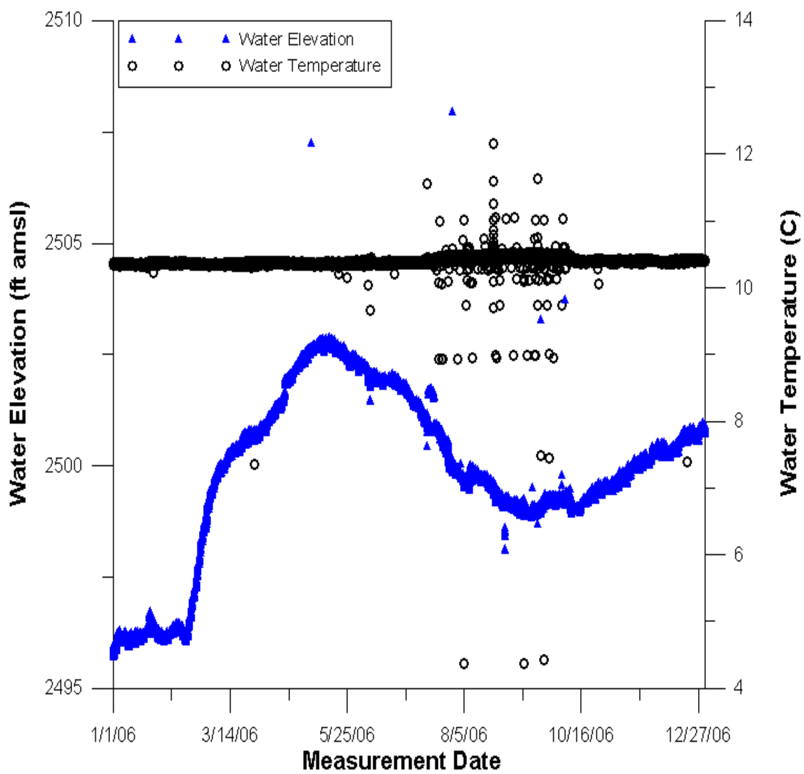


Figure 23. Groundwater Level Elevations and Temperatures for the Well D19D.

Table 13. Depth to Water and Water Level Elevations During Downloading for the Well D19D.

Site ID	Download 4/17/2006	Download 6/7/2006	Download 6/9/2006	Download 7/12/2006	Download 7/18/2006	Download 7/26/2006
D19D	DTW 42.38 ft BTOC	DTW 41.85 ft BTOC	DTW 42.05 ft BTOC	DTW 43 ft BTOC	DTW 42.43 ft BTOC	DTW 43.59 ft BTOC
Water Level Elevation	2503.6 ft amsl	2504.1 ft amsl	2503.9 ft amsl	2503 ft amsl	2503.5 ft amsl	2502.4 ft amsl
Site ID	Download 8/9/2006	Download 8/23/2006	Download 9/5/2006	Download 9/22/2006	Download 10/9/2006	Download 1/24/2006
D19D	DTW 44.28 ft BTOC	DTW 44.4 ft BTOC	DTW 44.83 ft BTOC	DTW 44.85 ft BTOC	DTW 44.61 ft BTOC	DTW 42.4 ft BTOC
Water Level Elevation	2501.7 ft amsl	2501.6 ft amsl	2501.1 ft amsl	2501.1 ft amsl	2501.3 ft amsl	2503.6 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.13 Elliott Well

Figure 24 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the Elliott well. Periods with "flat" water levels reflect times when the data logger was inadvertently over-submerged beyond the reading capabilities after downloading. Only pumping water levels were recorded. The water temperature in the Elliott well rose gradually over the monitoring period.

The three distinct breaks in data structure (delineated by red arrows) are attributed to downloading errors when the data logger was removed from the well and reset combined with active pumping within the well. The offsets are not thought to be real and the data should be shifted downward relative to the baseline data. The Elliott data logger number is 54708. No well log exists for the Elliott well. Table 13 presents the depth to water measurements and groundwater level elevations during downloading periods for the Elliott well.

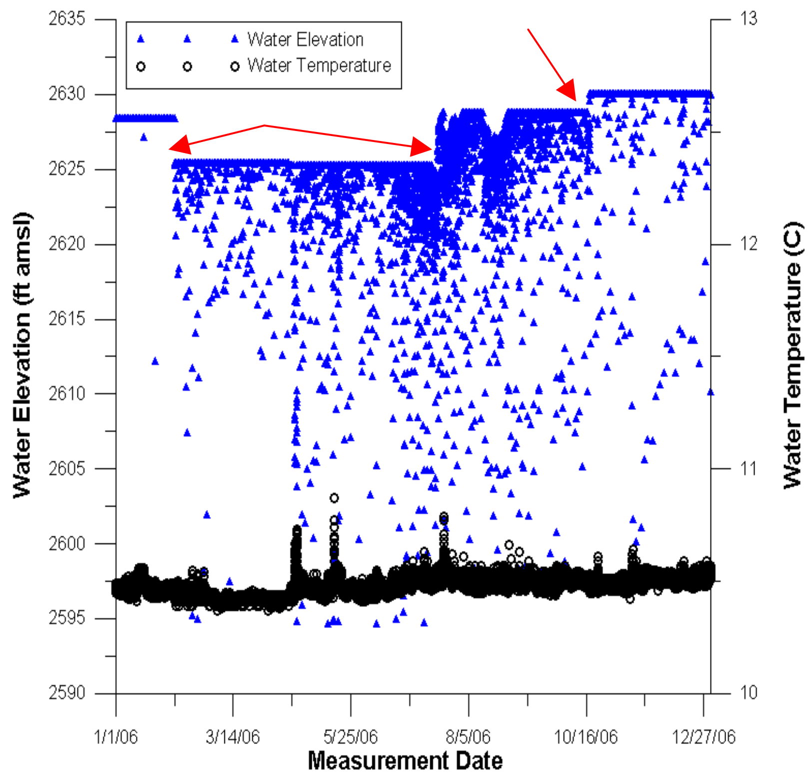


Figure 24. Groundwater Level Elevations and Temperatures for the Elliott Well.

Table 14. Depth to Water and Water Level Elevations During Downloading for the Elliott Well.				
Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/26/2006
Elliott	DTW 76.62 ft BTOC	DTW 80.85 ft BTOC	DTW 73.28 ft BTOC	DTW 71.99 ft BTOC
Water Level Elevation	2625.3 ft amsl	2621.1 ft amsl	2628.7 ft amsl	2630 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.14 Palouse Clearwater Environmental Institute (PCEI) Well

Figure 25 presents an arithmetic plot of groundwater level elevations versus measurement date for the PCEI well. The plot depicts seasonal groundwater level fluctuations in the PCEI well. The groundwater levels followed an overall downward trend. The three breaks in the PCEI data structure (delineated by red arrows) are due to downloading errors when the data logger was removed and reset. The offsets are not thought to be real and the second data segment should be shifted downward and the third data segment should be shifted upward relative to the baseline data. The PCEI data logger was 04704 for the year 2006; it was replaced with a newer data logger 54706 on 1/24/2007 that records water temperatures as well as water levels.

The PCEI well was completed in 2001 to a depth of 165 ft in Wanapum basalt. The well is cased with 8 in. diameter steel casing from 2 ft ags to 58 ft bgs. A 6 in. diameter PVC inner casing exists from 5 ft bgs to 165 ft bgs. The inner casing is perforated in basalt from 145 ft bgs to 165 ft bgs. At the time of drilling, the well yield was approximately 100 gpm, and the static water level was 55 ft bgs. Table 15 presents the depth to water measurements and groundwater level elevations during downloading periods for the PCEI well.

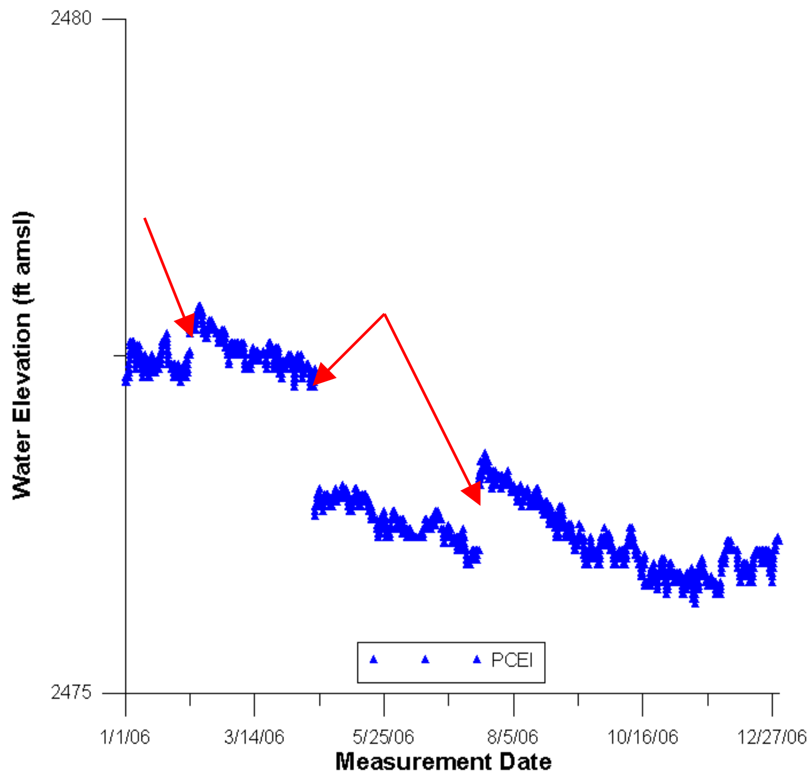


Figure 25. Groundwater Level Elevations for the PCEI Well.

Table 15. Depth to Water and Water Level Elevations During Downloading for the PCEI Well.

Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/24/2006
PCEI	DTW 122.6 ft BTOC	DTW 123.95 ft BTOC	DTW 123.98 ft BTOC	DTW 123.85 ft BTOC
Water Level Elevation	2477.4 ft amsl	2476 ft amsl	2476.02 ft amsl	2476.1 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.15 Moscow Cemetery Well

Figure 26 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for the Moscow Cemetery well. The plot depicts seasonal water level fluctuations and stable groundwater temperatures in the Moscow Cemetery well. An overall downward water level trend existed. No major breaks exist in the dataset structure. The Moscow Cemetery data logger is 43700.

The Moscow Cemetery well was drilled to a depth of 552 ft in granitic sand and completed to a depth of 508 ft bgs. The well is cased with 8 in. diameter steel casing from ground surface to 456 ft bgs and is screened in granitic sand from 456 ft bgs to 508 ft bgs. The well log does not specify yield or static water level at the time of drilling. Table 15 presents the depth to water measurements and groundwater level elevations during downloading periods for the Moscow Cemetery well.

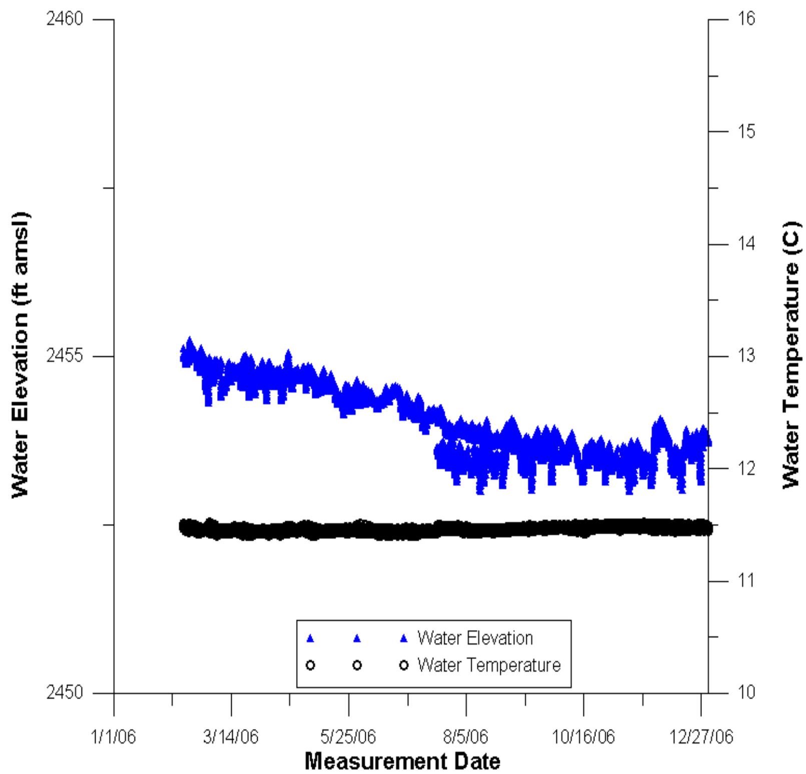


Figure 26. Groundwater Level Elevations and Temperatures for the Moscow Cemetery Well.

Table 16. Depth to Water and Water Level Elevations During Downloading for the Moscow Cemetery Well.				
Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/24/2006
Moscow Cemetery	DTW 156.63 ft BTOC	DTW 153.31 ft BTOC	DTW 153.82 ft BTOC	DTW 153.78 ft BTOC
Water Level Elevation	2450.8 ft amsl	2454.1 ft amsl	2453.6 ft amsl	2453.6 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.16 Stalnaker Well

Figure 27 presents an arithmetic plot of groundwater level elevations versus measurement date for the Stalnaker well. The plot depicts a generally declining water level trend throughout the year. One major break in the data structure (delineated by red arrow) exists due to downloading when the data logger was removed and reset.

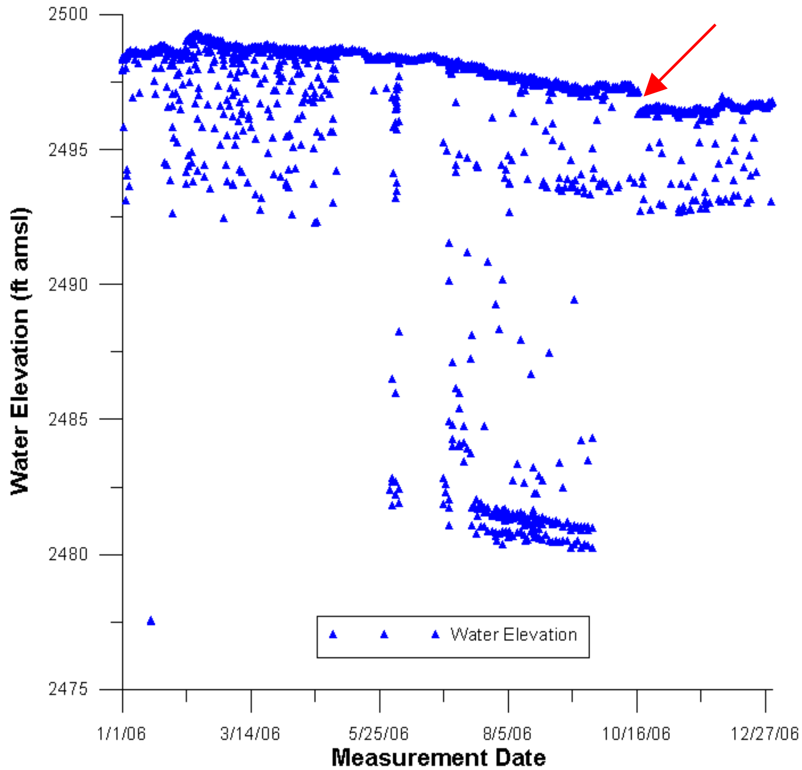


Figure 27. Groundwater Level Elevations for the Stalnaker Well.

The offset is not thought to be real and the data should be shifted upward relative to the baseline data.

The Stalnaker well was completed in 1991 to a depth of 229 ft in Wanapum basalt. The well is cased with 8 in. diameter steel casing from 1 ft ags to 68 ft bgs. The well is a open hole in basalt from 68 ft bgs to 229 ft bgs. At the time of drilling, the well yield was approximately 50 gpm, and the static water level was at 92 ft bgs. Table 16 presents the depth to water measurements and ground water level elevations during downloading periods for the Stalnaker well.

Table 17. Depth to Water and Water Level Elevations During Downloading for the Stalnaker Well.

Site ID	Download 4/17/2006	Download 7/17/2006	Download 10/17/2006	Download 1/26/2006
Stalnaker	DTW 108.86 ft BTOC	DTW 109.34 ft BTOC	DTW 110.27 ft BTOC	DTW 110.7 ft BTOC
Water Level Elevation	2498.5 ft amsl	2498 ft amsl	2497.1 ft amsl	2496.7 ft amsl

DTW = Depth to water BTOC = below top of casing amsl = above mean sea level

3.3.17 Paradise Creek Stage and Temperature

Figure 28 presents a plot of stream stage elevations versus measurement date for Paradise Creek. The plot depicts the seasonal and intra-seasonal fluctuations in stream stage elevation recorded at the USGS Paradise Creek gage station on Perimeter Drive (Figure 2). Streamflow decreased followed by a slow increase in mid-October through December 2006. Stream stage data from the USGS Paradise Creek gage station are presented in Appendix A.

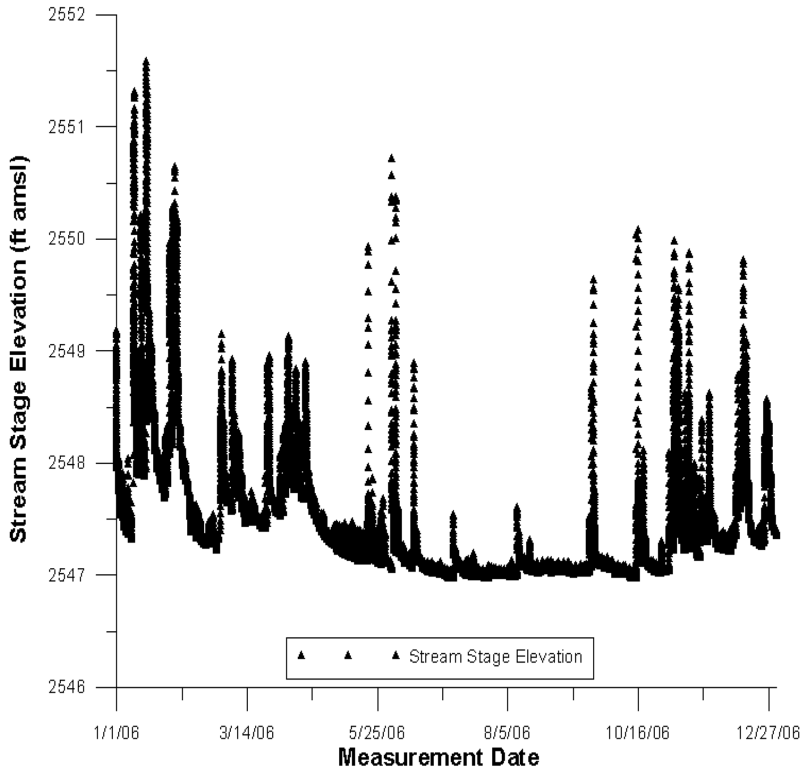


Figure 28. Stream Stage Elevations for Paradise Creek for 2006.

Dr. Jan Boll (UI Associate Professor) collected water temperature data for Paradise Creek at the MWWTP Site as part of his research. The MWWTP site consists of a stream monitoring station, and a Davis weather station. The stream monitoring station is located just upstream from the outlet of the city of Moscow wastewater treatment plant approximately 200 meters west of the UIGFL. Figure 29 presents an arithmetic plot of water temperature versus measurement date for Paradise Creek. Water temperature in Paradise Creek increased from 1/1/2006 to 5/25/2006 before decreasing. Some negative outliers with values of –6999 C are not shown due to scaling. These occurred on April 14, 2006 at 8:10 am; October 6, 11, 20, and 22, 2006 at 1 pm and 1:05 pm, 1:35 pm, 11:15 pm, and 9:15 am, respectively. Water temperature data for Paradise Creek are presented in Appendix A.

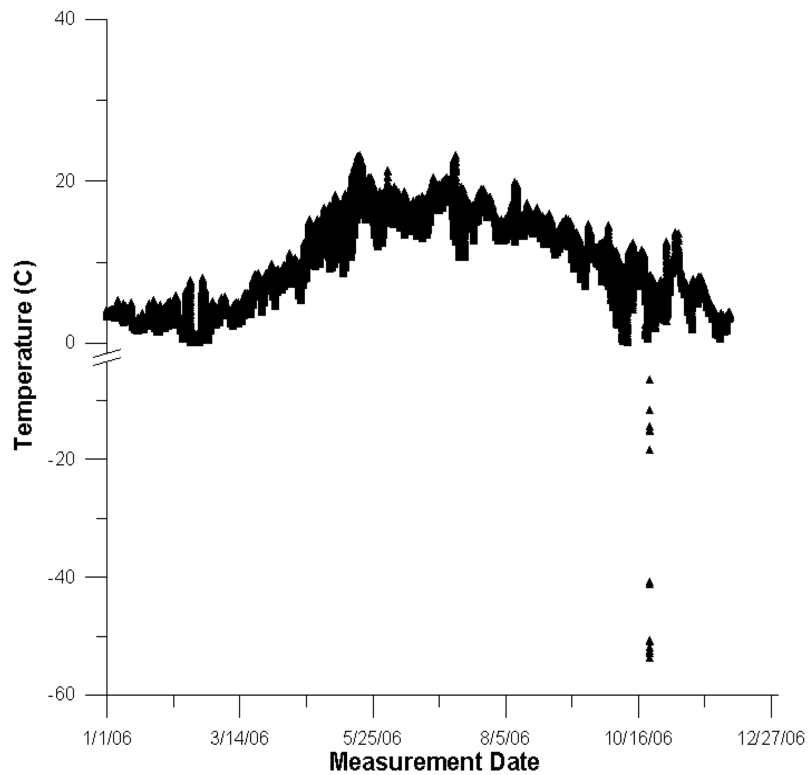


Figure 29. Water Temperatures for Paradise Creek in 2006.

3.4 UIGFL Water Level and Temperature Records

Eleven wells at the UIGFL were monitored for changes in groundwater levels and groundwater temperatures at various times from June 7, 2006 to November 11, 2006. The majority of the UIGFL monitoring wells displayed water level fluctuations. A qualitative analysis was performed on the water level records for the UIGFL monitoring wells. No barometric corrections were made. All raw groundwater levels and groundwater temperatures can be found in Appendix B. Well completion depths are displayed in Table 1.

3.4.1 Well S12D2

Figure 30 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus the measurement date for well S12D2 at the UIGFL.

The water level elevation in S12D2 was first measured at 2511.58 ft amsl. From July until September the water level declined to a low of 2508.95 ft amsl. Intra-seasonal fluctuations were minimal. The small downward projected spikes in water level are attributed to aquifer tests at the UIGFL on July 13, 2006; August 3, 2006; August 27, 2006. Water temperature in S12D2 was relatively constant during the monitoring period except for a spike that occurred on September 22, 2006; that spike in temperature is attributed to downloading and resetting of the data logger. The S12D2 data logger number is 54736.

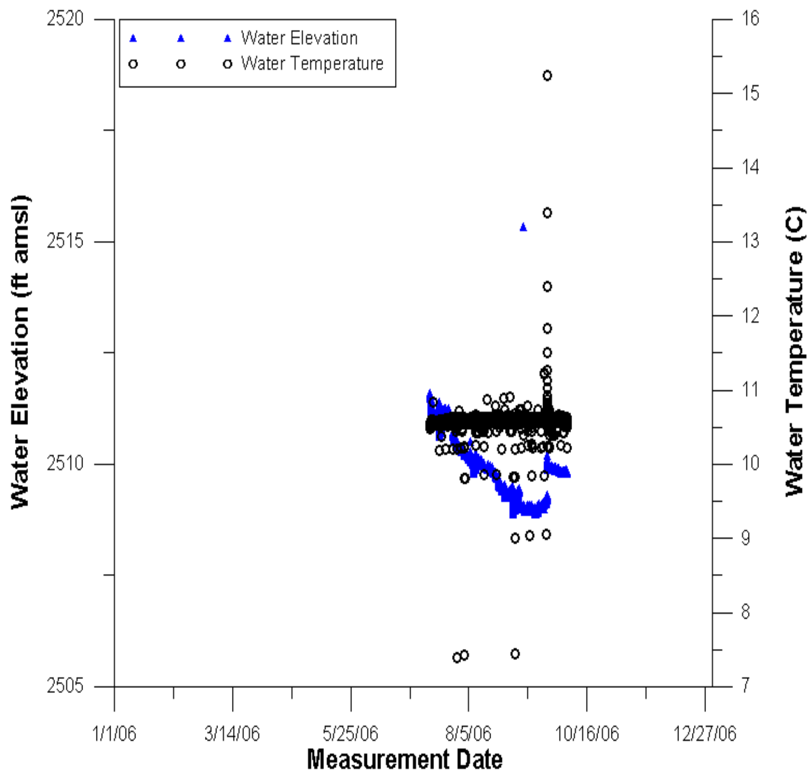


Figure 30. Groundwater Level Elevations and Temperatures for the S12D2 Well.

3.4.2 Well V16S

Figure 31 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well V16S at the UIGFL. The plot depicts two periods when groundwater levels and temperatures were monitored in V16S. During the first period, groundwater levels and temperatures were only monitored for six days and coincided with Aquifer Test #2. The second monitoring period coincided with aquifer tests conducted by the UI Geology 410 field techniques class. Aa rise in water temperatures occurred between the two monitoring periods. The V16S data logger number is 73116.

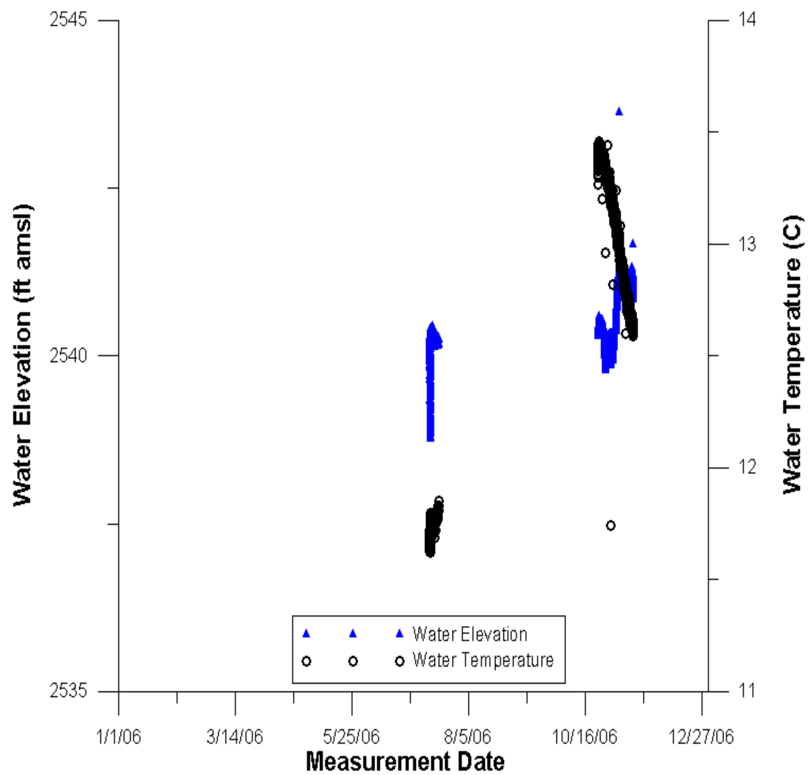


Figure 31. Groundwater Level Elevations and Temperatures for the V16S Well.

3.4.3 Well V16D

Figure 32 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well V16D at the UIGFL. The plot depicts two periods when groundwater levels and temperatures were monitored in V16D. During the first period, from 7/18/2006 to 10/9/2006, the water levels remained relatively constant though small inter-seasonal fluctuations are visible. The groundwater level elevation in V16D was first recorded at 2539.09 ft amsl. During the second period, water levels began to rise. The water level elevation was last recorded on November 15, 2006 at 2540.19 ft amsl. Downward projected spikes in the water level plot correlate with aquifer tests conducted at UIGFL on July 18, 2006; July 25, 2006; August 3, 2006; August 8, 2006; August 25, 2006; August 27, 2006; September 1, 2006, November 1, 2006; November 8, 2006; and November 11, 2006 as part of this thesis research. The groundwater temperature rose throughout the first monitoring period and declined during the second monitoring period. The upward projected spikes in water temperatures correlate with the data logger being removed and downloaded. The V16D data logger number is 73116.

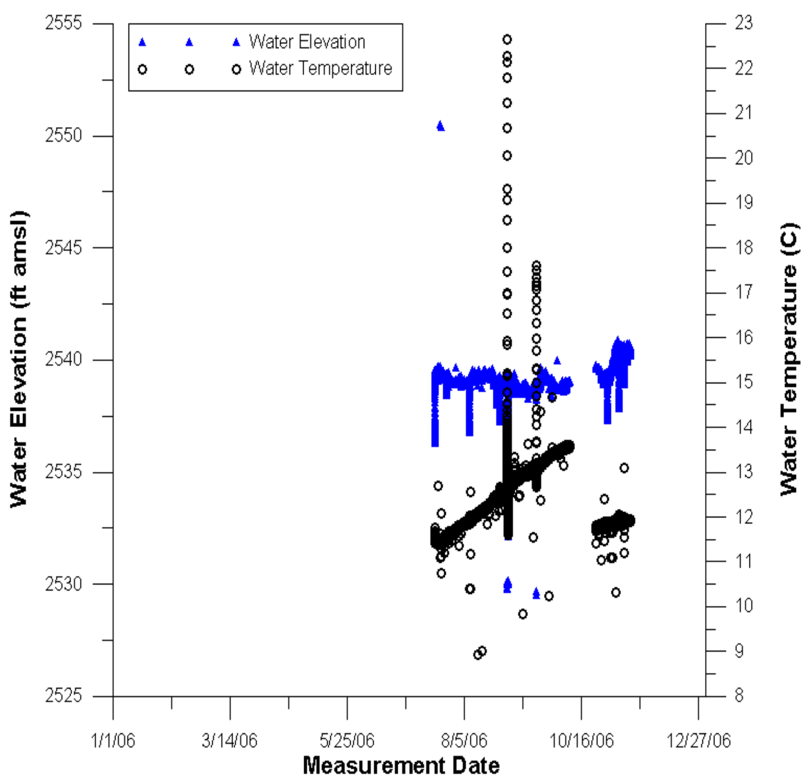


Figure 32. Groundwater Level Elevations and Temperatures for the Well V16D.

3.4.4 Well T16D

Figure 33 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well T16D at the UIGFL. The plot depicts a gradual decline in groundwater levels and a rise in groundwater temperatures during the monitoring period. The water level elevation in T16D was first recorded at 2540.55 ft amsl. The groundwater level was last recorded on October 9, 2006 at 2539.16 ft amsl. Intra-seasonal groundwater level and groundwater temperature fluctuations are minimal. Downward projected spikes in the water level data correlate with aquifer tests conducted at UIGFL on June 8, 2006; July 13, 2006; July 18, 2006; July 25, 2006; August 3, 2006; August 8, 2006; August 25, 2006; August 27, 2006; and September 1, 2006 as part of this thesis research.

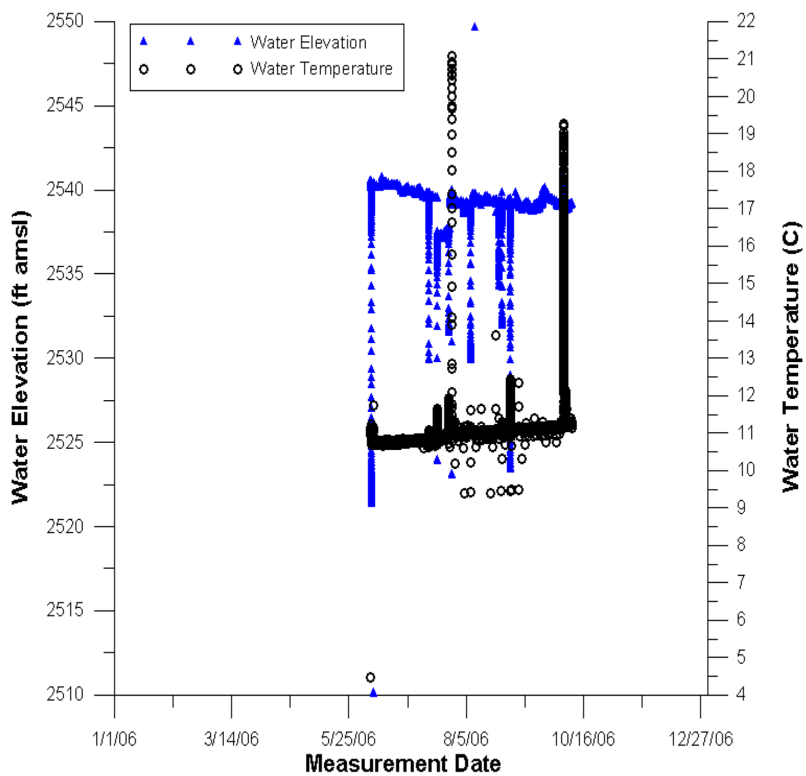


Figure 33. Groundwater Level Elevations and Temperatures for the Well T16D.

Groundwater temperature rose from 7/18/2006 to 10/9/2006. Comparatively, a decline in water temperatures occurred from 10/25/2006 to 11/15/2006. Upward projected spikes in groundwater temperatures correlate with downloading and resetting of the data logger. The break in data structure is attributed to errors when downloading and resetting the datalogger (distinguished by red arrow). The T16D data logger number is 71343.

3.4.5 Well Q17D

Figure 34 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well Q17D at the UIGFL. The plot depicts a subtle downward trend in water level from June until September, and an upward trend afterwards; a gradual upward trend in groundwater temperatures also occurred. The groundwater level elevation in Q17D was first recorded at 2539.87 ft amsl. The groundwater level elevation was last recorded on November 15, 2006 at 2539.89 ft amsl. Intra-seasonal fluctuations in water level are visible. Downward projected spikes in the water level data correlate with aquifer tests conducted at the UIGFL on July 13, 2006; July 18, 2006; July 25, 2006; August 3, 2006; August 8, 2006; August 25, 2006; August 27, 2006; September 1, 2006; November 1, 2006; November 8, 2006; and November 11, 2006. Upward projected spikes in groundwater temperatures are attributed to downloading and resetting of the data logger. The Q17D data logger number is 07458.

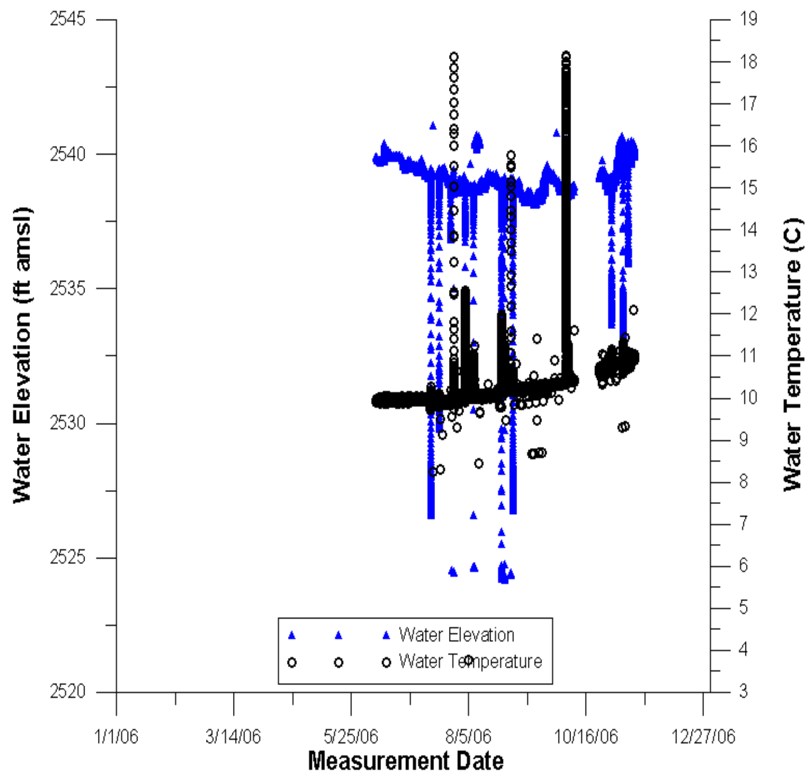


Figure 34. Groundwater Elevations and Temperature for the Q17D Well.

3.4.6 Well Q16S

Figure 35 presents an arithmetic plot of water level elevation and temperature versus measurement date for well Q16S at the UIGFL. The plot clearly depicts inter-seasonal water level fluctuations. The water level in Q16S was first recorded at 2539.05 ft amsl. Data were not recorded from June 7, 2006 to June 9, 2006; the data logger was reset and downloaded on July 12, 2006 only to discover that the data logger had been submerged too deep, so no measurements were recorded. The water level was last recorded on November 15, 2006 at 2539.63 ft amsl. Downward projected spikes in the water level data correlate with aquifer tests conducted at the UIGFL on July 13, 2006; July 18, 2006; August 8, 2006; August 25, 2006; August 27, 2006; and September 1, 2006. Water temperature in Q16S rises throughout the monitoring period. The upward projected spike on 9/22/2006 in water temperature corresponds with downloading and resetting the data logger. The Q16S data logger number is 54728.

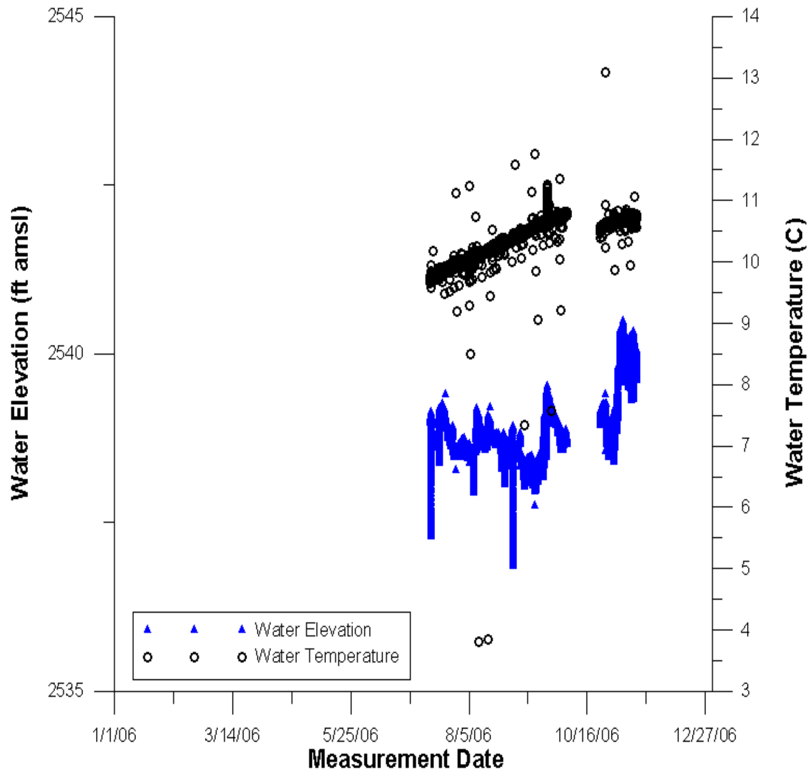


Figure 35. Groundwater Level Elevations and Temperatures for the Well Q16S.

3.4.7 Well Bovill 1

Figure 36 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well Bovill 1 at the UIGFL. The plot clearly depicts dynamic water level fluctuations. The groundwater level elevation in Bovill 1 was first recorded at 2539.38 ft amsl. An overall downward trend existed from June to September. Water levels then began to rise quickly and the last recorded water level elevation was 2539.37 ft amsl on November 15, 2006. Downward projected spikes in the water level data correlate with aquifer tests conducted at the UIGFL on June 8, 2006; July 13, 2006; July 18, 2006; August 8, 2006; August 27, 2006; and September 1, 2006 as part of this thesis research. The groundwater temperatures exhibited a seasonal trend, and rose from 6/7/2006 to 8/9/2006 then declined. Upward projected spikes in water temperatures are attributed to downloading and resetting the data logger. The Bovill 1 data logger number is 3849.

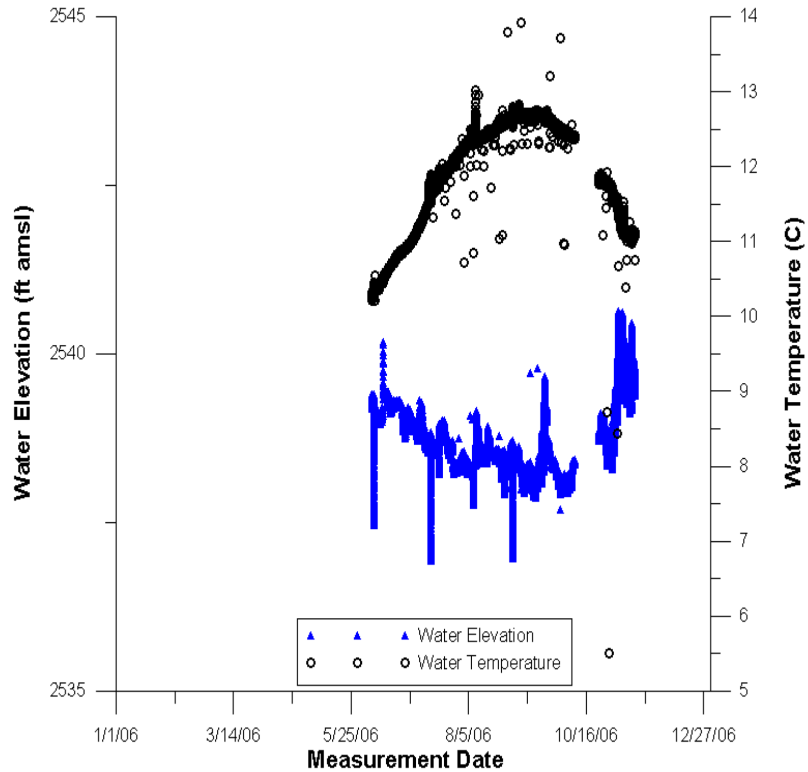


Figure 36. Groundwater Level Elevations and Temperatures for the Well Bovill 1.

3.4.8 Well Bovill 2

Figure 37 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well Bovill 2 at the UIGFL. The plot clearly illustrates dynamic water level fluctuations. The groundwater level elevation in well Bovill 2 was initially recorded at 2539.48 ft amsl. An overall downward trend existed from June to September. The groundwater level elevation was last recorded on October 9, 2006 at 2538.64 ft amsl. Downward projected spikes in the water level data correlate with aquifer tests conducted at the UIGFL on June 8, 2006; July 13, 2006; July 18, 2006; August 8, 2006; August 27, 2006; and September 1, 2006 as part of this thesis research. The groundwater temperatures rose from 6/7/2006 to 8/9/2006 before declining. Upward projected spikes in water temperature correspond to downloading and resetting of the data logger. The Bovill 2 data logger number is 33753.

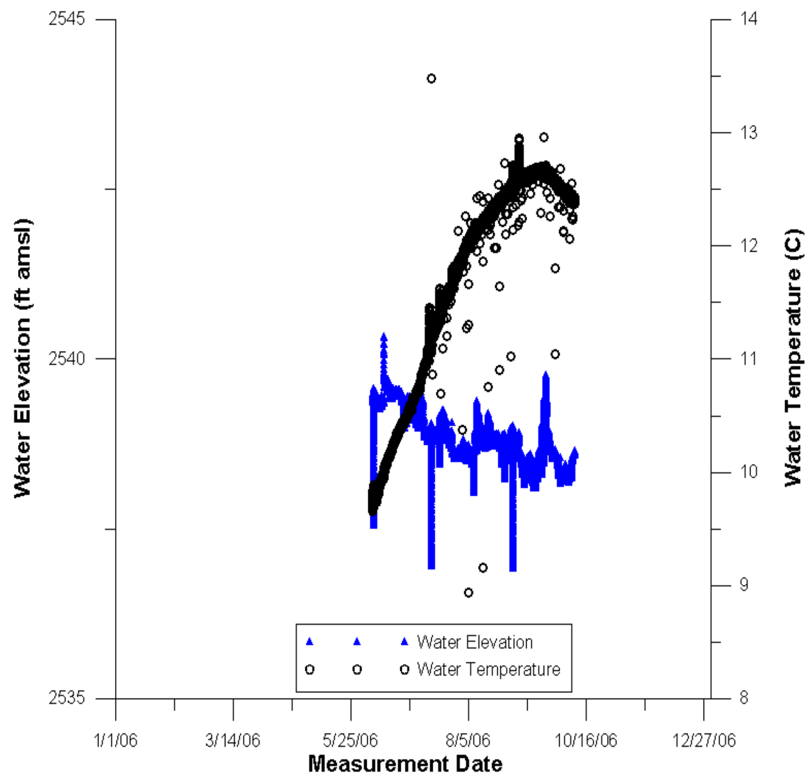


Figure 37. Groundwater Level Elevations and Temperatures for the Well Bovill 2.

3.4.9 Well Bovill 3

Figure 38 presents an arithmetic plot of groundwater level elevations and groundwater temperatures versus measurement date for well Bovill 3 at the UIGFL. The plot clearly illustrates dynamic water level fluctuations. The groundwater level elevation in Bovill 3 was initially recorded at 2540.03 ft amsl. An overall downward trend existed from June until September, and an upward trend existed afterwards. The groundwater level elevation was last recorded on November 15, 2006 at 2539.91 ft amsl. Downward projected spikes in the water level data correlate with aquifer tests conducted at the UIGFL on June 8, 2006; July 13, 2006; July 18, 2006; August 8, 2006; August 27, 2006; and September 1, 2006 as part of this thesis research. The water temperature rose from 6/7/2006 to 8/9/2006 before declining. The upward projected spikes in water temperature correspond with downloading and resetting of the data logger. The Bovill 3 data logger number is 73222.

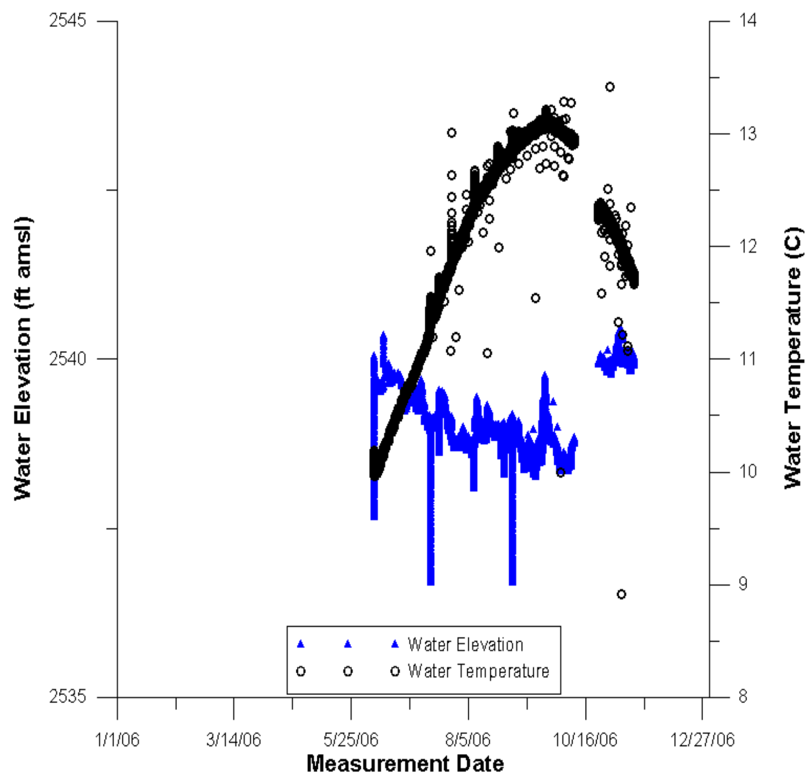


Figure 38. Groundwater Elevations and Temperatures for the Well Bovill 3.

CHAPTER 4
DESIGN AND IMPLEMENTATION OF SITE-SPECIFIC AQUIFER TESTS

4.1 Introduction

Nine aquifer tests were designed and conducted at the UIGFL for the purpose of evaluating groundwater/surface water interactions between Paradise Creek and the Wanapum Aquifer system. Discharge rates were held constant for six of the aquifer tests. Discharge rates could not be held constant during three of the aquifer tests. Aquifer test drawdown data were not corrected for barometric effects due to the short duration of the tests, and the assumption that barometric pressure did not change significantly during the tests.

Observation wells for these tests included three (3) deep basalt (>100 ft) wells, four (4) shallow basalt (<100 ft) wells, and three (3) sediments of Bovill (<20 ft) wells. Deep basalt wells were D19D, INEL-D, and S12D2; shallow basalt wells were Q17D, Q16S, T16D, and V16D; sediments of Bovill wells included V16S, Bovill 1, Bovill 2, and Bovill 3 (Table 1). Well logs for the basalt wells can be found in Li (1991), Pardo (1993), and Kopp (1993). According to (Osiensky, 2006) the wells Bovill 1, Bovill 2, and Bovill 3 are completed to a depth of 8.5 ft with 1 ft of hacksaw slots from 7.5 to 8.5 feet below land surface. A GPS survey was conducted to establish UTM coordinates for the UIGFL wells (Table 4).

4.2 Observation Well Setup

Multiple-well aquifer tests using a single pumping well and multiple observation wells were conducted at the UIGFL. Selection of wells for monitoring purposes was based on a literature review of previous hydrogeologic investigations at the UIGFL, and the proximity of the wells to Paradise Creek. Li and Kopp described hydraulic connections between Paradise Creek and the E-fracture zone (Figure 8). Pardo (1993) concluded during her study that Paradise Creek recharges the shallow sediments and E-fracture aquifer at the UIGFL. Li (1991) and Pardo (1993) also concluded that a hydraulic connection exists between the Wanapum basalt and the Latah Formation sediments. Production wells V16D, T16D, and Q17D were also selected based on information from Li (1991) (Figure 2, Table 1). All three wells were pumped for a minimum of three hours for each aquifer test. Production wells V16D and Q17D that were identified as being able to impact the sediments of Bovill observation wells were pumped for a longer duration (six hours) during separate aquifer tests. The objective of the longer aquifer tests was to ascertain if drawdown would stabilize. A steady-state system would suggest that groundwater recharge from Paradise Creek was induced during each test. Thus, a conceptual model could be developed with surface water migrating to the Wanapum Aquifer system via the streambed sediments of Paradise Creek.

4.3 Analysis of Site Specific Tests

Aquifer Tests #1, #2, and #3 were analyzed to develop a conceptual model of water flow from Paradise Creek into the Wanapum Aquifer system. Test wells were selected based on the responses observed during pretest aquifer tests, the ability to stress the aquifer system adequately, and the ability to maintain constant discharges. The Theis equation as modified for unconfined aquifers, with the method of superposition for multiple wells (one image well) was utilized for aquifer test analysis considering the immediate drawdown responses observed in the sediments of Bovill wells and the shallow basalt wells. Log-log plots were constructed to represent the profile of the cone of depression at each well as a function of distance squared (r^2) from the pumping well during the aquifer test. An imaginary (hereinafter referred to as an image well) injection well located an equal distance from the pumping well with the same pumping rate and duration was applied in AQTESOLV to simulate the boundary conditions believed to be created by Paradise Creek. No barometric corrections were needed due to the short duration of the aquifer tests. Additionally, groundwater temperature fluctuations observed in some wells were analyzed on a qualitative basis to evaluate hydraulic interconnectedness. A temperature analysis is presented for each aquifer test.

The transmissivity (T) and storativity (S) values presented in Figures 39, 40, 41, 43, 44, 45, 47, 48, and 49 are "apparent" values and should not be used to characterize the Wanapum Aquifer system at the UIGFL. These values may not be representative because the pumping wells were located in different stratigraphic units than some of the observation wells, and the producing zone for the tests within the E-fracture is dominated by fracture-flow conditions. Table 18 presents the distances of the observation wells from the pumping wells.

Table 18. Distances of the Observation Wells from the Pumping Wells.

Observation Well	Pumping Well V16D	Pumping Well Q17D
Bovill 1	75.69 ft	92.89 ft
Bovill 2	69.32 ft	114.75 ft
Bovill 3	43.46 ft	80.97 ft
V16S	11.31 ft	87.47 ft
Q16S	88.2 ft	18.97 ft
D19D	354.8 ft	258.52 ft
INEL-D	97.67 ft	55.56 ft
S12D2	104.73 ft	96.5 ft
T16D	28.28 ft	68.9 ft
V16D	----------	97.01 ft
Q17D	97.01 ft	----------

4.3.1 Aquifer Test #1

Aquifer Test #1 was conducted on July 13, 2006. Well V16D was pumped for 180 minutes (3 hours) at approximately 33 gpm. The following wells were monitored as observation wells: T16D, Q17D Q16S, D19D, INEL-D, S12D2, V16S, Bovill 1, Bovill 2, and Bovill 3 (Figure 2). T16D, Q17D, Q16S, Bovill 1, Bovill 2, Bovill 3, and V16S all responded to pumping. All drawdown and recovery data were compared to the type curve predicted by the Theis equation as modified for unconfined aquifer systems, with the method of superposition for multiple wells using AQTESOLV® (HydroSOLVE, 2003) software. Only 180 minutes of recovery data were plotted, full well recovery is not displayed on any of the figures. An image well was added 100 ft north of the pumping well in AQTESOLV to simulate boundary conditions created by Paradise Creek. All water level data and groundwater temperature data for Aquifer Test #1 are presented in Appendix C.

Figure 39 presents log-log plots of drawdown versus t/r^2 for observation wells Bovill 1, Bovill 2, Bovill 3, and V16S during Aquifer Test #1. The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) was manually adjusted for a best-fit match with the measured drawdown data. The plots illustrate that the type curve predicted by the modified Theis equation for unconfined systems with an image well generally describes the measured drawdown and recovery for the four observation wells. This illustrates that Paradise Creek may be acting as a boundary condition during pumping at the UIGFL. The Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) represents a "perfect system" (i.e., homogeneous, isotropic, and a fully penetrating stream). Deviations between the type curve predicted by the modified Theis equation and the measured drawdown data are due to heterogeneities, anisotropy, and the fact that Paradise Creek is a partially penetrating stream. Additionally, the image well represents the creek as a straight-line boundary whereas Paradise Creek actually meanders through the area.

The plots in Figure 39 clearly depict immediate responses to pumping in the observation wells; the response times observed in Bovill 1, Bovill 2, Bovill 3, and V16S were one minute, three minutes, three minutes, and two minutes, respectively. The maximum observed drawdown in Bovill 1, Bovill 2, Bovill 3, and V16S was 1.89 ft, 2.07 ft, 2.37 ft, and 1.62 ft, respectively.

The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) predicts faster recovery than that observed in both Bovill 1 and Bovill 2, and a slower recovery than that observed in Bovill 3 and V16S. These deviations may be attributed to the modified Theis equation for a fully penetrating stream of which Paradise Creek is not, the different distances from the pumping well, partial dewatering of the system, delayed yield, and/or leakage. The heterogeneous and anisotropic natures of the sediments of Bovill with respect to hydraulic conductivity also are believed to have affected both drawdown and recovery. Subsequent changes in storativity (S) between drawdown and recovery as a result of pumping may have affected the rate of recovery. Measured drawdown in V16S was less than that predicted by the modified Theis. The flat curve may be attributed to partial dewatering and/or delayed yield of the sediments of Bovill at V16S (the well was dry at the end of pumping).

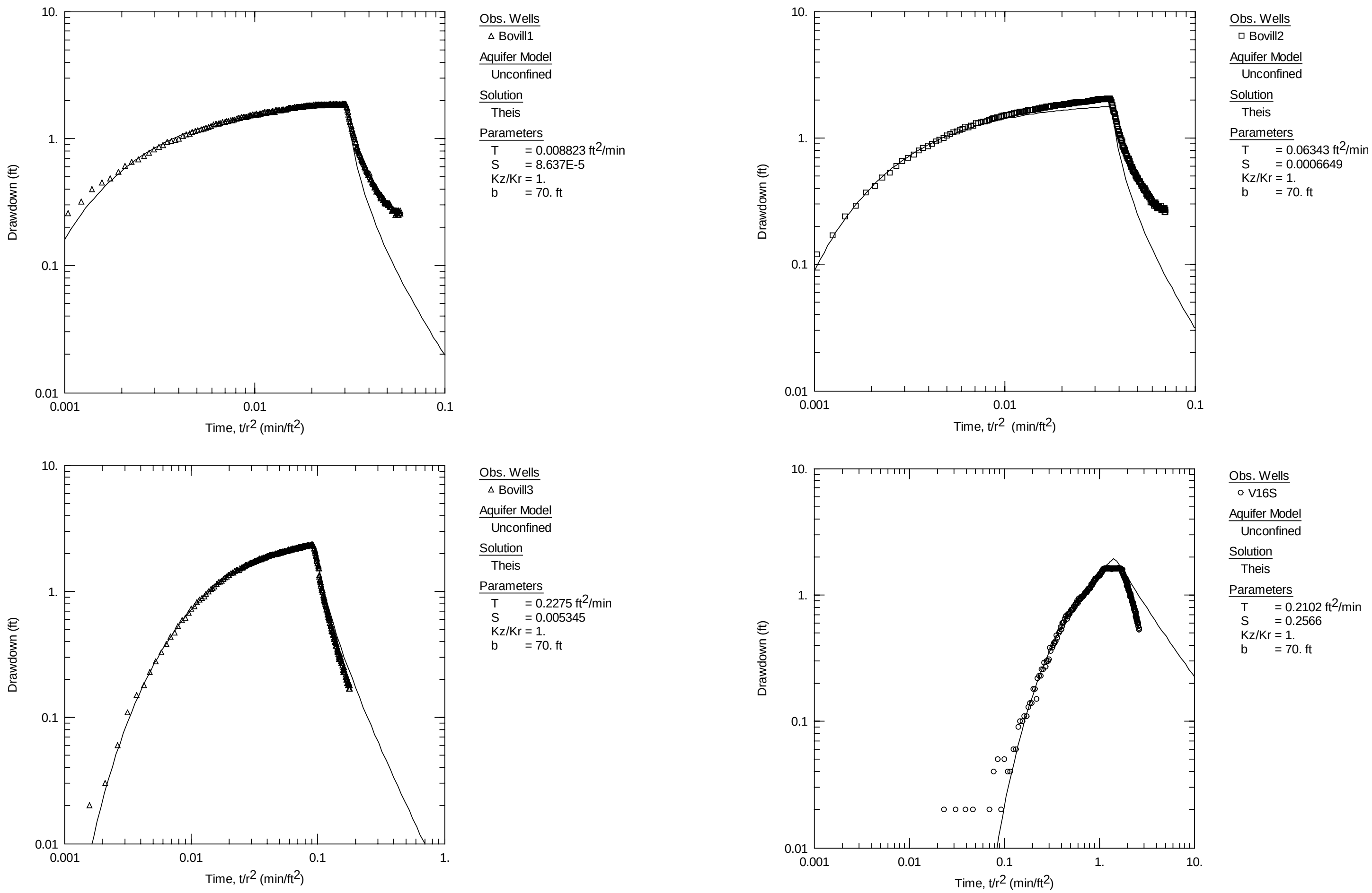


Figure 39. Log-log Drawdown and Recovery Plots for Observation Wells Bovill 1, Bovill 2, Bovill 3, and V16S During Aquifer Test #1. Table 18 lists the distances between the wells. Time represents elapsed time since pumping started.

Figure 40 presents log-log plots of drawdown versus t/r^2 for wells Q17D, Q16S, T16D, and D19D during Aquifer Test #1. The drawdown and recovery data recorded for Q17D, Q16S, D19D, and T16D deviates from the type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well). The plots clearly depict an immediate response to pumping in all the wells. The maximum observed drawdown in Q17D, Q16S, T16D, and D19D was 12.8 ft, 1.78 ft, 9.89 ft, 0.11 ft, respectively.

The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) has greater drawdown and slower recovery than measured in Q17D. These deviations may be attributed to the complex hydraulic connection between Q17D and the pumped well (V16D) via the E-fracture, potential hydraulic connection between the E-fracture and Paradise Creek via vertically oriented fractures, possible vertical leakage of water from the sediments of Bovill, and the unknown "effective" distance between the pumping well and observation well via fractures.

The predicted type curve matches drawdown in Q16S fairly well, but overestimates recovery. These deviations may be attributed to partial dewatering of the sediments of Bovill combined with the fact that Paradise Creek is a partially penetrating stream.

The predicted type curve appears to underestimate drawdown in D19D. The more significant aspect of the plot for D19D is that no recovery was measured compared to recovery that is predicted at that distance from the pumping well. These deviations may potentially be due to pumping on/off cycling of UI Aquaculture Wells 5, 6, and/or 7.

The drawdown and recovery predicted by the type curve deviate significantly from the drawdown and recovery measured in T16D. The deviations clearly illustrate that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) is the incorrect model for the hydraulic conditions that exist near well T16D. The shape of the drawdown curve for well T16D most closely resembles drawdown predicted by the Hantush and Jacob (1955) method for leaky aquifers. However, even the Hantush and Jacob (1955) method does not adequately describe the drawdown conditions measured at the UIGFL, such as drawdown in the overlying aquifer (i.e., sediments of Bovill). A possible explanation for the shape of the drawdown and recovery curves for well T16D is complex vertical leakage from the sediments of Bovill/Paradise Creek to the E-fracture through spatially variable vertical fractures.

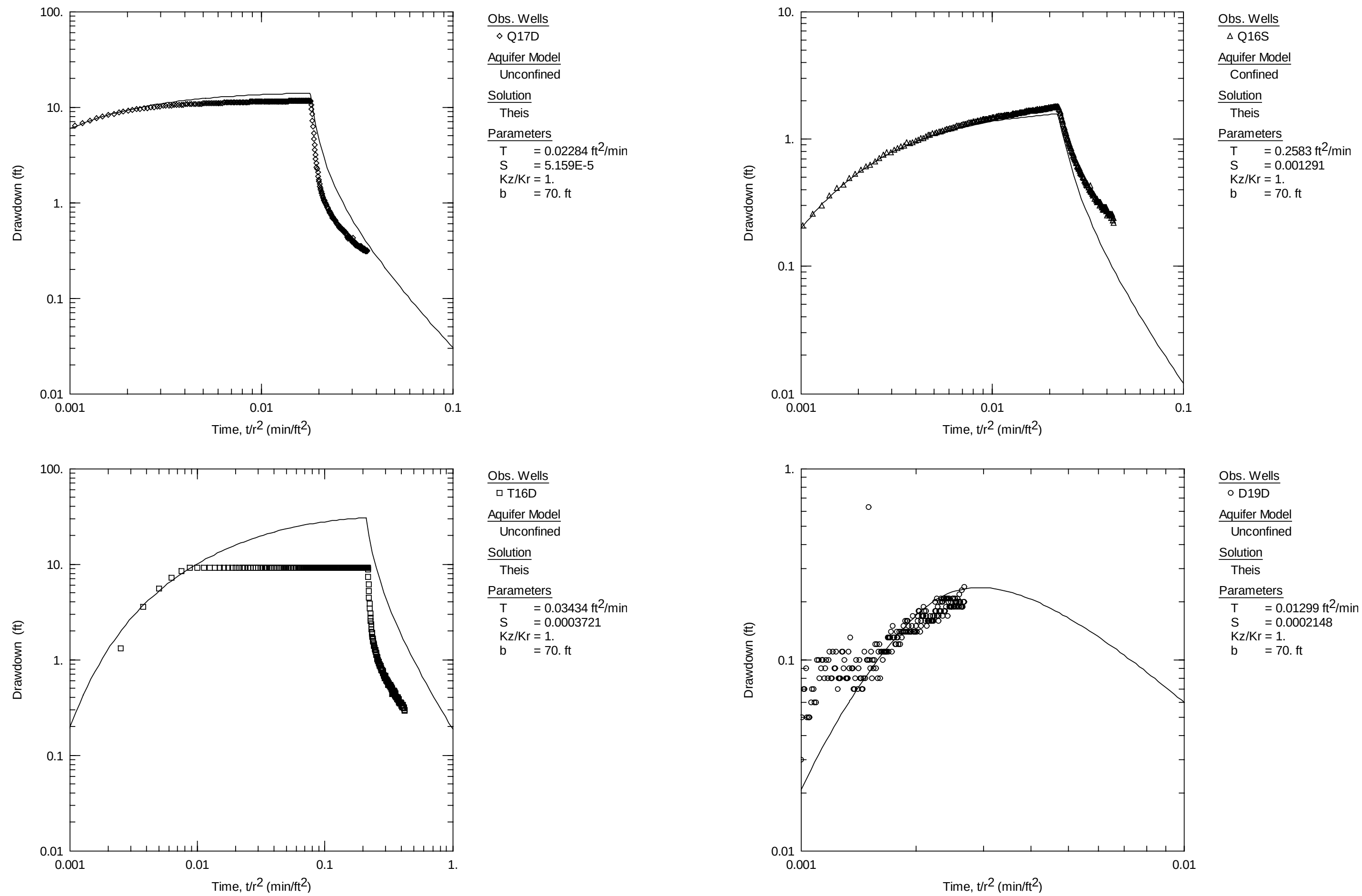


Figure 40. Log-log Drawdown and Recovery Plots for Observation Wells Q17D, Q16S, T16D, and D19D During Aquifer Test #1. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 41 presents log-log plots of drawdown versus t/r^2 for wells S12D2 and INEL-D. The plots illustrate the drawdown responses to pumping measured in these wells. The maximum drawdown measured in wells S12D2 and INEL-D was 0.18 ft and 0.07 ft, respectively. The plots illustrate that the type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) generally describes the observed drawdown, but not the lack of recovery for S12D2 and INEL-D. The drawdown measured in S12D2 is significant because it indicates a hydraulic connection between the E-fracture and the W-fracture. The INEL-D well is not completed in either the E-fracture or the W-fracture yet it responds to pumping in the E-fracture. The drawdown observed in the INEL-D well is significant because it indicates a hydraulic connection between the Vantage interbed, the E-fracture, and Paradise Creek. The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) predicts recovery in S12D2 and INEL-D; however, recovery did not occur. The lack of recovery clearly illustrates that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) is the incorrect model for the hydraulic conditions that exist near wells S12D2 and INEL-D. The well hydraulics in the UIGFL most likely reflects complex flow conditions within a multiple-aquifer-aquitard system.

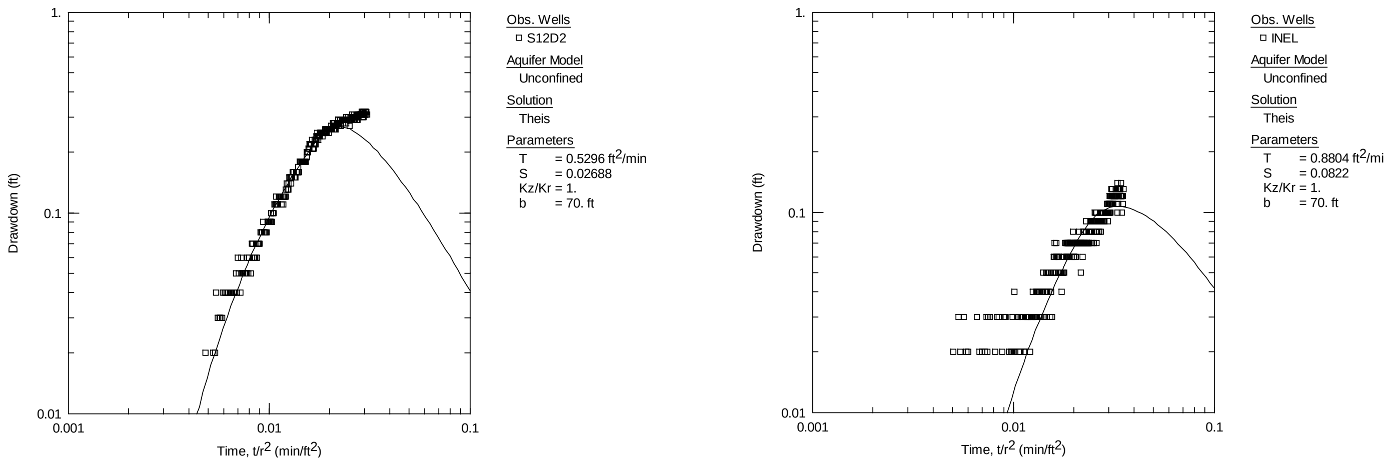


Figure 41. Log-log Drawdown and Recovery Plots for Observation Wells S12D2 and INEL-D During Aquifer Test #1. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 42 presents an arithmetic plot of groundwater temperature versus time for the observation wells during Aquifer Test #1. The plot illustrates that wells completed to a depth greater than 100 ft (Table 1) (INEL-D, D19D, and S12D2) did not exhibit temperature fluctuations during pumping of well V16D. The pretest temperatures for INEL-D, D19D, and S12D2 were 11.05 °C, 10.43 °C, and 10.53 °C, respectively. Wells completed in the E-fracture, and the sediments of Bovill exhibited a variety of temperature changes due to aquifer pumping. These variations may be attributed to heterogeneities in the E-fracture, degree of connectivity with Paradise Creek, the distance to Paradise Creek, and the distance to the pumping well.

At the beginning of the aquifer test, the groundwater temperatures in the sediments of Bovill wells rose; after 60 minutes of pumping well V16D, the groundwater temperatures decreased. After 170 minutes of pumping, the groundwater temperatures decreased at a greater rate; after pumping stopped groundwater temperatures rose. The initial rises in groundwater temperatures observed in the sediments of Bovill wells are attributed to water migrating from Paradise Creek and overlying sediments. The subsequent decline in water temperature is attributed to cold water in residence in the sediments of Bovill, possibly north of the UIGFL that is being drawn under Paradise Creek and into the cone of depression formed by pumping well V16D. The source of the declines in groundwater temperatures after pumping stopped can not be identified at this time. The water temperatures in V16S rose slightly for the first 60 minutes of the aquifer test and then declined slightly for the remainder of the test. The different response observed in V16S compared to Bovill 1, 2, and 3 may be attributed to its greater distance from Paradise Creek.

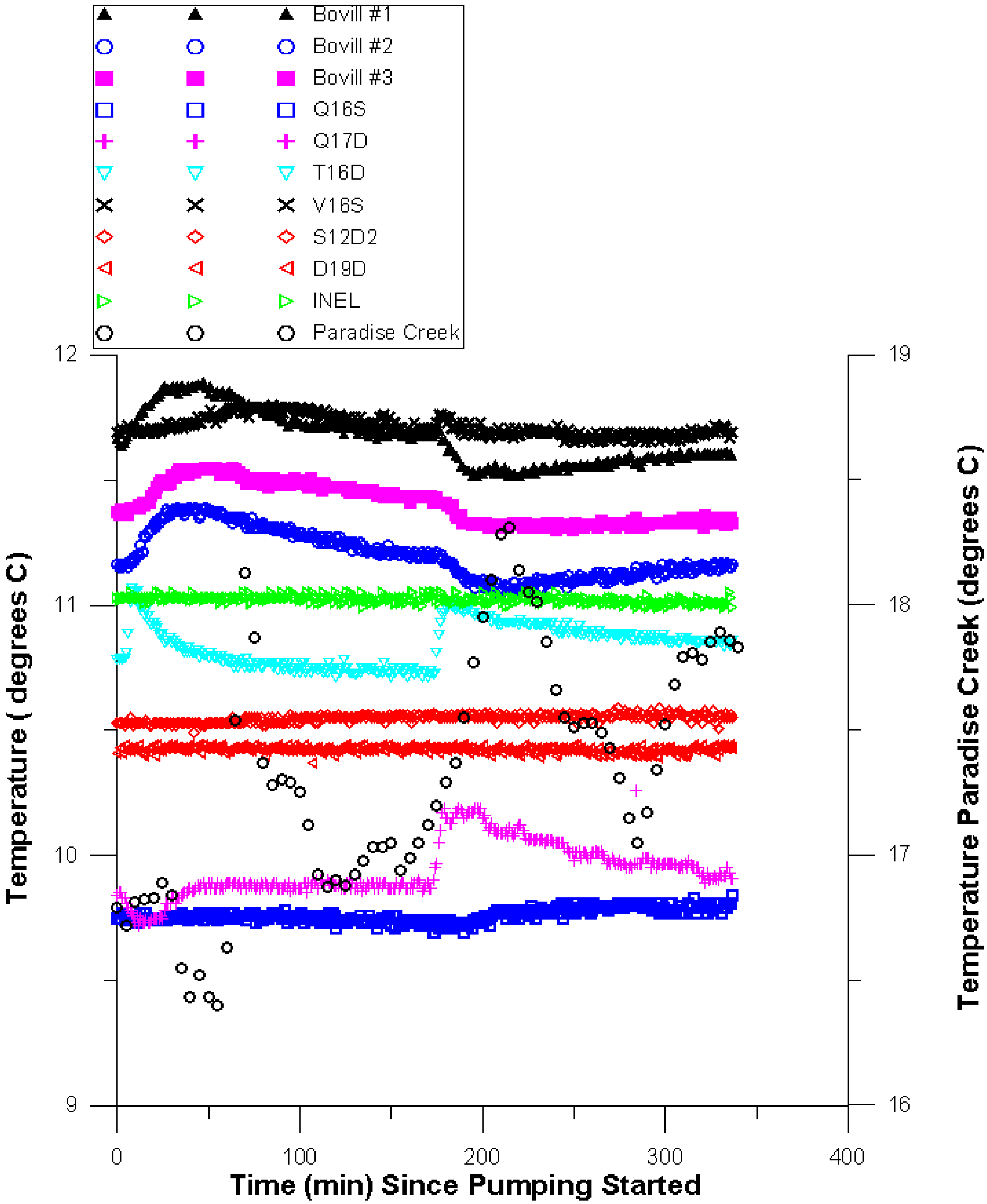


Figure 42. Arithmetic plots of Groundwater Temperatures in All Monitored Wells During Aquifer Test #1. Pumping stopped at 180 minutes. After 142 minutes of pumping well V16D, well V16S was dewatered. Temperature readings after that point are erroneous.

Temperature variations observed in Q16S, Q17D, and T16D differed markedly from the sediments of Bovill wells. Throughout the aquifer test the groundwater temperatures in Q16S remained relatively constant, but after pumping stopped a slight rise groundwater temperatures occurred. The rise in groundwater temperatures in Q16S at the conclusion of pumping suggests the arrival of water from the overlying and/or underlying materials, and possibly Paradise Creek. At the beginning of the aquifer test, a significant decrease in groundwater temperatures occurred in Q17D, followed by a rise in groundwater temperatures, after 170 minutes of pumping V16D, a sharp rise in groundwater temperatures occurred; groundwater temperatures decreased after pumping stopped. The source(s) of the groundwater temperature changes in Q17D measured at the beginning of the aquifer test is not known; however, the rise in groundwater temperatures at the end of the aquifer test is attributed to the arrival of a pulse of warm water from Paradise Creek through the E-fracture. The subsequent decline in groundwater temperatures at the end of pumping is attributed to the arrival of water from the surrounding matrix. The colder groundwater temperatures observed in Q16S and Q17D may reflect the farthest projection of winter water migrating from Paradise Creek into the E-fracture.

At the beginning of the aquifer test, a sharp rise in groundwater temperatures occurred in well T16D; this was followed by a period of decreasing groundwater temperatures. At the end of pumping another rise in groundwater temperatures occurred, followed by a period of decreasing groundwater temperatures. The vacillating groundwater temperatures probably reflect the arrival of different “bodies” of relatively warm and cool groundwater that percolated diurnally into the sediments of Bovill from

Paradise Creek under night-time/day-time temperature regimes. Groundwater temperatures remained relatively constant in wells S12D2, INEL-D, and D19D during and after the pumping period for the aquifer test. The lack of groundwater temperature changes in the deeper wells during the aquifer test indicates groundwater did not migrate that deep during the aquifer test. The locations and variable physical properties of vertical fractures intersecting the E-fracture relative to the observation well locations may be responsible for the variable water temperature responses measured during the aquifer test.

Water temperature in Paradise Creek is on average 5 degrees C higher than the water temperature observed in the Bovill 1 well and on average 7.5 degrees C higher than the water temperature observed in the Q16S well. Water temperature in Paradise Creek during Aquifer Test #1 fluctuates between 16 degrees C and 19 degrees C.

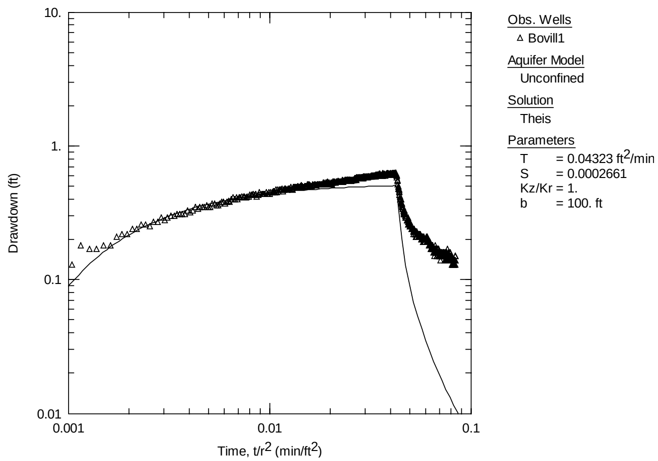
4.3.2 Aquifer Test #2

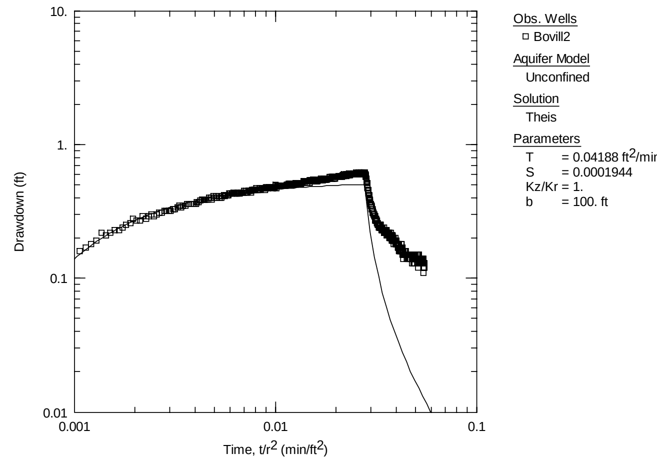
Aquifer Test #2 was conducted on August 27, 2006. This test was conducted to test the response of the system to pumping from a different well than well V16D as for Aquifer Test #1. Well Q17D was pumped for 360 minutes (6 hours) at a rate of 7.23 gpm. Wells monitored included Bovill 1, Bovill 2, Bovill 3, V16D, T16D, Q16S, S12D2, INEL-D, and D19D. All drawdown and recovery data were matched to the type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) using AQTESOLV® (HydroSOLVE, 2003); an image well was added 124 feet from the pumping well to simulate the boundary condition produced by Paradise Creek. Only 360 minutes of recovery data are plotted; full well recovery was not achieved in any of the monitored wells during the period of record. All groundwater levels and groundwater temperatures for Aquifer Test #2 are presented in Appendix C.

Figure 43 presents log-log plots of drawdown versus t/r^2 for observation wells Bovill 1, Bovill 2, and Bovill 3, during Aquifer Test #2. The plots illustrate that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) generally describes the measured observation well drawdown, but not the measured observation well recovery during the test. The maximum observed drawdown in Bovill 1, Bovill 2, and Bovill 3, was 0.63 ft, 0.62 ft, and 2.46 ft, respectively.

The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) underestimates late-time drawdown for Bovill 1 and Bovill 2, and overestimates recovery for Bovill 1, Bovill 2, and Bovill 3. The reasons for the overestimation of recovery most likely are related to the facts that Paradise Creek is a partially penetrating stream, and the sediments of Bovill were partially drained during the pumping portion of the test. The Bovill wells clearly respond differently to the pumping of Q17D than V16D. Some of the differences in drawdown and recovery between the two tests are due to the lower pumping rate for Aquifer Test #2, and subsequently a smaller cone of depression intersecting Paradise Creek combined with the different distances between the pumping well and observation wells.

Additionally, the image well location and distance from the pumping well used to simulate Paradise Creek was different. The greater pumping rate of well V16D during Aquifer Test #1 resulted in a larger cone of depression, more drawdown, and more rapid recovery because a greater area of the cone of depression was in contact with Paradise Creek. The decreased pumping rate for Q17D resulted in a smaller cone of depression, less drawdown, and slower recovery because a smaller area of the cone of depression was in contact with Paradise Creek. Also, the hydraulic conductivity of the sediments of Bovill is contributing to the slow rate of recovery. The lower pumping rate resulted in flatter gradients and less leakage. Dewatering of the sediments of Bovill to the point of causing any wells to go dry was not observed during Aquifer Test #2.





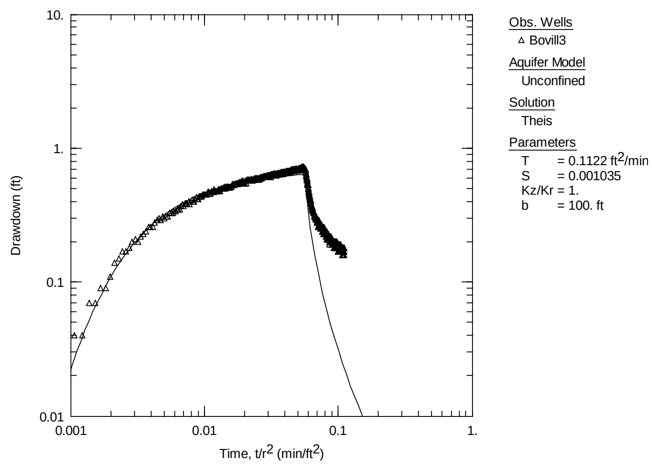


Figure 43. Log-log Drawdown and Recovery Plots for Observation Wells Bovill 1, Bovill 2, and Bovill 3 During Aquifer Test #2. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 44 presents log-log plots of drawdown versus t/r^2 for wells T16D, V16D, Q16S, and S12D2 during Aquifer Test #2. The plots illustrate that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) generally describes the observed drawdown, but not recovery during Aquifer Test #2. The prompt response in T16D, V16D, and Q16S is most likely due to these wells being directly hydraulically connected to the pumping well by the E-fracture. Drawdown observed in S12D2 indicates a hydraulic connection between the W-fracture system and the E-fracture system. The maximum measured drawdown in T16D, V16D, Q16S, and S12D2 was 7.36 ft, 1.92 ft, 0.64 ft, and 0.20 ft, respectively.

The type curve predicted by the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) overestimates the recovery for T16D, V16D, Q16S, and S12D2. The deviations in recovery are most likely due to the fact that Paradise Creek is a partially penetrating stream combined with partial dewatering of the sediments of Bovill during the pumping portion of the test. The lack of predicted recovery in S12D2 is most likely a result of possible influence from the pumping of the UI Aquaculture Wells 5, 6, and 7 or pumping of another nearby well such as the AHC well.

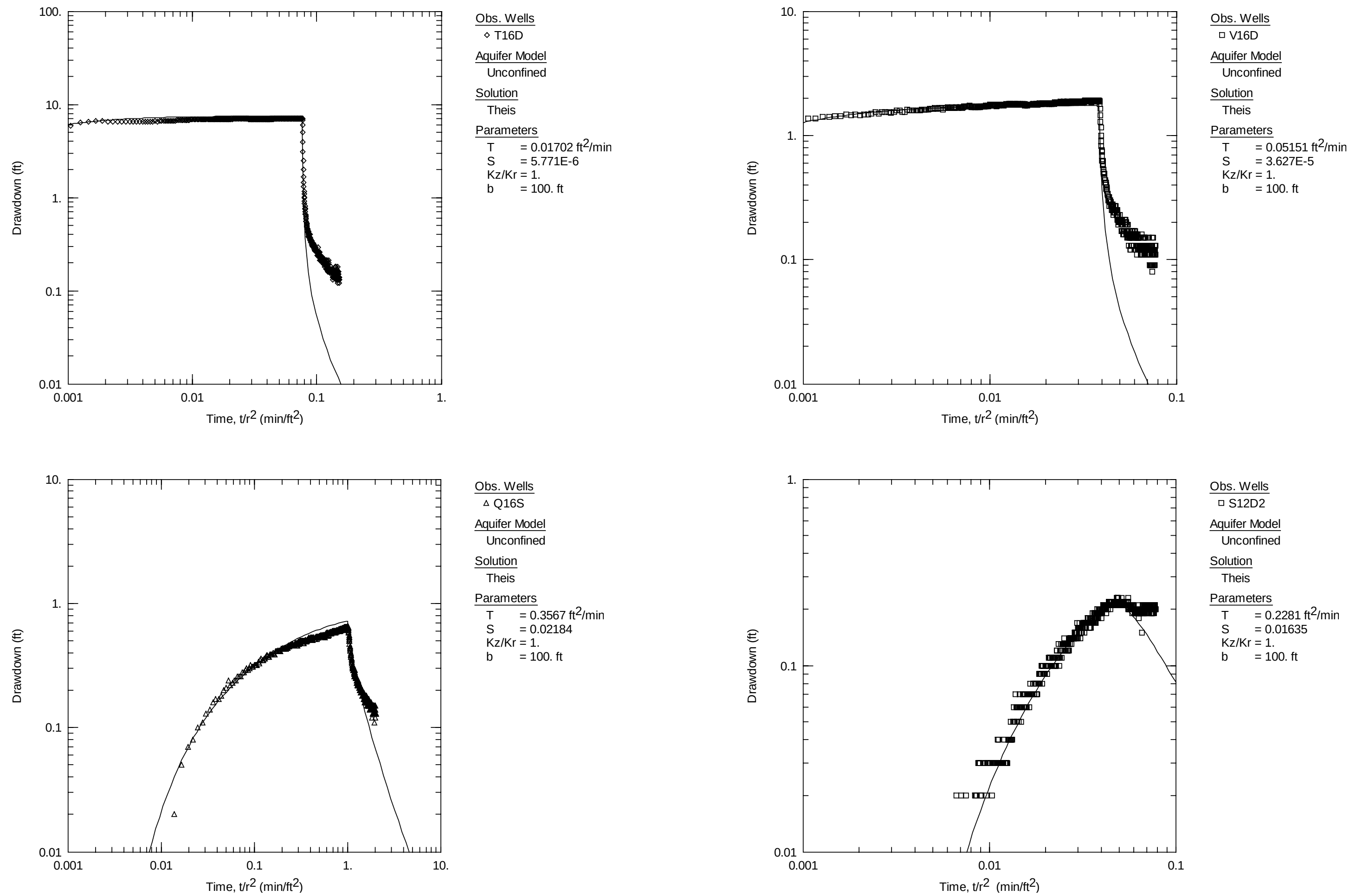


Figure 44. Log-log Drawdown and Recovery Plots for Observation Wells, T16D, V16D, Q16S, and S12D2 During Aquifer Test #2. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 45 presents log-log plots of drawdown versus t/r^2 for wells INEL-D and D19D during Aquifer Test #2. The plots illustrate that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) poorly describes the observed drawdown and recovery for wells INEL-D and D19D. The maximum measured drawdown in INEL-D and D19D was 0.13 ft and 0.12 ft, respectively. The discrepancies between the drawdown measured in INEL-D and D19D and the drawdown predicted indicate that the Theis equation, as modified for unconfined conditions, with the method of superposition for multiple wells (one image well) is not the correct model for the hydraulic conditions that exist near these wells. The well hydraulics in the UIGFL most likely reflects complex flow conditions within a fractured, multiple-aquifer-aquitard system. However, it is also possible that the responses observed in INEL-D and D19D are due to other pumping wells in the area, either the UI Aquaculture wells or the Appaloosa Horse Club well.

The drawdown observed in well INEL-D is significant because it suggests that the Vantage equivalent interbed responds to pumping in the E-fracture even at a low pumping rate. Pardo inferred a hydraulic connection exists between Paradise Creek and the Vantage equivalent interbed at least at the UIGFL. The response in INEL-D during Aquifer Test #2 also suggests a possible connection between Paradise Creek and the Vantage equivalent interbed.

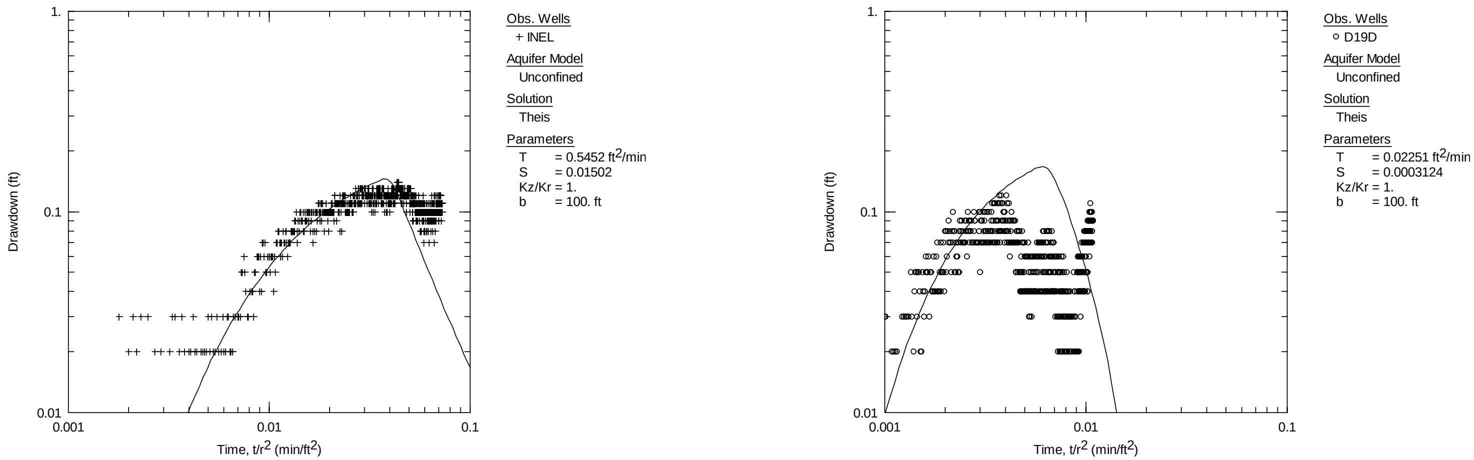


Figure 45. Log-log Drawdown and Recovery Plots for Observation Wells INEL-D and D19D During Aquifer Test #2.
Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 46 presents an arithmetic plot of groundwater temperature versus time for some of the wells during Aquifer Test #2. No groundwater temperature changes were detected in wells INEL-D, D19D, and S12D during the aquifer test; the baseline water temperatures in these wells were 11.1 °C, 10.47 °C, and 10.6 °C, respectively. However, minimal groundwater temperature changes occurred in wells Bovill 1, Bovill 2, and Bovill 3 at the beginning and end of aquifer pumping. The baseline groundwater temperatures for these wells were 12.58 °C, 12.44 °C, and 12.77 °C, respectively; groundwater temperatures in these wells increased 1 °C between the end of Aquifer Test #1 and the beginning of Aquifer Test #2. The baseline groundwater temperatures for Q16S, Q17D, and T16D were 10.31 °C, 10.21 °C, and 11.1 °C, respectively; these temperatures equate to a 0.5 °C rise since the end of Aquifer Test #1. The baseline groundwater temperature in V16D was 12.53 °C. The baseline groundwater temperature in V16D was similar to those values observed in the Bovill wells. No groundwater temperatures were recorded for well V16D during Aquifer Test #1 so it can't be determined if the groundwater temperatures changed in that well.

The groundwater temperatures in the Bovill wells remained relatively constant throughout Aquifer Test #2. The lack of groundwater temperature changes suggests that little water with different temperature signatures from the baseline groundwater temperatures was percolating into the system from Paradise Creek. The water temperature in Paradise Creek rose for the majority of the aquifer test.

At the beginning of the aquifer test the groundwater temperatures in well V16D rose; after 50 minutes the groundwater temperatures decreased, and remained relatively constant for the remainder of the aquifer test. After pumping ended, groundwater temperatures decreased nine minutes after pumping stopped; 34 minutes after pumping ended the groundwater temperatures began to rise. Temperature fluctuations after pumping stopped probably reflect the redistribution of the groundwater in the system as the hydraulic gradients changed during recovery. The rise in groundwater temperatures may be attributed to water from the sediments of Bovill and/or Paradise Creek. The subsequent decline in groundwater temperatures is attributed to mixing with colder water from lower strata. The cause of the sharp decline in groundwater temperatures after pumping ended is not known at this time.

Groundwater temperatures in T16D rose for the first 14 minutes of the aquifer test, and then decreased until six minutes after pumping stopped, and then rose for 29 minutes before decreasing again. The initial rise in groundwater temperatures may reflect the movement of warmer water from the overlying strata and/or Paradise Creek. The rise in groundwater temperature after pumping stopped is not understood at this time.

At the beginning of the aquifer test, groundwater temperatures in well Q17D rose, stabilized after 160 minutes, declined slightly after pumping stopped, rose for 11 minutes, and then declined again. The rise in groundwater temperature is attributed to contributions from overlying strata, stabilization is attributed to mixing of waters, and the decline is attributed water from underlying strata.

Groundwater temperatures in Q16S remained relatively constant throughout the aquifer test; however, a slight rise was observed after pumping stopped. The rise in groundwater temperatures is attributed to contributions from Paradise Creek and the overlying strata. No groundwater temperature fluctuations were observed in S12D2, INEL-D, and D19D.

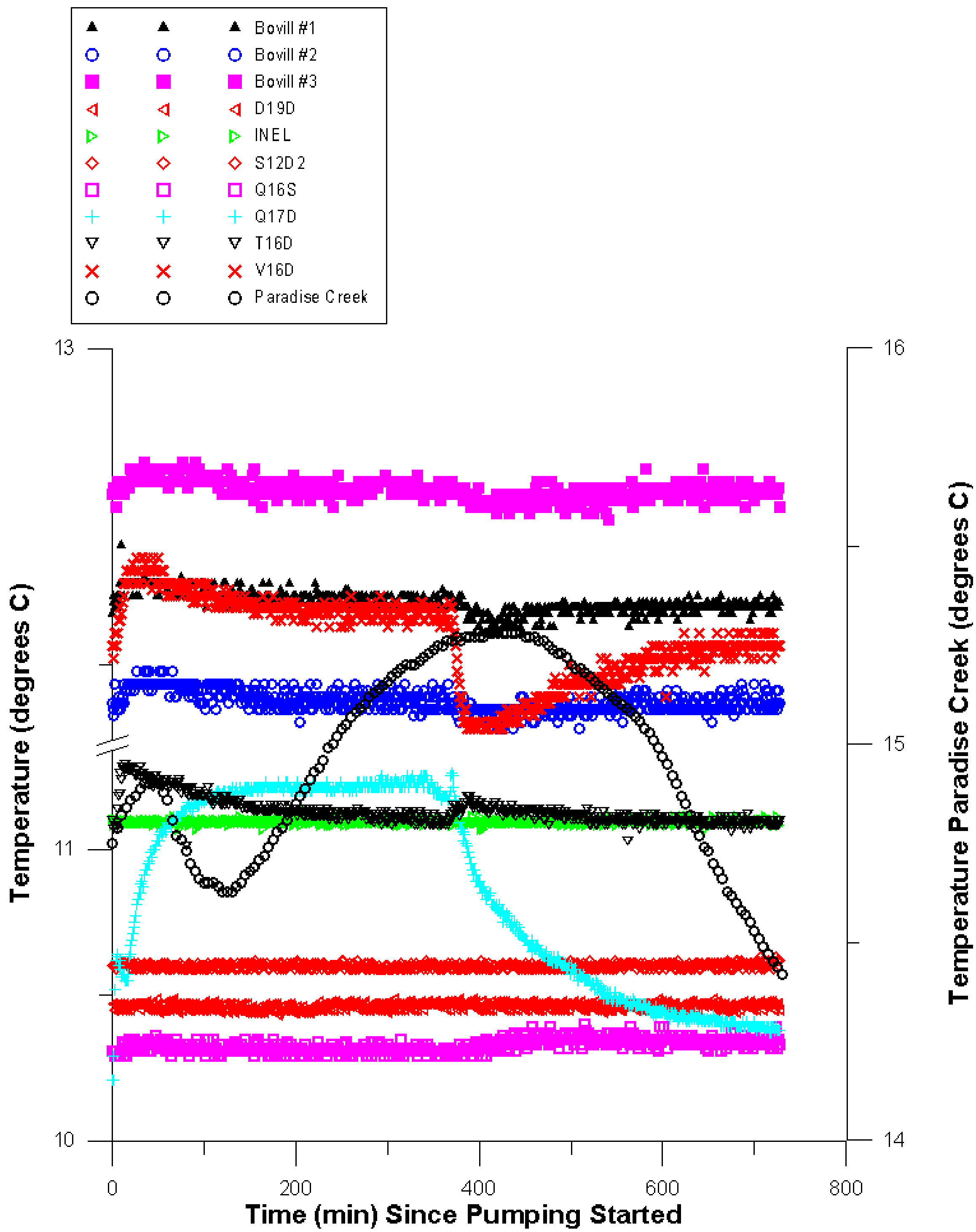


Figure 46. Arithmetic Plots of Water Temperature Versus Time for All Monitored Wells During Aquifer Test #2. Pumping ceased at 360 minutes.

Water temperature in Paradise Creek during Aquifer Test #2 was on average 2 degrees C higher than that observed in the Bovill 3 well and was on average 5 degrees C higher than that observed in Q16S. Water temperature in Paradise Creek fluctuated between 14.5 degrees C and 15.25 degrees C.

4.3.3 Aquifer Test #3

Aquifer Test #3 was conducted on September 1, 2006 to replicate the results for Aquifer Test #1, and to stress the system for a longer period of time. V16D was pumped for 360 minutes (6 hours) at a rate of 30.9 gpm. The generator inexplicably shut-off three minutes into the aquifer test; it was promptly restarted two minutes later. Wells monitored included Bovill 1, Bovill 2, Bovill 3, Q17D, T16D, Q16S, S12D2, INEL-D, and D19D. All drawdown and recovery data were matched to the type curve predicted by the Theis equation modified for unconfined conditions with the method of superposition for multiple wells (i.e., one image well) using AQTESOLV® (HydroSOLVE, 2003) software. Only 360 minutes of recovery data are plotted; full well recovery is not plotted on any of the figures. An image well was added 100 feet from the pumping well to simulate the boundary condition created by Paradise Creek. All groundwater levels and groundwater temperatures for Aquifer Test #3 are presented in Appendix C.

Figure 47 presents log-log plots of drawdown versus t/r^2 for wells Bovill 1, Bovill 2, and Bovill 3 during Aquifer Test #3. As expected the drawdown data for this aquifer test look much like those for Aquifer Test #1. The response times observed in Bovill 1, Bovill 2, and Bovill 3 were three minutes, one minute, and three minutes, respectively; compared with one minute, three minutes, and three minutes measured during Aquifer Test #1. The maximum measured drawdown in Bovill 1, Bovill 2, and Bovill 3 was 1.69

ft, 2.08 ft, 2.46 ft, respectively; very similar to the drawdown observed during Aquifer Test #1. Similar to the analysis for Test #1 the type curve predicted by the Theis equation modified for unconfined conditions with the method of superposition for multiple wells (i.e., one image well) underestimates initial drawdown and overestimates the rate of recovery for the Bovill wells.

These deviations are indicative of a negative boundary. Deviations in predicted and observed drawdown may be attributed to Paradise Creek being a partially penetrating stream, heterogeneities and anisotropy in the sediments of Bovill that impact hydraulic conductivity (K) and storativity (S). Additionally, the slow rate of recovery may be attributed to heterogeneities and anisotropy of hydraulic conductivity, an aquitard created by overlying material, partial dewatering and/or delayed yield of the sediments of Bovill.

There is a marked difference between the drawdown measured in well Bovill 1 during Aquifer Test #3 compared to Aquifer Test #1: the drawdown curve flattened during the later portion of Aquifer Test #3. It is unclear why the drawdown in Bovill 1 approached stabilization during Aquifer Test #3, but not during Aquifer Test #1. However, the fact that Aquifer Test #3 was twice as long as Aquifer Test #1 suggests that the effects of delayed yield in the sediments of Bovill caused the flattening of the drawdown curve during Aquifer Test #3. The drawdown curves for Bovill 2 and Bovill 3 also started to flatten at the end of Aquifer Test #3. A much longer aquifer test than 360 minutes would be needed to evaluate the conditions of delayed yield at the UIGFL.

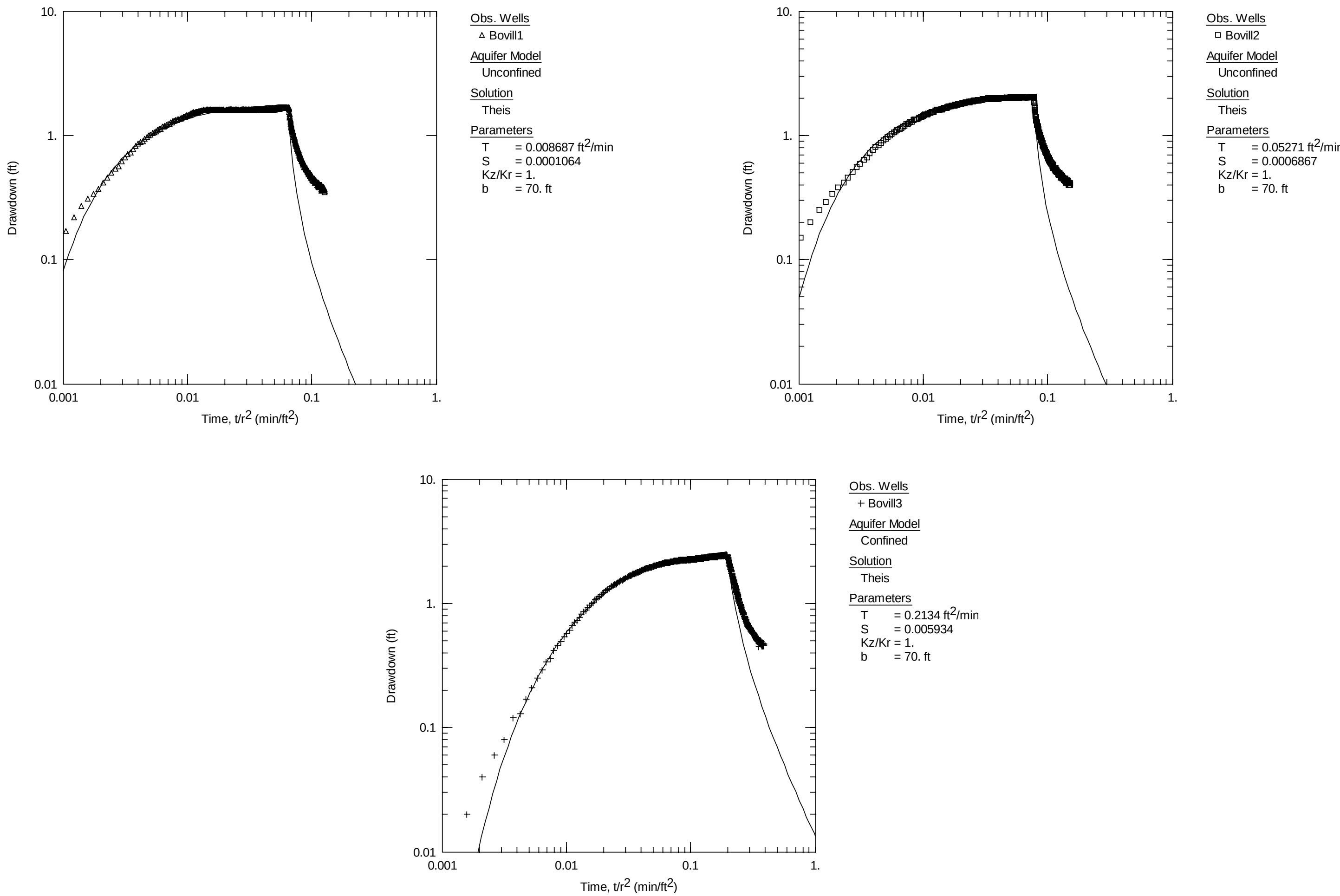


Figure 47. Log-log Drawdown and Recovery Plots for Observation Wells Bovill 1, Bovill 2, and Bovill 3 During Aquifer Test #3. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 48 presents log-log plots of drawdown versus t/r^2 for wells Q16S, Q17D, S12D2, and T16D during Aquifer Test #3. Similar to Aquifer Test #1, the type curve predicted by the Theis equation modified for unconfined conditions with the method of superposition for multiple wells (i.e., one image well) 1) overestimates the rate of recovery compared to that observed in Q16S, 2) overestimates drawdown and underestimates the rate of recovery compared to that observed in Q17D and T16D, and 3) overestimates the rate of recovery compared to that observed in S12D2. The slow rate of recovery observed in Q16S probably is due to partial dewatering of the sediments of Bovill during pumping. The fluctuation in drawdown observed in T16D during the early part of the aquifer test is attributed to the generator stopping. The flattening of the drawdown curves in Q17D and T16D during the later portion of the aquifer test is attributed delayed yield and/or water derived from Paradise Creek. The faster rate of recovery observed in Q17D and T16D suggests possible direct connection between the E-fracture and Paradise Creek. The lack of predicted recovery in S12D2 after pumping stopped is most likely due to heterogeneity between S12D2 and the pumping well, and/or possibly an influence from the pumping of UI Aquaculture lab Wells 5, 6, and 7 or another nearby pumping well such as the AHC well.

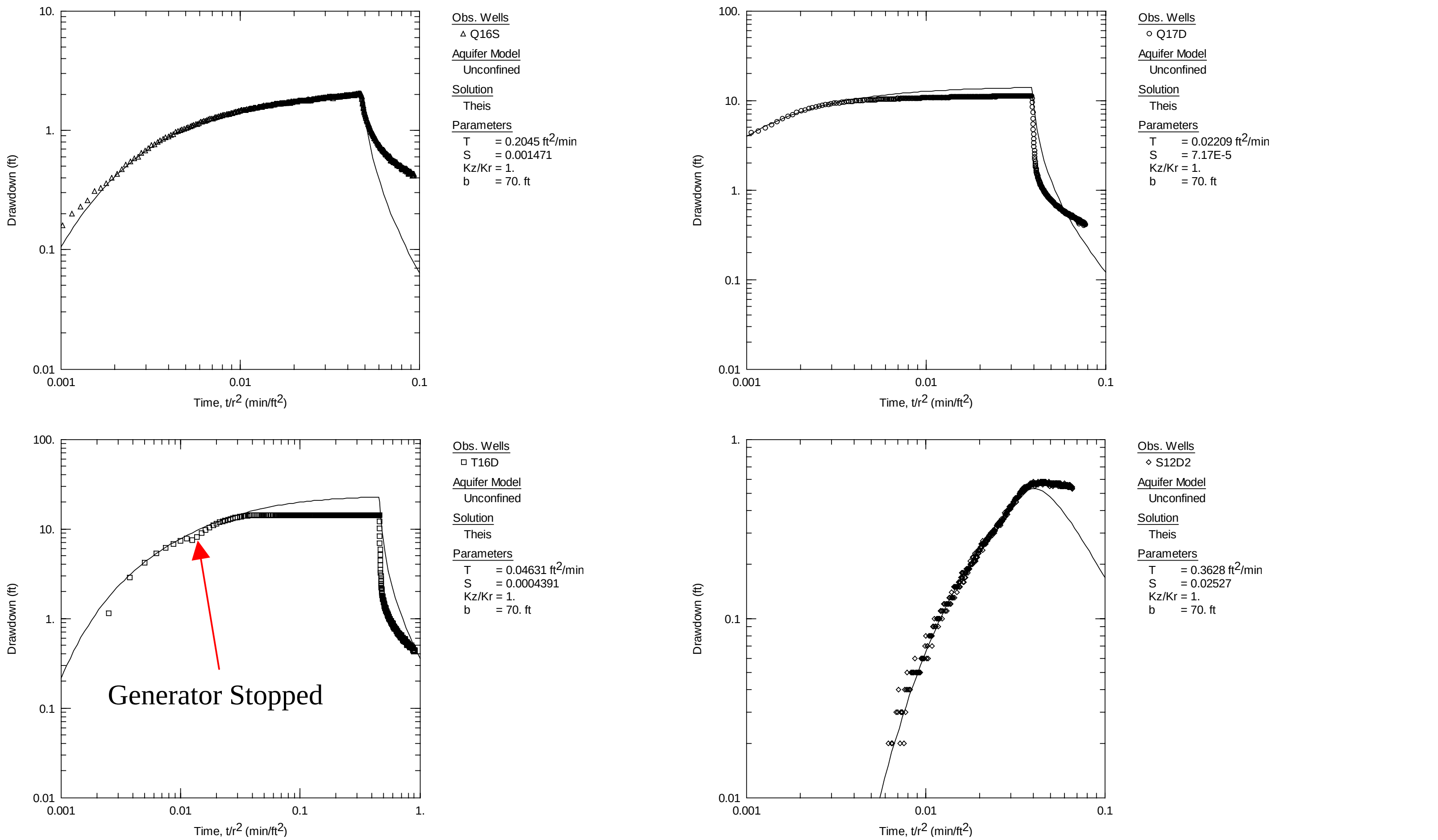


Figure 48. Log-log Drawdown and Recovery Plots for Observation Wells Q16S, Q17D, S12D2, and T16D During Aquifer Test #3. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 49 presents log-log plots of drawdown versus t/r^2 for wells INEL-D and D19D during Aquifer Test #3. No measurable drawdown occurred in well INEL-D and D19D wells during Aquifer Test #3. This suggests that drawdown in both well INEL-D and well D19D during Aquifer Test #1 was caused by an unknown pumping well and not pumping of well V16D at the UIGFL.

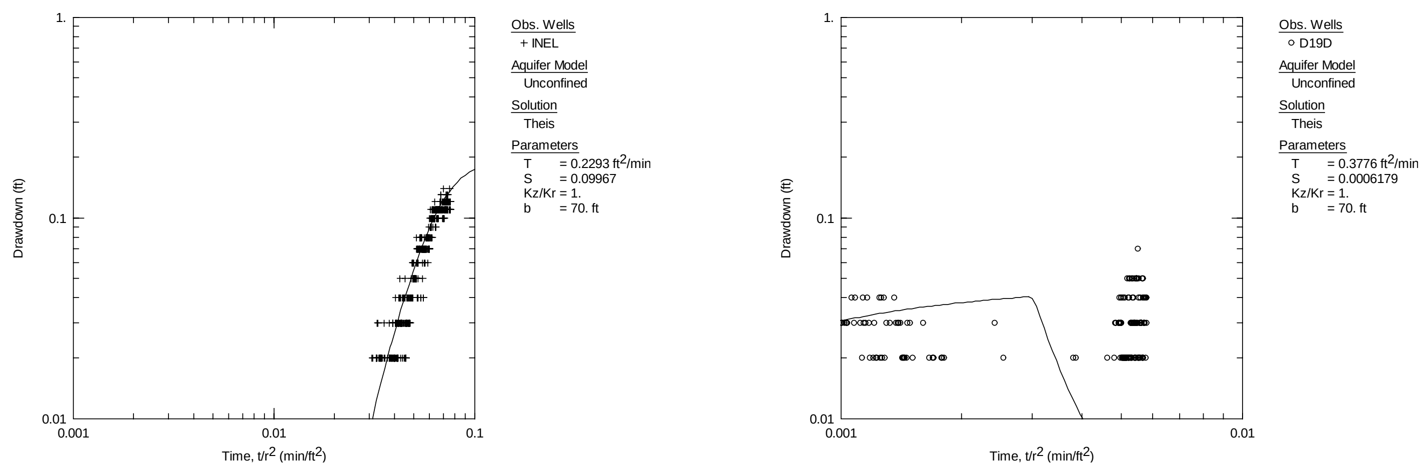


Figure 49. Log-log Drawdown and Recovery Plots for Observation Wells INEL-D and D19D During Aquifer Test #3. Table 18 lists the distances between the observation wells and the pumping well. Time is elapsed time since pumping started.

Figure 50 presents a composite plot of groundwater temperature versus time for all the wells monitored during Aquifer Test #3. The plot illustrates that wells INEL-D, D19D, and S12D did not exhibit temperature fluctuations due to aquifer pumping. The plot depicts significant groundwater temperature changes in Bovill 1, Bovill 2, and Bovill 3 at the beginning and end of aquifer pumping. The plot shows that no perceptible groundwater temperature changes occurred in Q16S. Groundwater temperatures in well T16D rose dramatically at the start of the aquifer test followed by a decline and another temperature rise at the end of the pumping period followed by a period of declining groundwater temperatures. Groundwater temperatures in Q17D rose dramatically at the start of the aquifer test followed by a period of decline; a spike in ground water temperatures occurred at the end of the aquifer test, followed by a period of decreasing groundwater temperatures. The initial rise in water temperature observed in T16D and Q17D may be attributed to water migrating through the E-fracture from V16D.

Groundwater temperatures in well V16D, the pumping well, declined dramatically at the start of pumping followed by a period of stable temperatures until the end of pumping. At the end of pumping, groundwater temperatures decreased dramatically followed by a long period with continuously rising temperatures. The decline in water temperature at the start of the test is attributed to water from Paradise Creek. The temperature rise in V16D during the recovery period is attributed to Paradise Creek and/or the sediments of Bovill. It is not known whether the groundwater temperatures in V16D would have continued to rise to the pre-test baseline temperature. However, the fluxes of warm and cool water illustrate a hydraulic connection between the sediments of Bovill and the E-fracture, as well as a source of induced recharge water.

The initial water temperature of Paradise Creek was cooler than that observed in the Bovill 1, Bovill 2, Bovill 3, and V16D wells. Water temperature in Paradise Creek rose throughout Aquifer Test #3 and the recovery period. At the end of the aquifer water in Paradise Creek was still cooler than that observed in the sediment of Bovill wells.

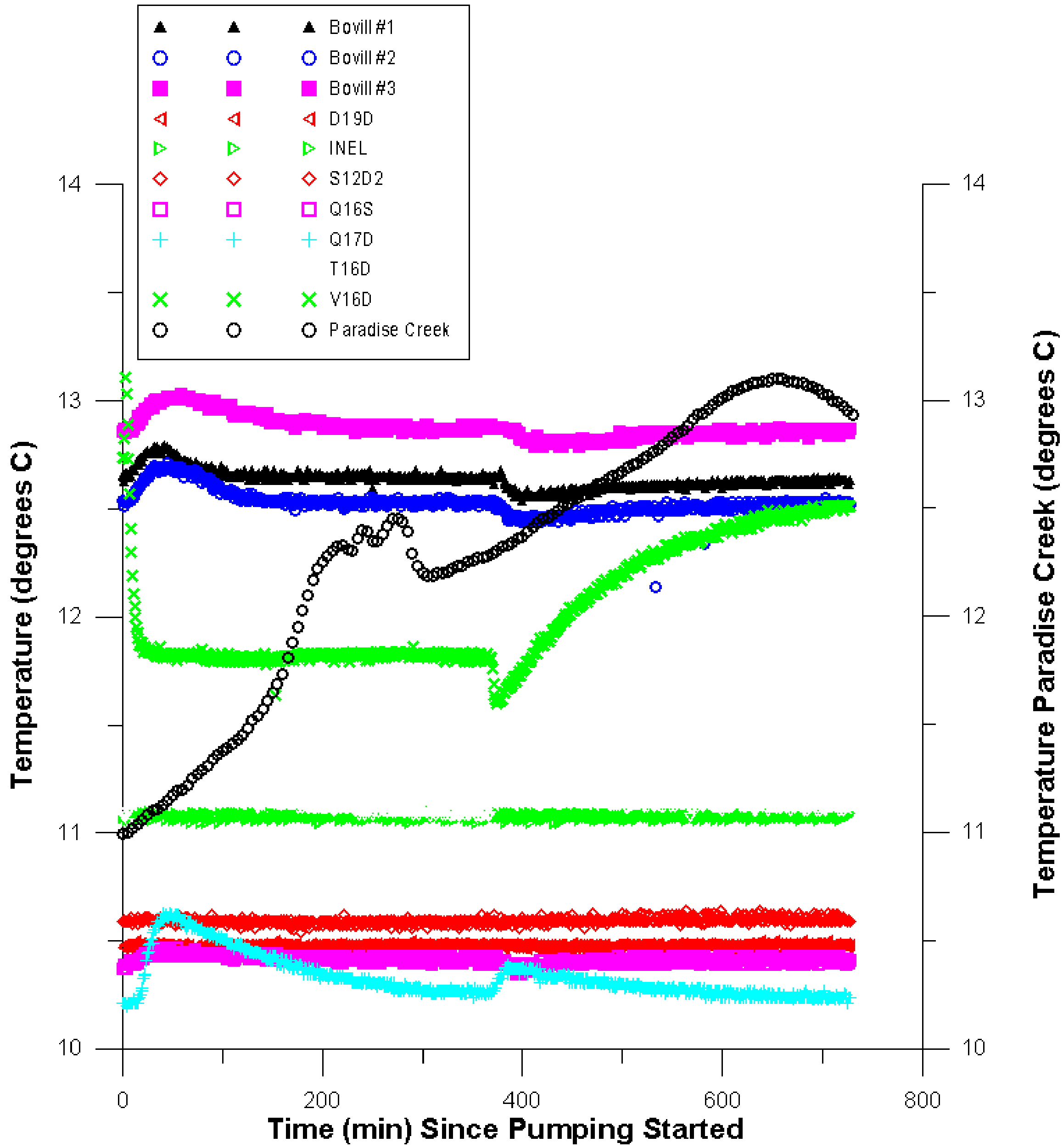


Figure 50. Arithmetic Plots of Groundwater Temperatures for All Monitored Wells During Aquifer Test #3. Pumping ceased at 360 minutes.

CHAPTER 5
HYDROGEOLOGIC CONCEPTUAL MODEL OF GROUNDWATER AND SURFACE WATER INTERACTION

5.1 Introduction

Based on qualitative analysis of water levels for monitoring wells located near Paradise Creek, the stream stage record for Paradise Creek, and the UIGFL aquifer test data and analyses, a conceptual hydrogeologic model of groundwater and surface water interaction at the UIGFL was developed. The conceptual model also incorporates concepts developed by Li (1991), Pardo (1993), Kopp (1994), Heinemann (1994), Wright (1996), Namlick (1998), and Hopster (2003). This conceptual model may provide a basis for assessing the potential feasibility of inducing groundwater recharge to the Wanapum Aquifer system in the area of the UIGFL. Other conditions likely control groundwater recharge in other areas of Moscow-Pullman.

Groundwater and surface water interactions in the Moscow-Pullman area are dynamic, site specific, and related the specific season(s) of the year. In general, streams in the Moscow-Pullman area losing water to the Wanapum Aquifer system flow on top of the Priest Rapids member (Heinemann, 1994). Wright (1996) characterized the Paradise Creek reach along the Sweet Avenue Site as being a source of recharge to the Wanapum Aquifer system. Differences in water level elevations observed between SAS1 and SAS2 support this assessment. Kopp (1994) characterized the Paradise Creek reach along the UIGFL site as being a source of recharge to the "shallow" and "E-fracture" aquifers. The immediate response observed in the sediments of Bovill wells to pumping of the E-fracture, and water level stabilization in the sediments of Bovill wells, and wells V16D, T16D, and Q17D during the aquifer tests, indicate direct hydraulic connection of the groundwater and near surface water near the UIGFL. In addition, water temperature fluctuations measured in the sediments of Bovill wells, V16D, T16D, and Q17D, support this assessment. Lines of evidence in support of the conceptual model for groundwater and surface water interactions in the Moscow-Pullman area are illustrated in Figures 51 through 54.

5.2 Description of the Conceptual Model for Groundwater and Surface Water Interactions

The primary water producing zones in the Wanapum Aquifer system are fractures in the Lolo flow of the Priest Rapids member, and sediments of the Latah Formation in the Moscow-Pullman area. Producing zones located in the basalt comprise large horizontal fractures that may be located at various horizons, as suggested by monitoring well water completion intervals. These horizontal fractures are known to be interconnected by vertical fractures at various depths in the basalt (Figures 51 and 52). Large, areally continuous horizontal fractures similar to the one in Figure 6, and the E-fracture (Figure 8) are connected by large vertical fractures similar to those in Figure 7. The areal extent of the large horizontal is unknown and vertical fractures are not extensive areally; however for this conceptual model the assumptions are: 1) horizontal fractures occur throughout the Priest Rapids member and exist at various depths; and 2) vertical fractures extend through much of the Lolo flow in the Moscow-Pullman area. Water infiltrating into the basalt either from overlying sediments or streambeds may follow three potential pathways; 1) near surface horizontal fractures are interconnected to the surficial sediments via vertical fractures; 2) vertical fractures connect shallow horizontal fractures with deeper horizontal fractures; and 3) smaller conchoidal fractures (Figure 51) in the upper portion of the Lolo flow are connected to larger horizontal fractures by vertical fractures (Figure 7). The presence or absence of these geological features near streams within the Moscow-Pullman area may be a controlling factor on whether or not recharge and subsequent induced recharge occurs spatially.

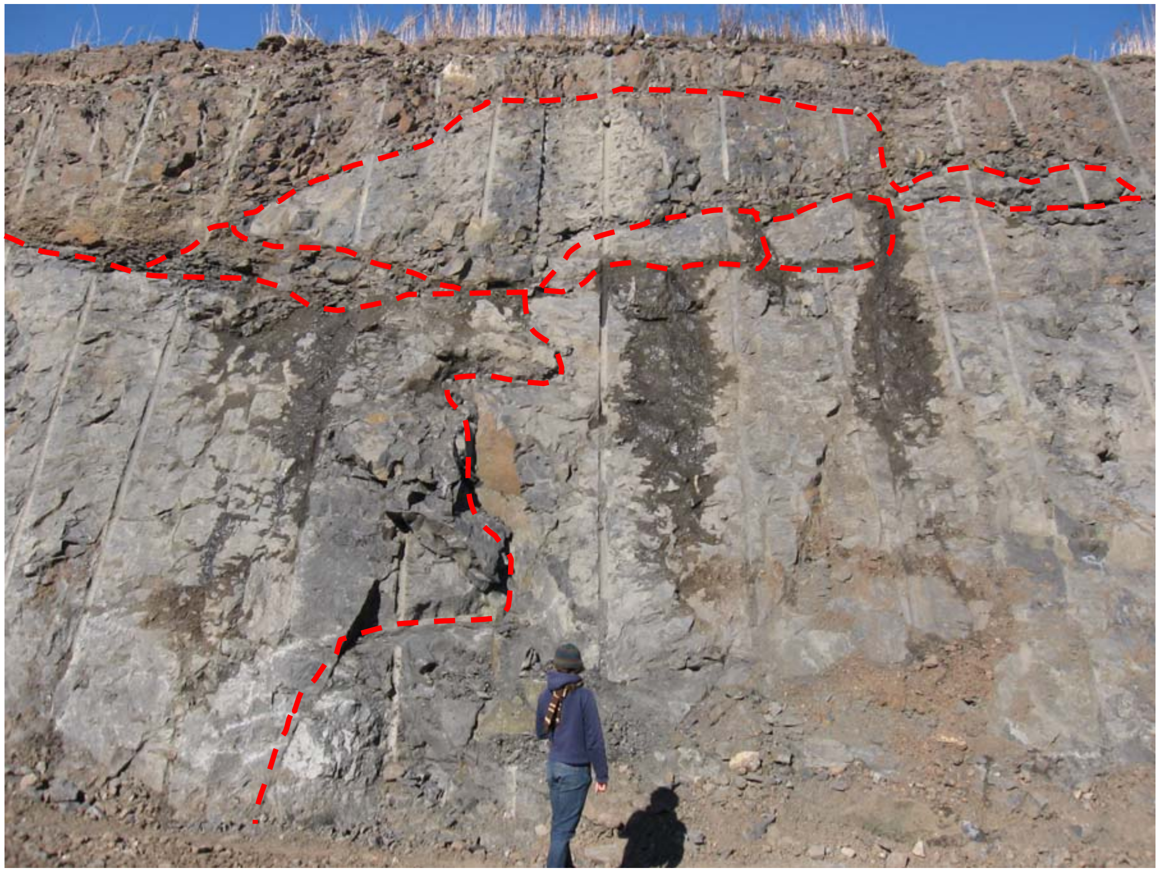


Figure 51. Oxidized flow top of the Lolo Basalt Flow with conchoidal, vertical, and horizontal Fractures. Red dashed lines indicate conchoidal, vertical, and horizontal fractures.

Water infiltrating from the surface through the loess and the sediments of Bovill may first contact the conchoidal fractures and migrate to vertical fractures that are connected to larger horizontal fractures. Water that percolates into the Wanapum Aquifer system and groundwater in residence in the basalt may migrate through the fracture network in a "zigzag" or "step-like" manner as illustrated in Figure 52.

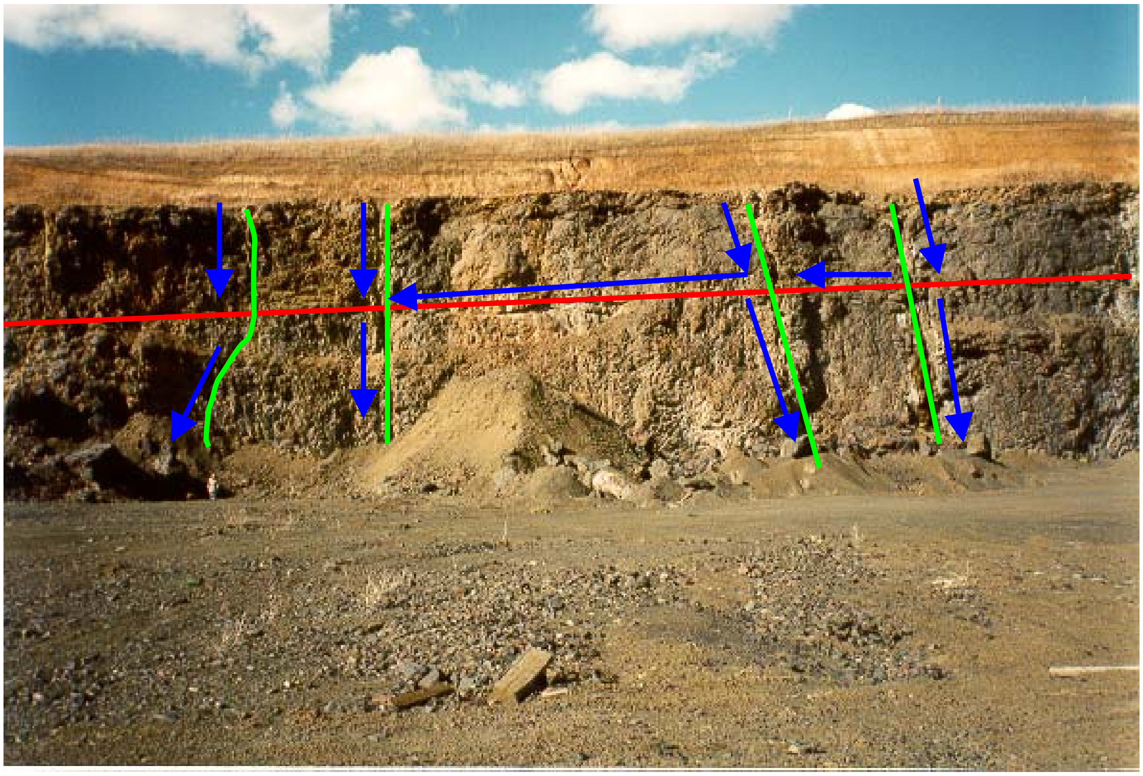


Figure 52. Conceptual model for groundwater and surface water interactions. Red dashed line represents horizontal fracture, green dashed lines represent vertical fractures, and blue arrows represent conceptual water flow paths.

In areas where the loess and the Latah Formation sediments are thicker, more time may be required for infiltrating water to reach the fracture network; infiltrating water may be sequestered in small perched aquifers in the Latah Formation, and/or interflow may be discharged to surface water resources. Similarly, there are two possible ways that losing streams in the Moscow-Pullman area may contribute water to the Wanapum Aquifer system. Streambeds may either be in direct contact with the basalt (Figure 53) as observed in the western Moscow-Pullman area by Heinemann (1994), or streambeds may lie on sediment deposits that overlie the basalt (Figure 54) as observed in the eastern Moscow-Pullman area by Heinemann (1994).

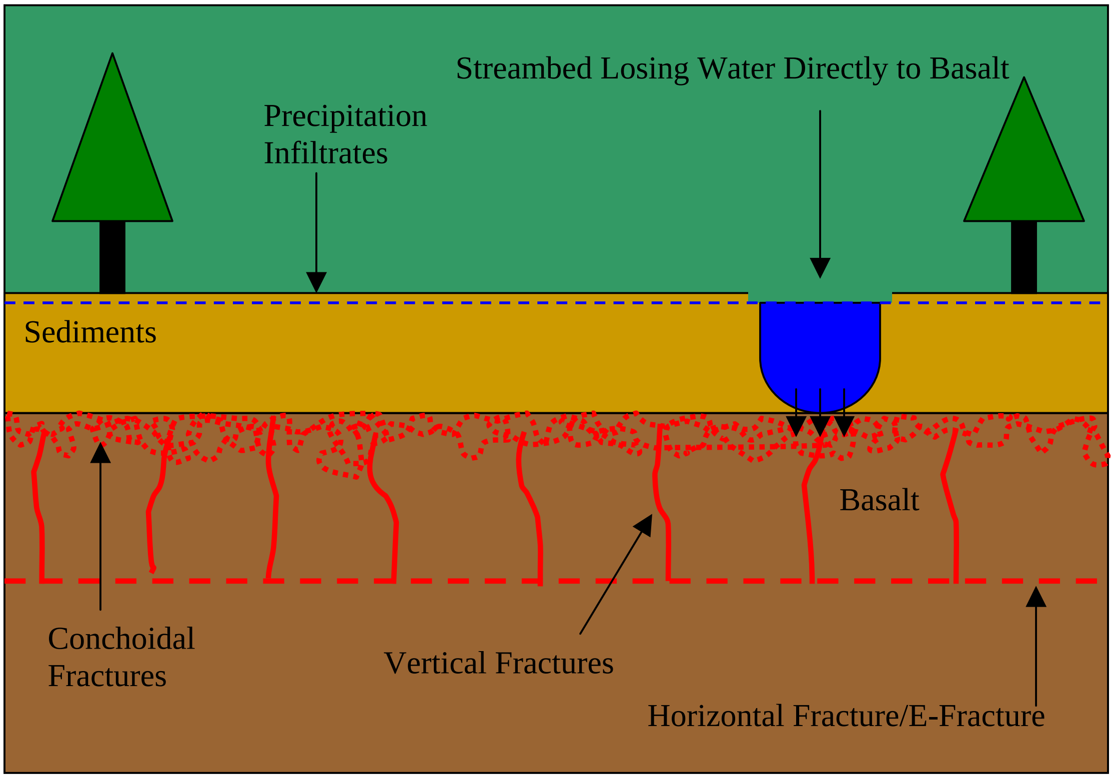


Figure 53. Schematic of streambed in direct contact with basalt.

Where the streambed is in direct contact with the basalt, the fracture network may be such that infiltrating water travels first through conchoidal fractures, and then through vertical fractures before reaching laterally continuous horizontal fractures. The streambed may also be in direct contact with vertical fractures (e.g. either the length of the streambed or a segment of the streambed bisects the vertical fracture). Thus, a strong hydraulic connection with laterally continuous horizontal fractures occurs.

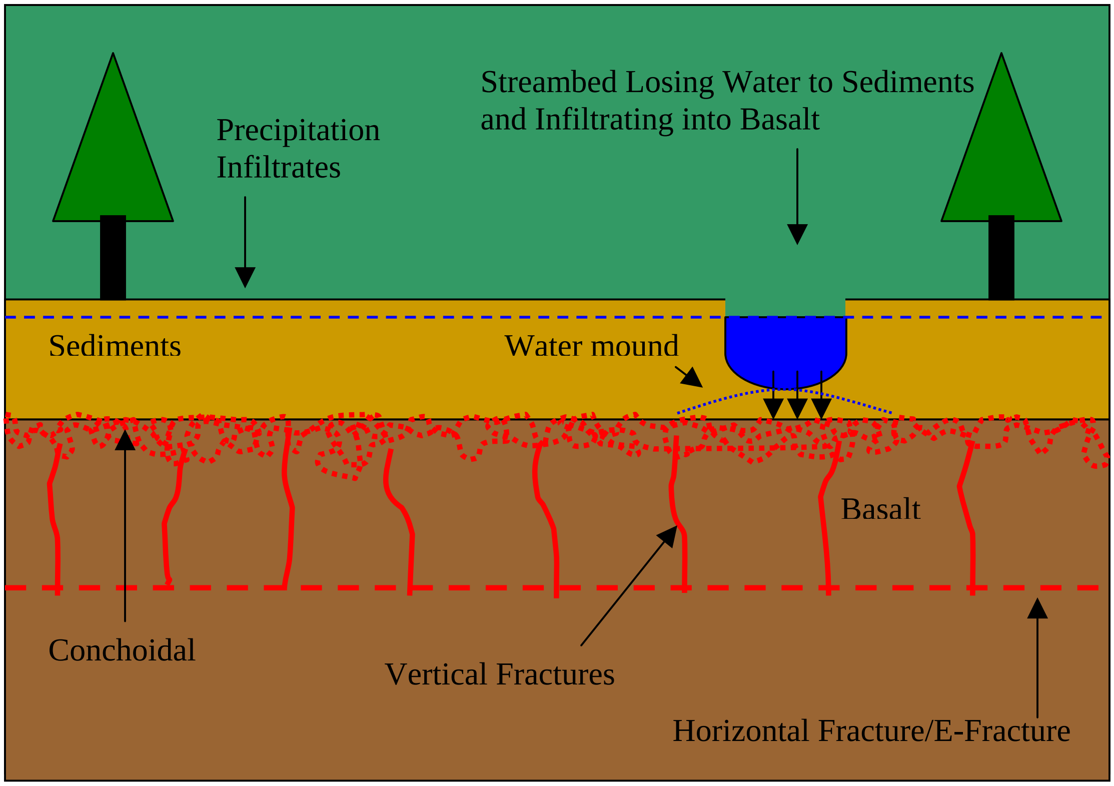


Figure 54. Schematic of streambed in indirect contact with basalt.

Where the streambed is not in direct contact with the basalt, but cuts into sediments, the potential for recharge is controlled by the saturated thickness and hydraulic conductivity of the sediments. Additionally, the heterogeneity and anisotropy of the sediments may create preferential flow paths. Water infiltrates from the streambed into the sediments prior to connecting with a fracture network in the Lolo basalt. This scenario is thought to occur at the UIGFL and the Sweet Avenue Site. Groundwater recharge to the Wanapum Aquifer system in the Moscow-Pullman area is believed to occur where saturated sediments of Bovill are in direct connection with the Lolo flow.

During large flow events due to storms or spring runoff the water mound extends from the top of the creek outwards into the sediments of Bovill. Bank storage is increased. When Paradise Creek is at low flow, late summer, the water mound is limited to the bottom of streambed. Bank storage is not increased.

5.3 Implications for Induced Groundwater Recharge to the Wanapum Aquifer system in the Moscow-Pullman Area

Recharge to the Wanapum basalt in the Moscow area is believed to be controlled primarily by the presence or absence of saturated sediments of Bovill. Along Paradise Creek and the South Fork of the Palouse River, where the sediments of Bovill are saturated, a direct hydraulic connection is maintained with vertical and conchoidal fractures in the basalt. This allows direct flow of groundwater into the fractures under saturated conditions. It is believed that seepage from the creeks is the primary source of recharge to the sediments of Bovill. Where the sediments of Bovill are unsaturated, the vertical and conchoidal fractures probably form capillary barriers and minimize the potential for recharge.

The areal extent of saturated sediments of Bovill varies seasonally and spatially within the Moscow, Idaho area. Recharge to the sediments of Bovill is believed to occur primarily from losing stream reaches along Paradise Creek, the South Fork of the Palouse River, and tributaries during seasonal periods of high streamflow. The primary period for this recharge is generally during winter and spring months, and occurs predominantly between February and May each year. The sediments of Bovill can be viewed as a "recharge distribution system" that stores water temporarily and redistributes that water across the top of the Lolo basalt flow allowing it to percolate into fractures as "recharge". Water that does not percolate vertically into the Lolo basalt discharges into gaining reaches of the streams and effectively becomes unavailable for groundwater recharge. This process is repeated year-after-year as the aquifer system reaches some degree of equilibrium. It is feasible to "disrupt" this equilibrium by strategically locating wells that "induce" recharge during wet periods of water availability (high streamflow periods) by systematically controlling pumping induced hydraulic gradients spatially and temporally.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The complex geology of the Moscow, Idaho, area exerts a major influence on the occurrence of natural groundwater recharge to and discharge from the Wanapum Aquifer system. The following conclusions are based on the data collected during groundwater monitoring of the Wanapum Aquifer system. Monitoring well data indicate:

1) Groundwater flow in the Moscow, Idaho area is highly variable both spatially and temporally.

2) Multiple groundwater flow systems possibly exist in the Moscow, Idaho area.

3) A hydraulic connection may exist between wells AHC, D19D, and INEL-D in the Lolo basalt.

4) A hydraulic connection may exist between the Shumway, TuckBurns, Carson, and Elliott wells.

5) The Carson well is a local groundwater discharge area most of the year.

In addition, based on the data collected during the three aquifer tests conducted at the UIGFL, the following conclusions can be drawn:

1) The shallow alluvial aquifer and the E-fracture aquifer are contiguous is suggested based on the immediate responses observed in the sediments of Bovill wells during aquifer tests conducted at the UIGFL.

2) The shallow alluvial aquifer and the E-fracture aquifer could be connected because of the immediate water temperature fluctuations observed in the sediments of Bovill wells due to pumping wells completed in the E-fracture, in addition to other temperature variations that coincided with pumping cessation.

3) Temperature changes in the sediments of Bovill wells indicate water movement from within the sediments, from Paradise Creek, and mixing of both sources.

4) The slow recovery observed in the sediments of Bovill wells probably indicates that the sediments were partially dewatered during the pumping portion of the aquifer tests.

5) The drawdown observed in well INEL-D in response to pumping of Q17D suggests a hydraulic connection between the Vantage equivalent interbed and the E-fracture.

6) The lack of recovery in wells INEL-D and S12D2 probably indicates either influence from pumping of the UI Aquaculture wells and/or the Appaloosa Horse Club well.

7) The pumping of the UI Aquaculture wells and/or the Appaloosa well impacted INEL-D, D19D, and S12D2 during all of the aquifer tests and caused the non-theoretical responses measured in these wells.

6.2 Recommendations

Several recommendations are offered for improvement on existing studies and for additional studies to more aptly characterize groundwater surface water interactions in the Palouse Basin:

1) Establish precise data logger depths, measure suspension ropes and the exact wellhead elevations so as to more accurately measure water level fluctuations and hydraulic gradients between wells.

2) Compare well logs of monitoring wells to production wells to determine those completed in similar stratigraphic units. Then filter and perform cross-correlation between monitoring wells and Moscow city production wells to determine if there is a response.

3) Establish more monitoring wells in the areas identified as being possibly “unique” systems.

4) Conduct a more comprehensive analysis of water temperature in the Wanapum Aquifer system monitoring wells.

5) Establish more monitoring wells adjacent to surface water resources.

6) Establish a series of nested piezometers along the length of Paradise Creek to more accurately characterize the hyporheic zone.

7) Conduct longer aquifer tests (several days) at the UIGFL to determine if stabilization observed in the monitoring wells is due to delayed yield or

boundary effects due to Paradise Creek. Placement of additional monitoring wells in the north bank of Paradise Creek would help characterize the extent of the cone of depression.

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APPENDIX A

WANAPUM AQUIFER SYSTEM DATABASE

The Wanapum Aquifer System water level data and temperature data are too extensive to be included in a printed format. All the raw and corrected data can be found in the DVD disk in the envelope attached to the back cover of this thesis.

APPENDIX B

UIGFL GROUNDWATER LEVELS AND GROUNDWATER TEMPERATURES

The UIGFL water level and temperature data are too extensive to be included in a printed format. All the raw and corrected data can be found in the DVD disk in the envelope attached to the back cover of this thesis.

APPENDIX C

UIGFL AQUIFER TESTING DATABASE

The UIGFL aquifer test data are too extensive to be included in a printed format. All the data for Aquifer Tests #1, #2, and #3 can be found in the DVD disk in the envelope attached to the back cover of this thesis.

The Theis (1935) solution as modified for unconfined aquifers is described below. The Theis (1935) solution is an analytical solution for describing the two-dimensional radial flow to a well in an infinite, homogeneous, and confined aquifer. The solution is

$$s = \frac{Q}{4\pi T} W(u)$$

$$u = \frac{r^2 S}{4Tt}$$

Where s is the drawdown (change in hydraulic head at a point from the beginning of the aquifer test), u is the dimensionless time parameter, Q is the discharge (pumping) rate of the well [L^3/T], T and S are the transmissivity [L^2/T] and storativity [dimensionless], respectively, for the aquifer around the well, r is the distance from the pumping well to the monitoring well [L], t is the time since pumping began, and $W(u)$ is the "Theis well function." The well function is essentially an exponential integral that may be represented by an infinite series (Freeze and Cherry, 1979) as the following:

$W(u) = [-0.5772 - \ln(r^2S/4Tt) + (r^2S/4Tt) - (u^2/2*2!) + (u^3/3*3!) - (u^4/4*4!) + -\ldots \infty]$

The Theis (1935) solution as applied to an unconfined aquifer is based on the following assumptions: 1) the aquifer has infinite areal extent; 2) the aquifer is homogenous, isotropic, and of uniform thickness; 3) the pumping well fully penetrates the aquifer; 4) flow to the pumping well is horizontal; 5) the aquifer is unconfined; 6) the flow is unsteady; 7) water is released instantaneously from storage with decline of hydraulic head; 8) the diameter of the pumping well is very small so that storage in the well can be neglected; 9) no delayed gravity response in the aquifer; 10) the flow velocity is proportional to the tangent of the hydraulic gradient instead of the sine (which is actually the case); 11) the flow is horizontal and uniform in a vertical section through the axis of the well; and 12) the displacement is small relative to the saturated thickness of the aquifer (AQTESOLV®, 2003). Additionally, AQTESOLV applies the Jacob (1944) correction for drawdown data in an unconfined aquifer. The correction follows:

$$s' = s - (s^2 / 2b)$$

The corrected displacement is s', the observed displacement is s, and the saturated thickness of the aquifer is b. The corrected displacement (s') predicted by the equation reaches a maximum of one-half the saturated aquifer thickness ($0.5b$) when observed displacement is equal to the saturated aquifer thickness ($s = b$). Complete dewatering ($s = b$) of the aquifer is not realistic however, in some cases displacement predicted with the correction equation along the type curve may exceed the saturated aquifer thickness.

APPENDIX D

BAROMETRIC RECORDS FOR 2006

The barometric records for the year 2006 are too extensive to be included in a printed format. All the raw and corrected data can be found in the DVD disk in the envelope attached to the back cover of this thesis. The effects of barometric pressure are described below.

Water-table fluctuations in unconfined aquifers aside from recharge can be attributed to evapotranspiration, atmospheric pressure variations, entrapped air, temperature variations, air solubility, wind, and density. These other mechanisms are considered noise when trying to decipher recharge, hydraulic gradient, and flow direction.

Atmospheric pressure (otherwise known as barometric pressure) fluctuations can have discernible impact on well water level measurements and may lead to erroneous indications of hydraulic head within the aquifer Barometric fluctuations represent changes in areal blanket stress applied directly at land surface and to the open well water level surface (Spane, 1999). The observed response of a well/aquifer system to barometric fluctuations is contingent on the degree of aquifer confinement and hydraulic/storage characteristics. Rasmussen and Crawford (1997) noted that an unconfined aquifer well completed below the water table is distinguished by a decreasing water level response pattern for a step change in pressure for increasing time lags. That is barometric pressure changes result in an instantaneous well response but a delayed response in the water table. Increases in barometric pressure result in water level decreases, conversely decreases in barometric pressure result in water level increases. Barometric pressure can vary by 25 mb in a day during stormy weather. Since one millibar (mb) equals one centimeter of water, this equates to almost 10" of water level error or an error of over 2.5% for a 30' range sensor (GWI, 2007).

Barometric pressure measurements are used to establish the barometric efficiency (BE), which is the ratio of change in hydraulic head [L] to the change in barometric pressure head [L] (Rasmussen and Crawford, 1997) in consistent units.

$BE = -\Delta W/\Delta B$

ΔW = Change in Water Surface Elevation in the Well

ΔB = Change in Barometric Pressure

Rasmussen and Crawford (1997) state that knowledge of the barometric efficiency is important for understanding the relationship between water levels and the total head. Total head, H, is the sum of barometric pressure head, B, and the surface water elevation, W, so $H = B + W$

There are two cases for which an unconfined aquifer can respond to barometric pressure. For a shallow unconfined aquifer a change in barometric pressure results in an immediate total head change in the aquifer. Consequently barometric efficiency is zero. The alternative is for a deep unconfined aquifer where a change in barometric pressure doesn't result in an immediate total head change in the aquifer.

A barometric record for the year 2006 for the Moscow-Pullman area was obtained from the Moscow-Pullman airport (Figure 55). The barometric record was converted from millibars to feet of water so as to be in consistent units with water level measurements in feet of water. Barometric corrections to water level data were performed using Barometric and Earth Tide Response Correction (BETCO ©) software. All monitored wells in the Wanapum Aquifer system network were processed for barometric pressure influences. According to the BETCO © software the Wanapum Aquifer system has a barometric efficiency near zero; the well water level is representative of the aquifer water level. Barometric corrections to water level data are presented in Appendix A.

Figure 55 presents a plot of barometric pressure measurements versus date of measurement (Moscow-Pullman Airport). The barometric pressure measurements were recorded on one-hour intervals. More extreme barometric fluctuations are observed in the fall, winter, and spring than the summer. Barometric pressure ranged from 30.1 ft H_2O to 31.7 ft of water in 2006.

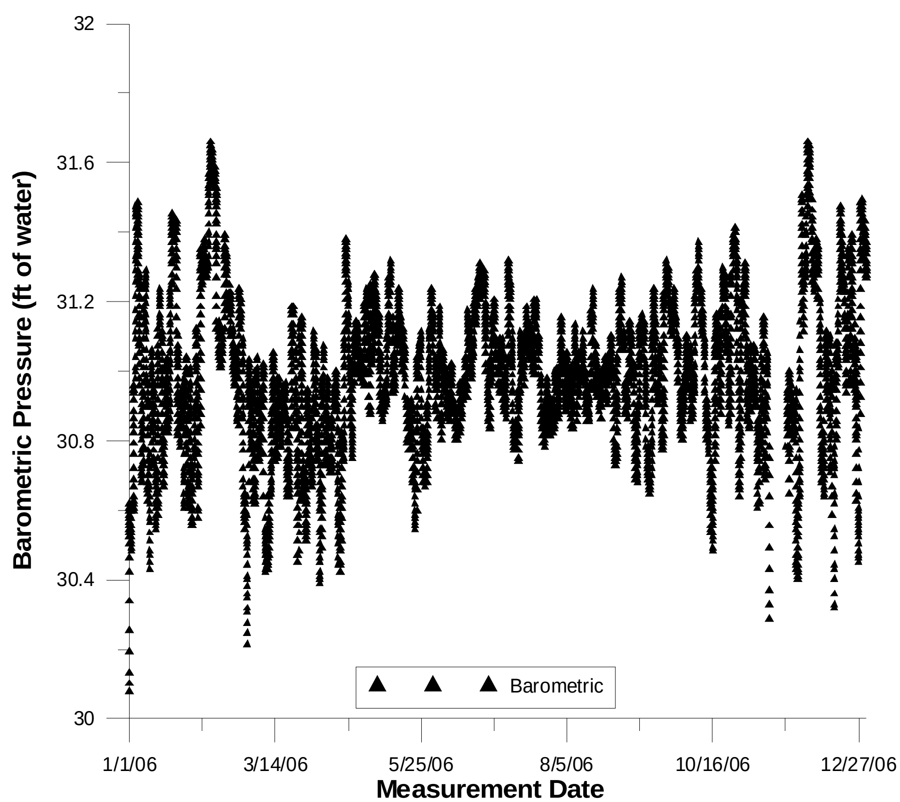

Figure 55. Moscow-Pullman Airport Barometric Record for 2006.

APPENDIX E

GPS SURVEY DATA FOR THE UIGFL

On October 23, 2006 a GPS survey of UIGFL well locations was conducted. A base station was established on the roof of the mines building (Figure 56). The base station location was recorded on five-second intervals for 24 hours. The long recording period increases the accuracy of the location position for triangulation purposes. The well locations were recorded on five-second intervals for ten minutes (Figure 57). All UIGFL wells locations were recorded from the top of the casing. GPS coordinates are included in Table 19.

Figure 56. Base Station GPS #7.

Figure 57. Rover Station V16D GPS #8**.**

Photos by Hernandez (2006)

Table 19. GPS Survey of UIGFL Well Locations.

Point ID	DD_LAT	DD_LON	ELLIPSIODAL HEIGHT	GEOIDAL SEPERATION	ORTHOMETRIC HEIGHT (m)	UTM NORTHERING Y (m)	UTM EASTING X (m)
Mines Base	46.728496633	-117.011162486	787.138	-18.402	805.54	5174993.705	499147.076
V16D	46.731704508	-117.024822964	757.7804	-18.43	776.2104	5175350.406	498103.394
T16D	46.731735811	-117.024948006	758.1851	-18.43	776.6151	5175353.888	498093.841
S12D2	46.731527592	-117.025128400	758.5602	-18.43	776.9902	5175330.754	498080.050
Q17D	46.731797364	-117.025203617	758.3083	-18.431	776.7393	5175360.734	498074.313
Q16S	46.731742658	-117.025188419	758.5736	-18.431	777.0046	5175354.654	498075.473
Paradise Creek	46.731906847	-117.024898975	757.2683	-18.43	775.6983	5175372.892	498097.593
INEL-D	46.731631081	-117.024988267	758.3141	-18.43	776.7441	5175342.251	498090.761
D19D	46.731944492	-117.026278600	757.5902	-18.433	776.0232	5175377.110	497992.184
Bovill 3	46.731813842	-117.024891983	757.3923	-18.43	775.8223	5175362.557	498098.124
Bovill 2	46.731891203	-117.024826386	757.2335	-18.43	775.6635	5175371.152	498103.139
Bovill 1	46.731899211	-117.024926997	757.2845	-18.43	775.7145	5175372.044	498095.452