Recharge Implications of Strategic Pumping of the Wanapum Aquifer System in the Moscow Sub-basin

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By

Bradley Bennett

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Major Professor: Dr. James L. Osiensky, Ph.D.

Authorization to Submit Thesis

This thesis of Bradley Bennett, submitted for the degree of Master of Science with a major in Hydrology and titled "Recharge Implications of Strategic Pumping of the Wanapum Aquifer System in the Moscow Sub-basin" 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.

Major Professor _____ Date May 6, 2009

Dr. James L. Osiensky, Ph. D.

Committee Members _____ Date 5/5/2009

Dr. Gary S. Johnson, Ph. D.

_____ Date 5-4-09

Dr. Stanley M. Miller, Ph. D.

Department Administrator _____ Date 5-6-09

Dr. Mickey E. Gunter, Ph. D.

Discipline's College Dean _____ Date 5-7-09

Dr. Scott A. Wood, Ph. D.

Final Approval and Acceptance by the College of Graduate Studies

_____ Date _____

Dr. Margrit von Braun, Ph. D.

Abstract

The city of Moscow currently pumps groundwater from both the Wanapum and Grande Ronde aquifer systems. Water levels in the deeper Grande Ronde aquifer system have been declining steadily for the past century. The Wanapum aquifer system hydraulically is much more dynamic than the Grande Ronde, and is known to receive substantial recharge annually. Currently the Wanapum aquifer system shows seasonal water level fluctuations, but also much more stable and controllable water levels than the Grande Ronde aquifer system. The Wanapum is used primarily as a supplemental source of water to help mitigate the declining groundwater levels in the Grande Ronde by reducing the need to pump the deeper, older groundwater. Moscow city well #2 (Moscow #2) is the primary municipal pumping well in the Wanapum aquifer system. As part of a Palouse Basin Aquifer Committee (PBAC) funded research project, this well was used to conduct a long-term aquifer stress test (68 days) in the winter of 2007-2008. Pumping during the 68-day period, by design, and in cooperation and with the aid of the city of Moscow Water Department, essentially doubled the normal pumping stress exerted during typical winter seasons. Area groundwater levels declined during the pumping period of the test; however, drawdown appears to have stabilized during active pumping to a new equilibrium. During the test, mechanical failure of the pump caused pumping to cease, and the water levels were allowed to recover. After mechanical failure ended the Moscow #2 Aquifer Test, a second long-term (70 day) aquifer test was conducted using Moscow #3 as the primary pumping well. Moscow #3 Aquifer Test analysis suggests the Wanapum aquifer system may consist of at least two aquifers separated by a leaky aquitard. Observations made during the pumping and recovery portions of the aquifer tests suggest that it may be feasible to stress the Wanapum aquifer system strategically during the winter and spring months when more runoff and snowmelt water is available areally to induce as recharge to the aquifer. Aquifer stress test results are presented that suggest it may be possible to maximize the sustained yield of the Wanapum aquifer system by programming pumping episodes strategically in time and space to maximize induced recharge during times of maximum recharge water availability.

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Chapter 1 - Introduction

Overview

The Moscow, Idaho, area relies on groundwater as the sole source of municipal and domestic water supplies. Groundwater development in the area began in the late 1800's, when water was supplied by flowing artesian wells, penetrating the Wanapum aquifer system. The Wanapum aquifer system is the shallower of two aquifer systems that supply water to citizens in the Moscow area, and was the main groundwater resource system until the 1960's. Although many wells were originally flowing artesian wells, the continued draw on the groundwater resource system caused water levels in the shallow aquifer system to decline by rates up to several feet annually.

In 1963, not even 100 years since flowing wells were typical in Moscow, the water level in Moscow city well #2 (Moscow #2), a municipal well, had fallen to 120 feet below ground surface (bgs). Water shortages in the 1950's resulted in the need to drill new, deeper wells; since the early 1960's all new municipal wells have been drilled into the deeper Grande Ronde aquifer system. Since then, water levels in the Wanapum aquifer system have recovered by as much as 70 feet in 1990 to a static water level around 50 feet bgs. As of April 2008, the static water level in Moscow #2 was approximately 71.5 feet bgs. The relatively quick recovery of the Wanapum aquifer system indicates water does in fact recharge the aquifer system, and a balance between pumping and recharge likely can be established over a time period of several years under proper management.

Currently, municipal pumping of the Wanapum aquifer system is conducted primarily to relieve the pressure placed on the municipal wells of the deeper Grande Ronde aquifer system during periods of high demand, such as the irrigation season. However, many domestic wells and a few irrigation wells still pump from the shallow groundwater system. The Wanapum aquifer system may be able to supply a larger amount of water than is currently being exploited. This study aims to evaluate whether it is possible to pump the Wanapum aquifer system strategically in time and space in order

to increase and maximize withdrawals seasonally while maintaining stable groundwater levels over periods of several years.

Statement of Problem

Currently (2009), the Grande Ronde aquifer system is the main source of drinking and irrigation water in the Palouse Basin, an area of approximately 250 square miles (Figure 1). The cities of Moscow and Pullman, along with the University of Idaho and Washington State University, are concerned over the significant rate of water level decline, approximately 1.0-1.5 feet annually. Local groundwater systems may not be able to support the current population without continually declining water levels, let alone accommodate for future growth of the two cities and universities. A groundwater management plan has been implemented wherein the cities and universities limit their annual pumping increases by 1%, with an upper ceiling of 125% of the 1981-1985 average pumping amounts. Even with the support and cooperation of water users in the area, water level declines have not stopped, and the Idaho Department of Water Resources (IDWR) has expressed concern over the possible "mining" of groundwater in the area. Groundwater mining is the extraction of water beyond the rate of natural recharge.

It is essential to understand the Wanapum aquifer system, and utilize the groundwater resource system to its fullest capacity while not adversely impacting water levels. Recharge of the Wanapum aquifer system appears to occur at a much higher rate than recharge to the deeper aquifer system. Under proper management, groundwater in the Wanapum aquifer system can be considered a renewable resource and should be managed to help mitigate the falling water levels in the Grande Ronde aquifer system.

Hypothesis and Objectives

Previous researchers have observed that, in the vicinity of Moscow, the Wanapum aquifer system is hydraulically interconnected with local streams through the overlying sedimentary unit (sediments of Bovill) over which the streams flow. Recharge from Paradise Creek to the Wanapum aquifer system has been observed at the University of Idaho Groundwater Field Lab (UIGFL) (Hernanadez, 2007). Other researchers (Li, 1991; Pardo, 1993; Heinemann, 1994) have suggested that local streams have seasonal

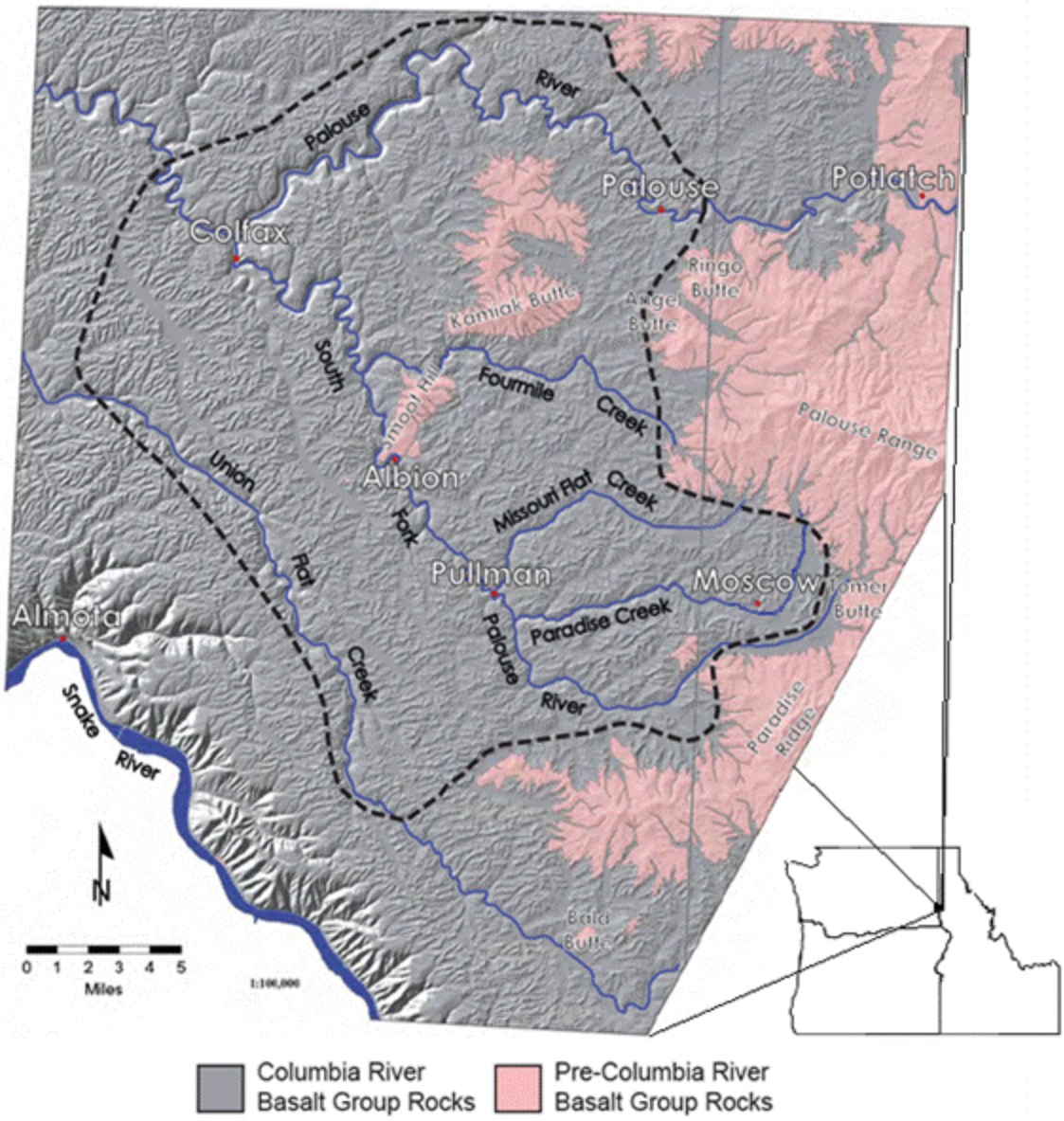

Figure 1. Physiographic map of the Palouse Basin (modified from Bush 2006). Study area is the eastern portion of the Palouse Basin in the Moscow area.

discharge/recharge relationships with the shallow aquifer system. When stream flows are high, the streams are losing water through the streambed alluvial deposits to the sediments of Bovill; during the late summer, the streams are gaining water from the sediments of Bovill.

Throughout the year, a downward gradient exists from the sediments of Bovill to the fractured basalt of the Wanapum aquifer system. The amount of water moving between the streambed/sediments of Bovill and the Wanapum aquifer system is controlled by the hydraulic gradients between the two systems, and the wetted perimeter of the stream/streambed contact. Darcy's Law states that for a given hydraulic conductivity, the steeper the gradient is between two points, the more water will move between the two locations. Based on this principle, if the water level in the Wanapum aquifer system were to be lowered while a considerable amount of surface water is available (i.e., high stream flows), both the hydraulic gradient and the wetted perimeter would be maximized. Maximizing the hydraulic gradients when the wetted perimeters of streams are the largest will result in maximum water flow (recharge) into the shallow aquifer.

Hypothesis:

> Additional groundwater recharge to the Wanapum aquifer system can be induced by controlling hydraulic gradients strategically in time and space.

Objective:

> Investigate the potential for managed pumping of the Wanapum aquifer system to increase and maintain drawdown in the system while surface water is available for recharge, thereby inducing the maximum amount of water to enter the groundwater system each recharge season.

Method of Study

In 2005, the Palouse Basin Aquifer Committee (PBAC) established a groundwater monitoring network for the Wanapum aquifer system. PBAC maintains two groundwater monitoring networks in the Palouse Basin, one for the deeper Grande Ronde aquifer system, and one for the Wanapum aquifer system. Wanapum aquifer system observation wells (Figure 2) consist of privately owned wells, municipal wells, and state or university established monitoring wells, completed at different intervals within the Wanapum aquifer system (Table 1). The purpose of the monitoring network is to provide PBAC with long-term water level records to assist in the evaluation of current groundwater management strategies.

The monitoring network for the Wanapum aquifer system consists of 19 wells in and around the Moscow area. Well locations and elevations (top of casing) for most wells have been determined using Leica 500™ high precision global positioning system survey equipment. Each well has a programmable Solinst Levelogger™ (data loggers) submerged within the water column to record the water pressure above the data logger (as feet of water) and the water temperature in degrees Celsius. Measurements are recorded at pre-determined, programmed time intervals (generally at one-hour). Simple calculations are performed to convert the pressure readings into water levels. However, the data loggers record total pressure exerted on the transducers; this includes water pressure plus atmospheric pressure (barometric pressure). Barometric influences can significantly affect a water level record, potentially masking small changes in water level that are due to pumping. Therefore, barometric pressure is measured at several locations within the Palouse Basin, including in well UI #2 on the University of Idaho campus, in the WSU test well in Pullman, and in Palouse well 2. Solinst Barologger Gold™ data loggers built to accurately measure barometric pressure are used at all three locations. Records of barometric pressure are used to remove the barometric influence from the measured water levels during aquifer pumping tests.

Since the inception of the Wanapum aquifer system monitoring network, a database (Appendix A) consisting of water level records and depth to water measurements has been maintained by PBAC. The majority of the wells in the network

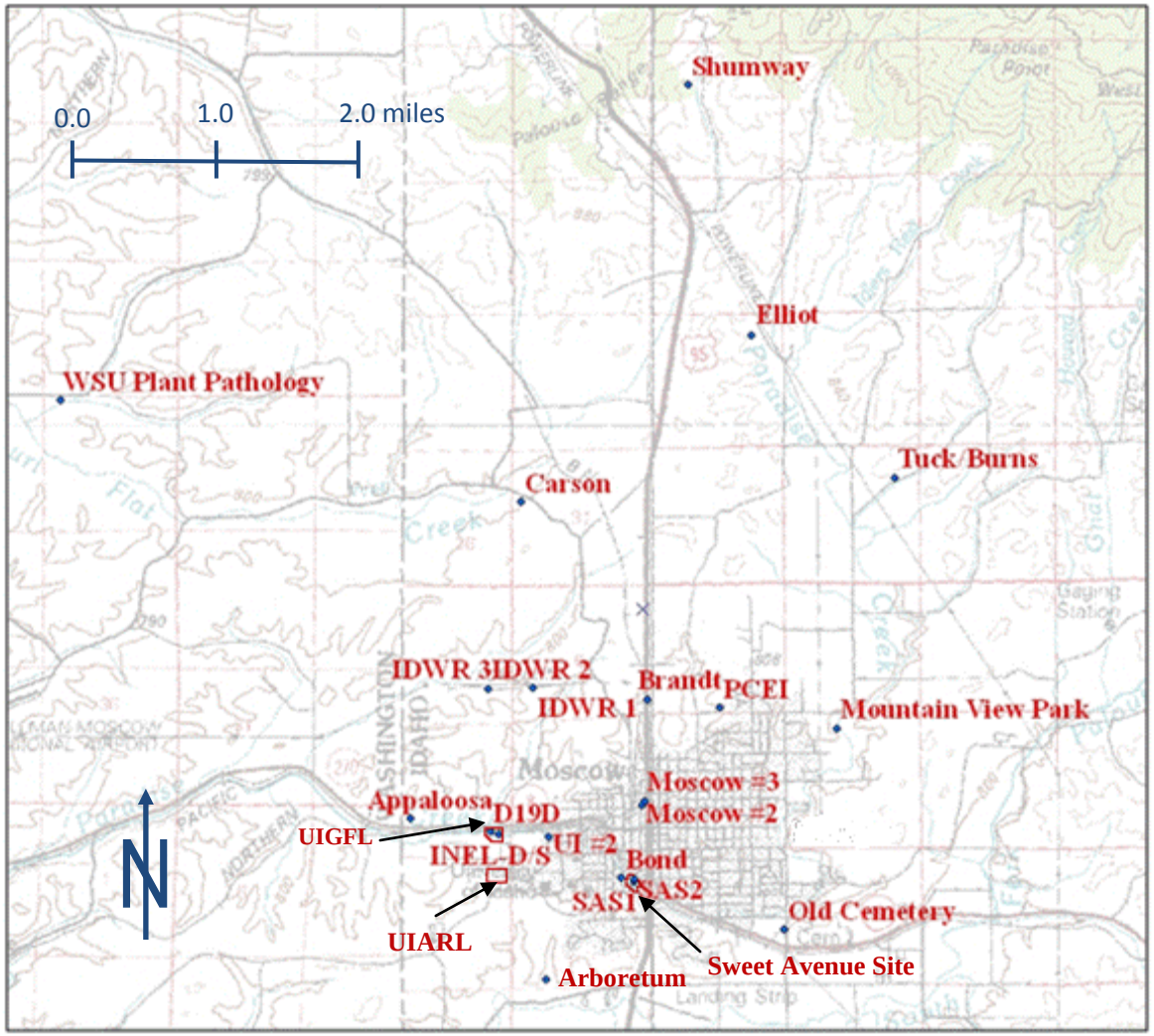

Figure 2. Wells monitored in the PBAC Wanapum aquifer system monitoring network. Moscow #2 and Moscow #3 pumping wells were used in long-term aquifer tests for this investigation.

Wanapum Aquifer System Wells Utilized in this Study					
Well Name	**Wellhead Elevation**	**Interval Open to Aquifer**	**Completion Medium**	**Monitoring Status**	**Well Status**
Appaloosa	2559.32	2504.32-2345.32	basalt	monitored	domestic
Bond	2587.8	unknown	basalt	unmonitored	unknown
Brandt	2643.89	2524.89-2364.89	basalt	monitored	domestic
Carson	2609.4	unknown	basalt	monitored	domestic
D19D	2543.97	2408.97-2403.97	basalt	monitored	observation
Elliott	2732	unknown	unknown	Monitored	domestic
IDWR 1	2637.25	2577.25-2567.25	sediments	Monitored	observation
IDWR 2	2624.98	2354.98-2344.98	sediments	Monitored	observation
IDWR 3	2625.51	2280.51-2270.51	sediments	Monitored	observation
INEL D	2546.71	2354.71-2344.71	basalt sediments	Monitored	observation
INEL S	2546.71	2456.71-2446.71	basalt	Monitored	observation
Moscow #2	2568	2534-2328	basalt sediments	unmonitored	municipal
Moscow #3	2568	2306-1999	sediments	unmonitored	municipal
Mountain View Park	2614.85	unknown	sediments	Monitored	irrigation
Old Cemetery	2600	2144-2092	sediments	Monitored	un-pumped
PCEI	2602*	2455-2435	basalt	Monitored	un-pumped
SAS1	2554*	unknown	sediments	Monitored	observation
SAS2	2545*	unknown	basalt	Monitored	observation
Shumway	2990.7	2970.7-2861.7	granite	Monitored	domestic
Tuck/Burns	2669.9	2539.9-2509.9	basalt	Monitored	domestic
UI #2	2557.4	2497.4-2467.4; 2367.4-2282.4; 2252.4-2207.4	basalt sediments	Monitored	un-pumped
WSU Plant Pathology	2531**	Unknown	basalt	Monitored	domestic
*Elevation estimated by DEM, **Elevation estimated using hand-held GPS unit					

Table 1. Well completion information for the Wanapum aquifer system monitoring network**.**

have water level records going back several years. Long-term water level records were used to evaluate seasonal fluctuations, as well as assess any apparent hydraulic connections between wells (i.e., wells showing similar responses during the same period of time) (Appendix B). Analyses of long-term water level fluctuations are presented in Chapter 5.

Aquifer tests for this thesis investigation were conducted with assistance and support from the city of Moscow Water Department. After developing a pumping strategy with the water department, Wanapum aquifer system municipal pumping rates and times were recorded by water department personnel. During aquifer tests, wells in the monitoring network were generally set to record measurements every hour on the hour. Some data loggers were occasionally set to record every minute in order to obtain more detailed observations of pumping effects. The two pumping tests completed for this study were conducted over a period of nine months. During each multiple-month aquifer test, pumping rates were variable and based on consumer demands.

The software program BETCO© was used to remove fluctuations in water levels due to barometric pressure changes during the aquifer tests. Once barometric pressure influences were removed from the water level records, pumping effects were more easily observed. Observations of drawdown due to pumping were analyzed using curve matching techniques in the software program AQTESOLV®, which is a computer software package designed specifically for aquifer test analyses. The software generates type curves for specified pumping conditions, and for specific aquifer conditions based on several published aquifer test solution methods. AQTESOLV® incorporates the principle of superposition for multiple pumping wells and variable pumping rates, as well as for image wells to simulate the aquifer boundaries. Aquifer tests will be discussed further in Chapter 4.

Geographic Setting

Moscow, Idaho, is located on the eastern edge of the Palouse Basin. The area lies at the eastern extent of the Columbia River Plateau. Moscow is surrounded on three sides by crystalline basement rocks, which extend above the basalts of the plateau and form a horseshoe-shaped ring of topographic highs (Figure 3). To the north is the Palouse

Range and Moscow Mountain with an elevation of 4,983 ft. Southeast of Moscow is Paradise Ridge (elevation 3,702 ft), and Tomer Butte with an elevation of 3,474 ft. These topographic highs surrounding Moscow and the University of Idaho (average elevation of 2,550 ft) delimit the study area to the north, east and south. The western boundary of this study area is defined by the conspicuous absence of sediments of Bovill and significant thinning of subsurface sediments approximately one-mile west of the Washington-Idaho border (Figure 4).

The horseshoe-shaped topography contains some of the world's most productive dryland wheat growing soils. Windblown loess deposits form dune-like features on a grand scale. The rolling hills of the Palouse consist of excellent soils that require no irrigation. This allows for dryland farming of wheat, dry peas, and lentils. The fine grained nature of the soils allow ample amounts of moisture storage, making irrigation unnecessary despite the warm, dry summers typical of the area.

Moscow receives approximately 24 inches of precipitation annually; however, the SNOTEL site on Moscow Mountain reports an average annual precipitation of approximately 41 inches. Precipitation in this area is greatly influenced by orographic uplift. This region is considered semi-arid with a typically mild climate, exemplified by cool wet winters and springs, with warm dry summers. The majority of precipitation occurs between November and May. Winters generally produce about 49 inches of snow with larger amounts occurring at higher elevations in the surrounding areas.

Several streams pass through the rolling hills in the Moscow area. Major streams in the area are: Missouri Flat Creek to the North, Paradise Creek running through the city of Moscow, and the South Fork of the Palouse River to the south (Figure 3). These streams are fed by several smaller unnamed tributaries which also play a role in surface water/groundwater interactions. Due to the uniform distribution of streams in the Moscow area, there are plentiful opportunities for recharge to the shallow aquifer via losing stream segments.

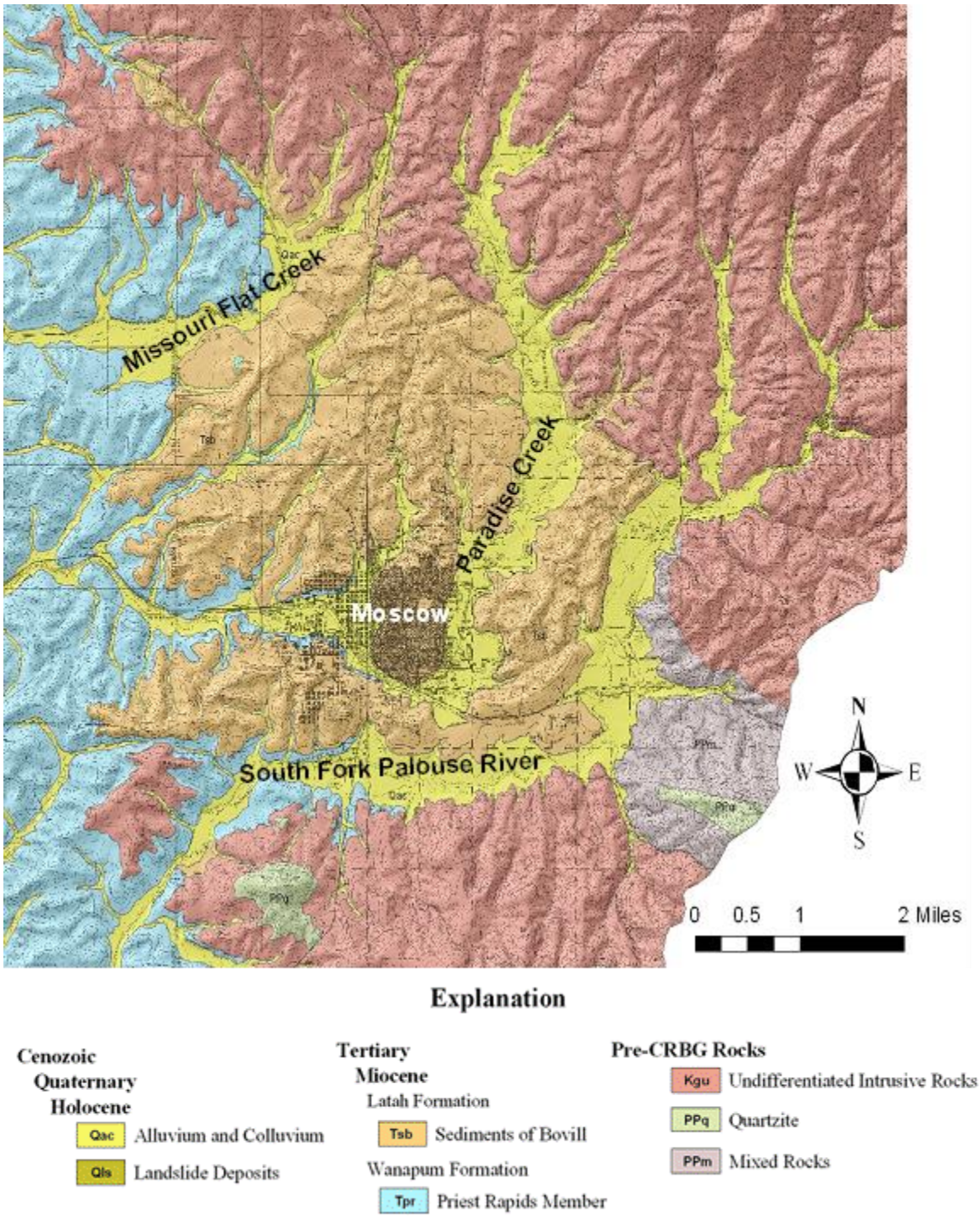

Figure 3. Geologic map of Moscow area surface geology (modified from Bush et al., 2007). Existence of the sediments of Bovill helps to delimit the western bounds of the study area. Local streams are marked in their floodplains.

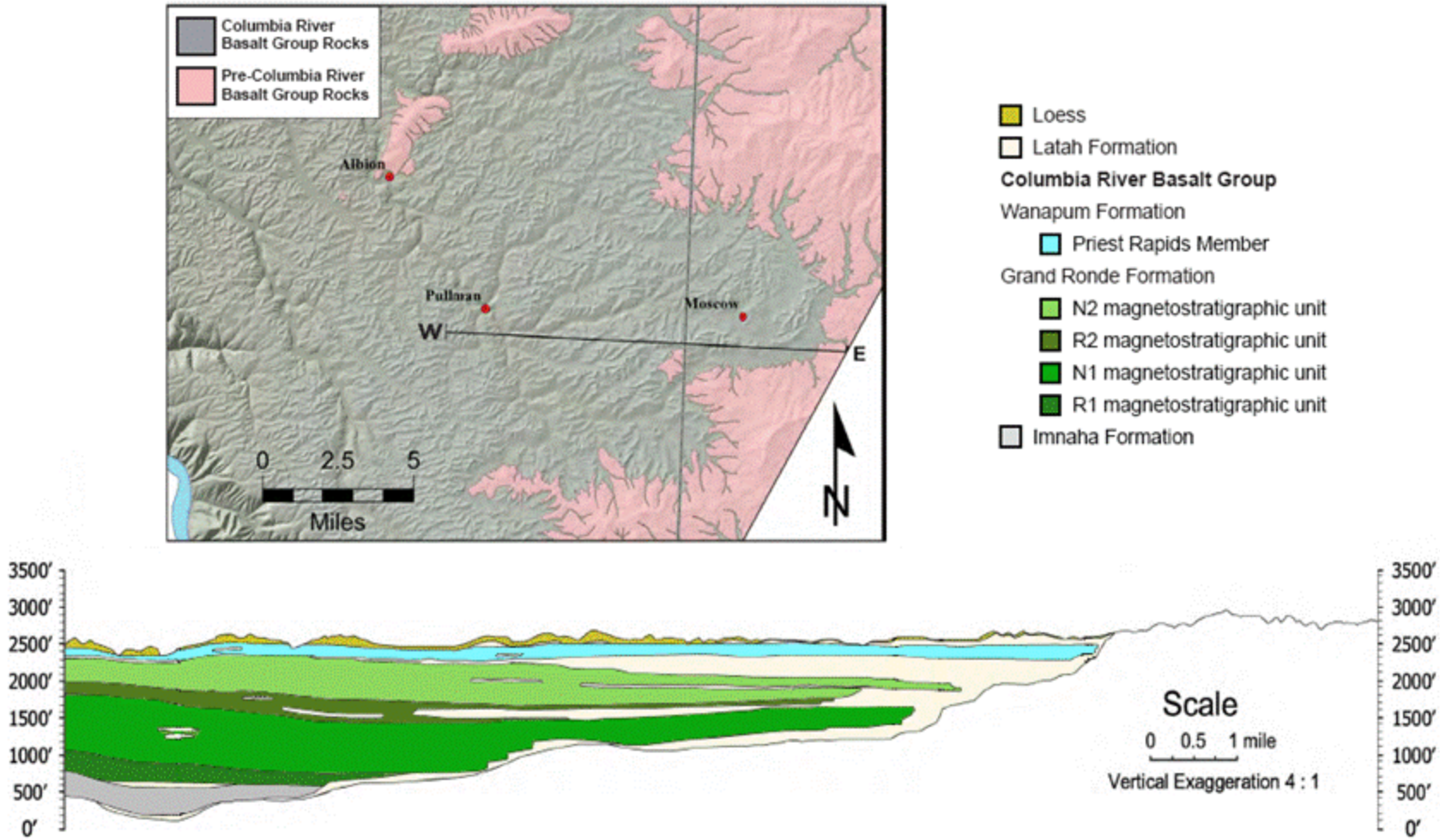

Figure 4. Geologic cross-section through the study area (modified from Bush and Garwood, 2004). Columbia River Basalt Group formations and associated interbeds are illustrated. Thinning sediment interbeds directly below the Wanapum Formation to the west of Moscow help to delimit the western bound of the study area.

Previous Investigations

Research of the groundwater resource systems in the Moscow area began in the 1890's. Russell (1897) was the first to characterize local groundwater basins. He warned of water resource issues to come after seeing uncapped artesian wells allowing groundwater to discharge freely into streams. Since then, water levels have consistently fallen, leading most research in the area to be focused on groundwater sustainability. Stevens (1959) believed groundwater entered the basin along the crystalline basement rocks/sediment contacts and percolated into the coarser grained sediments between the basalts and basement rocks; water then moved into fracture zones and sedimentary interbeds below Moscow. Foxworthy and Washburn (1963) delineated the local groundwater basin, suggesting that the Moscow-Pullman basin could be divided into two groundwater sub-basins and Lin (1967) suggested that paleochannels incised into the crystalline basement rocks are pathways for groundwater discharge out of the Moscow area.

Since then, the basin geology has been studied in order to identify physical controls of groundwater recharge (Provant, 1995; Pierce, 1998; Bush 1996). Many investigators have attempted to estimate the amount of recharge, and to define the mechanisms that control groundwater recharge in the Moscow area. Several studies have identified deep percolation through the loess and sediments as a likely mechanism (Barker, 1979; Douglas, 2004); others have suggested infiltration via sediments along the contact with the older crystalline basement rocks (Lin, 1967; Bush 2005). Losing streams have also been proposed as sources of aquifer recharge (Provant, 1995; Pierce 1998).

Age dating has been used to predict mechanisms of groundwater recharge, and to estimate groundwater residence times. Using ^{14}C age dating, Crosby and Chatters (1965) concluded that no measureable recharge has occurred in Moscow since the Wisconsin glacial stage. Larson (1997) used stable oxygen isotopes to derive relative dates for local water resources, and concluded that the Wanapum aquifer has experienced recent recharge. Later, Douglas (2006) used ^{14}C age dating to estimate the ages of groundwater in the Palouse Basin. ^{14}C sampling yielded a wide range of age dates for the Wanapum

aquifer system with spatially variable age dates from recent to about 14,600 years old. These variable ages support the conclusion by Badon (2007) that the Wanapum aquifer system is compartmentalized, and that the youngest groundwater occurs near streams.

Several analytical and numerical models that simulate groundwater resources of the Palouse Basin have been developed over the years. Jones and Ross (1969) conducted aquifer tests, and collected data from over 230 wells in the area to create a mathematical model of the basin. Their model predicted water resources in the area would last for approximately 100 years. Barker (1979) constructed a geologic foundation for groundwater movement using well logs and potentiometric surface measurements. Barker's two-dimensional, numerical model suggested water level declines would continue in the basin. Later, Smoot and Ralston (1987) developed a three-dimensional numerical model of the groundwater resource systems. The model indicated water levels would stabilize if the amount of pumping were to level off (Lum et al., 1990). A sensitivity analysis of the model developed by Smoot and Ralston was conducted by Brown (1991). Brown exposed numerous inaccuracies in the model's depiction of groundwater flow and indicated that the model simulations may not be accurate.

Several groundwater studies have been conducted at the University of Idaho Groundwater Field Lab (UIGFL). Li (1991) used aquifer pump tests, slug tests, surface water and groundwater hydrographs, and geophysics to characterize the hydrogeologic conditions at the UIGFL. He delineated three producing zones at the UIGFL, a shallow alluvial aquifer, the e-fracture aquifer, and the w-fracture aquifer. While conducting aquifer pump tests at the University of Idaho Aquaculture wells, Kopp (1994), found that some wells completed in Wanapum basalt at the UIGFL are hydraulically connected with both the overlying and underlying sedimentary units. Tracer tests conducted at the UIGFL by Nimmer (1998) showed that groundwater followed distinct, preferential, fracture flow paths in the Wanapum basalt over distances of tens of feet.

Heineman (1994) used well logs and water level data to identify relationships between local streams and groundwater resource systems in the Palouse Basin. He concluded that several streams in the area receive groundwater from the Wanapum aquifer system where the streams have incised into the Wanapum basalt. Where streams

flow over the sediments of Bovill, they generally lose water to the shallow groundwater systems. Pardo (1993) suggested that a seasonal groundwater recharge-discharge relationship exists between the Wanapum aquifer system and Paradise Creek. Wright (1996) and Namlick (1998) suggested a similar seasonal recharge-discharge relationship may exist approximately one mile east of the UIGFL, along at the Sweet Avenue Site (Figure 2). Hernandez (2007) monitored water levels and temperatures in several sediment of Bovill wells while conducting aquifer pumping tests at the UIGFL. Water levels in the shallow sediment wells declined due to pumping of fracture zones at a depth of about 75 feet bgs in the Wanapum basalt. Water temperature data collected during the aquifer pump tests indicate that water leaked from Paradise Creek into the sediments of Bovill during and immediately following the aquifer tests.

Two previous studies have been conducted pertaining to the same two city of Moscow municipal wells used in this research. An analysis of sustained yield for the Wanapum aquifer system was completed using water level records from United States Geological Survey (USGS), and pumping records from the city of Moscow and the University of Idaho; sustained yield was estimated to be 500 to 520 million gallons per year (Baines, 1992). He estimated that sustained yield was approximately 50 to 70 million gallons less than the annual recharge to the Wanapum aquifer system. Badon (2007) conducted several aquifer tests by pumping city of Moscow municipal wells. Test results suggested the Wanapum aquifer system is compartmentalized and poorly connected hydraulically in an east-west direction. She concluded the aquifer is heterogeneous and most likely anisotropic. Calculated values for transmissivity and storativity suggest the aquifer may be unconfined in the vicinity of the Moscow #2 well; however, this may be accounted for by the method of analysis used, which did not account for aquifer boundaries or aquitard leakage.

Chapter 2 - Hydrogeology

Introduction

In order to develop a conceptual model for groundwater movement in the Moscow area, it is essential to understand the physical controls in the subsurface. Understanding the geology and its evolution are vital to understanding the details of groundwater movement. Due to the complex nature of groundwater movement in basalt aquifers in general, it is important to develop an understanding of the internal structure and characteristics of individual basalt flows and flow packages. Further complicating the local hydrogeology is the close proximity of Moscow to much older and relatively impermeable rocks that form the local horseshoe-shaped topography discussed previously.

Regional Geology

Moscow sits at the eastern extent of the Columbia River Plateau, where the thick sequence of flood basalt flows and interbedded sediments making up the plateau are terminated by crystalline rock outcrops. These basalts and interbeds are collectively known as the Columbia River Basalt Group (CRBG). The CRBG is a vast sequence of Miocene flood basalts covering the majority of northeast Oregon, eastern Washington and western Idaho. These rocks are between 17 and 6 million years old, and form the geologic framework for a significant regional aquifer system. Within the CRBG, four formations, (Imnaha basalt, Grand Ronde basalt, Wanapum basalt, and the Saddle Mountain basalt) (Swanson et al., 1979) have been identified as being unique geochemically, magnetically, or stratigraphically.

The vast majority of the CRBG was emplaced in a 2.5 million year period between 17 and 14.5 million years ago (Swanson et al., 1979). Lava erupting from fissures or vents in eastern Washington, northeastern Oregon, and/or western Idaho churned out over the landscape. These eruptions (basalt flows) typically advanced as sheets of lava ranging in thickness from ten to over 300 feet. Some eruptions covered thousands of square miles and sent flows hundreds of miles from their origin. Over 300 individual flows have been identified giving the CRBG a total thickness up to 15,000 feet (Tolan et al., 1989; Reidel et al., 1989).

Limiting the expansion of these basalt sheets to the east was a mountain range consisting of Cretaceous age granites as well as Pre-Cambrian and Cambrian metasediments. Prior to the infilling of valleys with basalt, it is believed the area known as the Palouse consisted of significant topographic relief, similar to parts of northern Idaho today (Russell, 1897). Evidence of rugged topography exists in places like the Kamiak and Four Mile Creek gaps (Figure 1), where hills and buttes composed of older metamorphic rocks and/or granite are surrounded by younger basalt. Basalt flowed into the valleys covering the steep, high energy, stream channels, and damming the drainages. As basalt flows progressed eastward, lakes were formed and sediments were deposited between successive basalt flows. Sub-horizontal sedimentary layers developed between the basalt flows proximal to the margin.

Basalt flows are typically brecciated at the tops and bottoms of the flows due to the faster cooling rates at the edges of the flows compared to the flow interiors. As a basalt sheet begins to cool, the surfaces are solidifying while the interior is still fluid and the sheet continues to move causing the flow tops and bottoms to fracture. Vesicles (small cavities) typically form near the tops of the flows as gasses from the lava migrate toward the surface. Cooling rates of basalt flows depend primarily on the thickness of the flow. Relatively thin sheets of basalt will cool rapidly, and may be fractured throughout the entire thickness of the flow. However, thicker basalt flows will cool much slower resulting in dense, non-vesicular, crystalline flow interiors. During periods of little volcanism, soils may begin to develop or sediment may be deposited on the basalt flow. If the sedimentary layer is preserved after a subsequent, overlying basalt flow is emplaced, the sedimentary layer is known as an interbed.

Due to steep pre-basalt topography only three of the four formations within the CRBG occur within the study area. The Grande Ronde is the oldest of the CRBG present in western Idaho, it is located almost everywhere CRBG rocks are present. As many as 131 flows make up the expansive Grande Ronde Formation which accounts for as much as 80% of the CRBG by volume (Hooper et al., 2002). The Wanapum Formation is much thinner than the Grande Ronde, but in some places the formation may be as much as 1,000 feet thick (Whitehead, 1994) and is almost as extensive in terms of area. The

Saddle Mountains Formation is the youngest of the three basalt units in the study area. It is not nearly as extensive as either the Wanapum or the Grande Ronde basalts (Swanson et al., 1979). Further discussions on these formations are presented in the section subtitled: Moscow Sub-basin Geology.

Regional Hydrogeology

The Columbia Plateau regional aquifer system extends over 50,000 square miles in three different states (Whitehead, 1994). Miocene basalts along with sediment interbeds and unconsolidated sediments overlying the basalt make up most of the aquifers. Geologic structures are important controls within the regional aquifer system; folded and faulted rocks can expose highly permeable zones allowing recharge to readily enter the aquifer system, or form barriers to horizontal groundwater flow. Upon entering the aquifer system groundwater generally follows permeable interflow zones down gradient toward major regional discharge locations such as the Columbia and Snake Rivers, and/or municipal pumping centers.

The void space between a flow top and a flow bottom, together with an intervening sediment interbed (if it exists) form what is called an interflow zone. Permeable interflow zones within stacks of basalt flows form the primary conduits for horizontal groundwater movement. Interflow zones are generally permeable where basalt is fractured and vesicular. Basalt flow interiors are generally of low hydraulic conductivity due to their dense crystalline structure and few continuous fractures. Flow interiors typically are considered to form confining layers or leaky aquitards depending upon the amount of post emplacement deformation. The CRBG contains successions of aquifers separated by low permeability zones.

Despite the ability of many interflow zones to yield great amounts of water to wells, excessive pumping commonly results in falling water levels because basalts have relatively low porosity and little storage capacity. Water movement in basalt aquifers is tied directly to the size, shape, and continuity of fracture zones. Unfractured basalt has very little capacity for water storage or water movement. Throughout the Columbia River basalt province, water levels are declining due to excessive stresses placed on the water resources. Groundwater movement in basalt aquifers over large distances is

dependent upon lateral continuity of interflow zones. Fractures may fill with clay minerals, occurring as a byproduct of weathering basalt, or become disconnected or offset via tectonic activity limiting their ability to transmit water. Discontinuous fractures may result in *aquifer compartmentalization* when hydraulic connections do not exist between discrete sets of fractures.

Moscow Sub-basin Geology

The study area for this investigation encompasses a relatively small portion of the Palouse Basin that will be referred to in this thesis as the Moscow sub-basin as delimited by Bush (2005). Several researchers in the past have defined the same study area when focusing on the Moscow area, as the Moscow Basin (Crosby and Chatters, 1960; Lin, 1967; and Jones and Ross, 1975). Bush (2005) used the term Moscow sub-basin (i.e., geologic sub-basin) to delineate the area surrounded by older crystalline basement rocks to the north, south and east. Bush delimited the western extent of the sub-basin based on the significant lateral thinning of Latah Formation sediments approximately one-mile west of the ID-WA border (Figures 3 and 4). The term *sub-basin* in this instance is used to identify a geologic condition and not a separate groundwater sub-basin.

The geology of the Moscow sub-basin is defined by rocks from the CRBG as well as the overlying and interbedded sedimentary layers of the Latah Formation (Figure 5), and the pre-basalt crystalline rocks that bound the basin. The Latah Formation was deposited throughout the emplacement of the CRBG and consists of interbeds, as well as overlying and underlying sedimentary layers. No structural deformation has been documented in the Moscow sub-basin. Over 1700 feet of CRBG occurs below Moscow (Bush, 2005). However, in many locations Miocene sediments are more abundant than basalts (Lin, 1967). The amount of sediment in the subsurface gives Moscow a subsurface geology that is distinct from the rest of the Palouse Basin (Figure 4). These sediments may allow for greater amounts of water to be stored in the system; however, interbedded fine grained layers may retard recharge from entering the basin along the contact with the basement rocks. The lack of structural deformation may leave dense basalt interiors relatively unfractured, and thus of low hydraulic conductivity. In the following section, each geologic unit will be discussed in order from oldest to youngest.

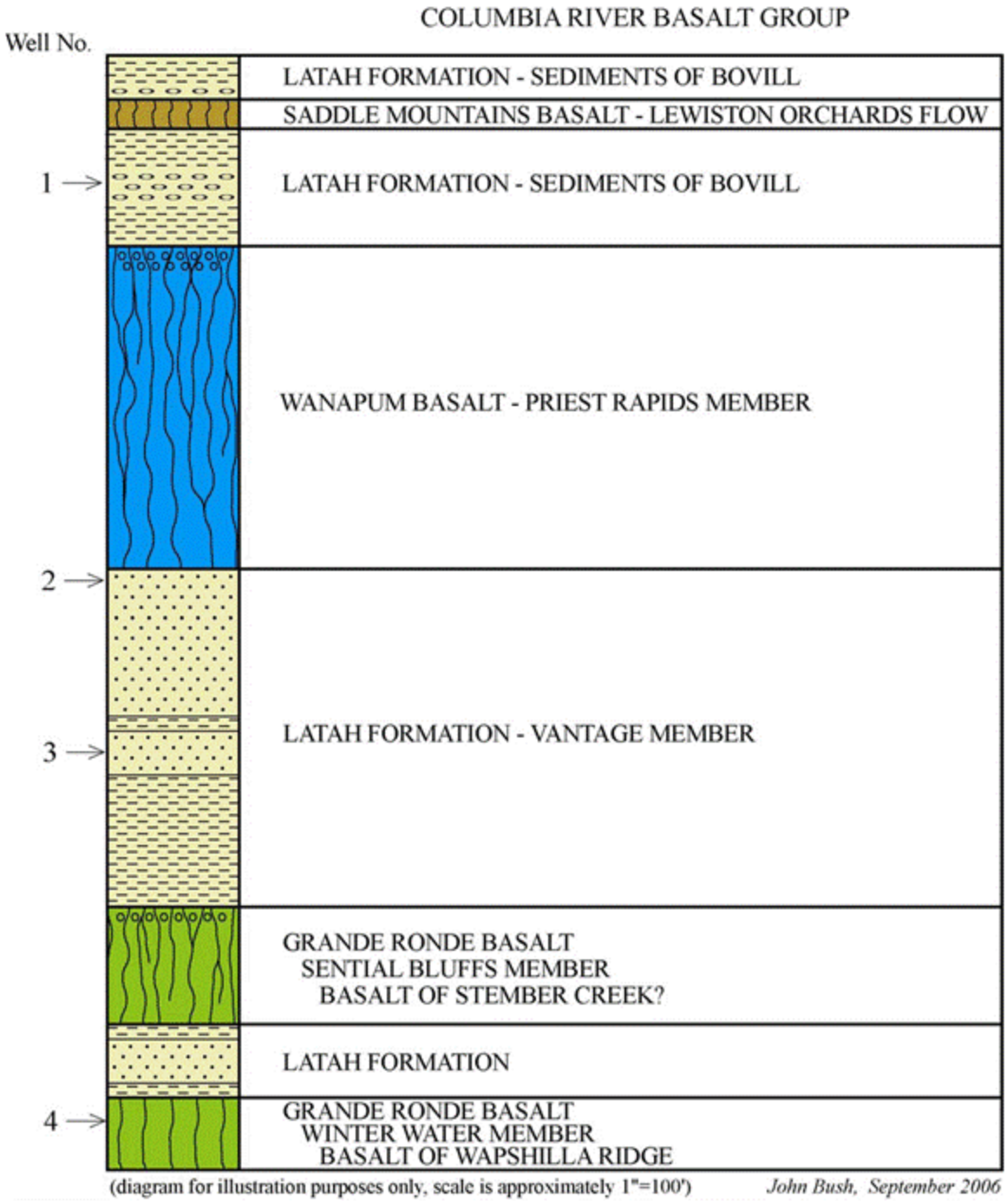

Figure 5. Stratigraphic nomenclature of the Columbia River Basalt Group as observed in the Idaho Department of Water Resources (IDWR) monitoring nest wells (from Bush, 2006)

Basement Rocks

Basement rocks beneath the CRBG consist of a thick base of ancient metamorphic and/or igneous crystalline rocks. These basement rocks also crop out at the land surface in the form of hills, buttes and ridges that bound the Moscow sub-basin. These rocks are believed to consist of Cambrian metamorphic rocks, and Pre-Cambrian metasediments associated with the Belt Supergroup, plus Cretaceous aged granites associated with the Idaho Batholith. The crystalline rock hills, buttes and ridges are remnants of the rugged, steep, pre-basalt topography that existed prior to emplacement of the relatively flat lying CRBG (Russell, 1897).

Latah Formation: Sediments of Moscow

The sediments of Moscow is the name given to the pre-basalt, Latah Formation sediments that accumulated on top of the crystalline basement rocks prior to advancement of the flood basalts into the Moscow sub-basin (Laney et al, 1923). Sediment sizes range from clay to gravel, with thicker and coarser grained deposits occurring proximal to the sediment source rocks associated with Moscow Mountain, Tomer Butte, Paradise Ridge, Kamiak Butte, and other hills along the perimeter of the basin. Several discontinuous interbeds exist between Grande Ronde flows (Bush, 2005). Two interbeds each more than 100 feet thick occur beneath the Moscow sub-basin (Lin, 1967).

Grande Ronde Formation

Grande Ronde basalt is Miocene in age and is between 15.6 and 17.0 million years old (Riedel et al., 1989). Locally, basalt flows of the Grande Ronde Formation dip to the east, toward the westward sloping basement rocks; however, basalt is not known to be in direct contact with basement rocks anywhere in the sub-basin. Several individual basalt flows of the Grande Ronde Formation exist within the Moscow sub-basin; however, no Grande Ronde basalt crops out within the study area. Approximately 1,000 feet of Grande Ronde basalt and associated sediment interbeds exist below Moscow (Bush, 2005). In the Moscow sub-basin, a larger amount sediment interbeds occur than is typical of the Columbia River Plateau in general. Interbeds are thicker in the eastern portion of the Moscow sub-basin, making up almost 60% of the total thickness (Lin, 1967); this is due to the close proximity of sediment source rocks (basement rocks).

Latah Formation: Vantage Equivalent

The Vantage Equivalent interbed (hereinafter called the Vantage in this thesis) is believed to be the equivalent of the Vantage Member of the Ellensburg Formation found in central Washington. It is Miocene in age and forms a very significant stratigraphic marker interbed between the top of the Grande Ronde Formation and the Lolo flow of the Priest Rapids Member of the Wanapum Formation. Locally, the Vantage averages about 200 feet in thickness, but is up to 300 feet thick in the eastern portion of the Moscow sub-basin (Brown, 1976; Kopp, 1994). This interbed thins dramatically west of the WA-ID border (Bush 2005). Sediments in this unit consist of interlayered fine gravels, sands, silts and clays with the coarsest deposits occurring under the city of Moscow and eastward. Coarse grained deposits represent buried stream channels (Bush, 2005); however the majority of the interbed is poorly sorted. No Vantage outcrops have been observed within the Moscow sub-basin.

Wanapum Formation

Locally the Wanapum Formation consists of only the Lolo flow of the Priest Rapids Member with a thickness ranging between approximately 160 and 200 feet (Provant 1995). The flow is of Miocene age and dated at approximately 14.5 million years old (Swanson et al., 1979). Within the Moscow sub-basin, the flow directly overlies the Vantage interbed of the Latah Formation. The Wanapum Formation is thickest in Moscow where it dips slightly to the east or the northeast. Wanapum basalt is exposed in a few locations throughout the Moscow sub-basin. There are also numerous exposures of the Wanapum basalt in road cuts and quarries along the Moscow-Pullman highway west of Moscow.

Latah Formation: Sediments of Bovill

The sediments of Bovill were deposited directly on top of the Lolo flow of the Priest Rapids Member of the Wanapum Formation as a bowl-shaped deposit only within the Moscow sub-basin. The sediments are of Miocene age and consist of sediment sizes ranging from clay to gravel (Bush 2005). The clays are kaolinite-rich, and the sands and gravels are generally poorly sorted; exposures occur along stream channels and road cuts. Coarser grained sediments are found proximal to the source rock hills while finer

sediments occur further from the sources. Most of these deposits are believed to be fluvial in nature (Bush 2005). The presence or absence of the sediments of Bovill helps to delimit the western margin of the Moscow sub-basin. Although these sediments are well over a 100 feet thick in the eastern portion of the sub-basin where they merge with the sediments of Moscow, they pinch out west of the ID-WA border.

Palouse Formation

Loess of the Palouse Formation creates the rolling hills of the Palouse in the Moscow area. Many layers of windblown clayey-silty loess comprise the Palouse hills. This formation was deposited approximately 2-4 million years ago during the Pleistocene epoch. This formation ranges from zero to well over 100 feet in thickness (Kopp, 1994). In contrast to most other sedimentary units, the Palouse Formation thins from west to east (Badon, 2007). In most places within the Moscow sub-basin, the Palouse Formation overlies the sediments of Bovill.

Alluvium and Colluvium

Holocene stream, slope-wash, and debris flow deposits make up the alluvium and colluvium deposits that occur at the land surface within the study area. Stream deposits include reworked loess and sediments of Bovill, as well as clay, sand and pebbles derived from weathered basalt and crystalline rock. Floodplains of streams in the Moscow area are generally broader than similarly sized streams in the region (Bush, 2005). Stream channels cut the clays and loess of the Palouse Formation and commonly are incised into the sediments of Bovill. In the Moscow area, mapped floodplain deposits of alluvial materials account for approximately 30% of the land surface area (Figure 3).

Moscow Sub-basin Aquifer Systems

Several aquifers have been identified within the Moscow sub-basin. These include the Grande Ronde aquifer system, the Wanapum aquifer system, perched aquifers within the Latah Formation and Palouse Formation sediments, and small systems within the crystalline rock hills, buttes and ridges that surround the sub-basin. Of these aquifer systems only the Grande Ronde aquifer system and the Wanapum aquifer system provide sufficient water to supply municipal uses. The Grande Ronde aquifer system is currently the main groundwater resource system for the city of Moscow. The Wanapum aquifer

system is used primarily as a supplemental municipal water source to help mitigate the stresses placed on the deeper system. Water table aquifers occur within the Palouse Formation but generally only supply enough water for domestic or stock uses. Also, fractures within the crystalline basement rocks are generally able to supply only enough water for domestic or stock use.

Grande Ronde Aquifer System

Multiple basalt flows of the Grande Ronde Formation occur in the Moscow area. Interflow zones between flows allow significant horizontal water movement toward pumping centers in the Grande Ronde aquifer system. Latah Formation sediments between the basalt and basement rocks, as well as within interflow zones, store water and may act as conduits for recharge; however, relatively little recharge is believed to occur locally. Grande Ronde aquifer system municipal wells are able produce in excess of 2,000 gallons per minute (gpm) by intersecting one or more interflow zones. Most wells in the Grande Ronde aquifer system are completed at depths beyond 500 feet in the Moscow sub-basin. The potentiometric surface in the Grande Ronde aquifer system is at an elevation of approximately 2220 feet above mean sea level (amsl) with water levels of 250 to 375 feet bgs depending upon the surface elevation at the well.

Wanapum Aquifer System

The Wanapum aquifer system is composed of the Priest Rapids Member of the Wanapum Formation, sediments of the upper Latah Formation (sediments of Bovill), and Vantage sediments of the Latah Formation. No interflow zones occur in the Wanapum Formation because locally the Wanapum basalt consists of only the Lolo flow. Water moves through fractured basalt and hydraulically connected Vantage sediments to municipal wells in Moscow. It is common for wells to be completed (screened in) in multiple producing zones to derive groundwater from both the Wanapum basalt and the Vantage sediments. Municipal wells completed in the Wanapum aquifer system typically produce between 500 and 1,000 gpm. Most wells in the Moscow area used for domestic supplies tap the Wanapum basalt. Domestic wells completed within the Wanapum basalt are generally uncased (open-holed) throughout the thickness of the basalt, maximizing the number of fractures intersected by the well bore. Domestic basalt wells can produce

up to 300 gpm although more commonly produce 100 gpm or less. Wells completed in the Wanapum aquifer system are generally drilled to depths between 100 and 500 feet depending on the surface elevation at a given location. Water levels in the Wanapum aquifer system are generally less than 150 feet bgs depending on the elevation at the well location. The Wanapum aquifer system is a steady producer within the Moscow sub-basin; however, the Wanapum basalt west of the Moscow area generally is a poor producer, rarely supplying enough water for domestic use (Bush, 2005). This may be due to the absence of the Latah Formation sediments west of the Moscow area.

Basement Rock Aquifer Systems

Fractures in the crystalline metasediments and granites form relatively minor producing zones in the crystalline basement rocks. Wells completed in these rocks are generally open holed and shallow. Sufficient water supply can be derived only if the well bore intersects a significant fracture or fracture system. Domestic wells producing more than a few gallons per minute are the exception. Recharge to this aquifer system is dependent entirely on ample precipitation and snowmelt recharging the fractures. Wells have gone dry in drought years due to insufficient recharge and storage for use throughout the dry season.

Palouse Formation Aquifer Systems

Unconsolidated loess deposits are able to store enough water recharged during wet periods in the winter and spring to maintain some small springs and seeps throughout the summer months (Hopster, 2003). Aquifers in the Palouse Formation typically are perched water table aquifers. Occasionally wells are able to exploit this groundwater resource and locally may produce upwards of 30 gpm.

Moscow Sub-basin Hydrogeology

While the Grande Ronde aquifer system provides the bulk of the municipal water used by Moscow and the University of Idaho, water levels within the producing zones continue to decline between about 0.6 and 1.5 feet per year. Development of the Grande Ronde aquifer system in the Moscow sub-basin began in the 1960's. Since then considerable research has been conducted on the Grande Ronde aquifer system to determine the extent of connections between the cities of Moscow, Pullman, Palouse and

Colfax. Recharge to the Grande Ronde aquifer system is believed to be very limited as evidenced by the continued water level declines in the area. Some researchers have postulated that recharge may occur via water movement along the contact between the basement rocks and sediments, and/or as downward flow through the Wanapum Formation.

Prior to the development of the Grande Ronde aquifer system, the Wanapum aquifer system provided the municipal water supply for the city of Moscow. Water levels in the Wanapum aquifer system began to fall dramatically in the 1950's, and water use had to be curtailed. When the Grande Ronde aquifer system was developed, water levels in the Wanapum aquifer system began to recover (Heinemann, 1994). At the location of the IDWR monitoring wells about ½ mile northeast of the Palouse Mall (Figure 2), there is a downward hydraulic gradient of approximately 0.6 exists between the Vantage sediments of the Wanapum aquifer system, and the primary producing zone in the Grande Ronde aquifer system in the Moscow area. This steep vertical gradient suggests that the Wanapum aquifer system probably is losing some water via slow leakage to the Grande Ronde. It also implies a poor vertical connection between the aquifer systems. Some researchers have suggested that layers of clay within the Vantage combined with a saprolite (weathered soil horizon) on top of the Grande Ronde Formation impede the vertical flow of water between the two systems (Reidel et al., 2002).

The water level in Moscow #2 at its lowest (1963) was 120 feet bgs; by 1990, the water levels in the same well had risen to 50 feet bgs. This rapid recovery (70 feet in 30 years) indicates that the Wanapum aquifer system receives significant recharge annually. Recharge locations have not been documented; however, recharge most likely occurs by a combination of mechanisms: 1) water movement through coarse grained sediments along the contact between the basalt and basement complex rocks, 2) losing stream segments in the Moscow area, and 3) limited amounts of deep percolation through the overlying sedimentary units.

Since the 1990's, the Wanapum aquifer system has been pumped by the city of Moscow to help mitigate the amount of water pumped from the diminishing Grande Ronde aquifer system. The purpose of this thesis is to evaluate whether additional groundwater recharge can be induced to flow into the Wanapum aquifer system. Exploiting the Wanapum aquifer system to its fullest capacity will help to mitigate the water level declines in the Grande Ronde aquifer system. The following chapter develops a conceptual model for groundwater flow in the Wanapum aquifer system, as well as the groundwater and surface water interactions that occur within the Moscow area.

Chapter 3 - Conceptual Model for the Wanapum Aquifer System

Groundwater-Surface Water Interaction

In the past, groundwater and surface water were viewed by many western states as being separate reservoirs and thus separate resources. However, surface water and groundwater are now widely viewed as a single resource and thus, must be managed accordingly. Groundwater management will have an impact on surface water and vice versa. Surface water bodies may be major sources of recharge water for local groundwater systems; groundwater may provide streams water during extended dry periods. Within the Moscow sub-basin several streams may lose water to the Wanapum aquifer system seasonally.

Overview of Groundwater – Surface Water Interactions

Groundwater flow occurs in three dimensions and is driven by differences in hydraulic head. Hydraulic head (h) is equal to the sum of elevation head (z) and pressure head (ψ) according to:

$$h = \psi + z$$

where: h is the hydraulic head or total head (L);

ψ is the pressure head equal to the height of the water column relative to the piezometer measurement point (e.g., bottom (L)); and

z is the elevation of the measurement point (L).

Hydraulic head is a term that describes the mechanical energy of the groundwater at a point within a flow system (Winter, 1998). Water that infiltrates into the ground and migrates vertically downward to the water table is called recharge; below the water table groundwater moves three-dimensionally through the subsurface. Groundwater moves down gradient, that is, from places of higher hydraulic head toward locations of lower hydraulic head.

Surface water bodies, in this case streams, typically interact with the groundwater flow systems. The hydraulic head of any water body is simply the elevation at the

water's surface. Streams interact with groundwater in two ways: 1) streams are either gaining water from the groundwater (gaining stream) or 2) losing water from the streambed to groundwater (losing stream). Streams can be gaining in some reaches and losing in others, a stream segment can also change from gaining to losing (or vice versa) seasonally. The nature of groundwater and surface water interaction is dependent upon the mechanical energy of the groundwater flow systems.

In order for a stream to be gaining, the elevation of the stream stage must be lower than the elevation of the water table adjacent to the stream. Losing streams are those with stream surface elevations greater than the elevation of the adjacent water table. Two types of losing stream segments are possible. One is hydraulically connected with the groundwater system, that is, the subsurface below the stream is fully saturated (Figure 6). The second type of losing reach (disconnected) is defined by an unsaturated zone between the streambed and the water table. The amount of water exchanged between (hydraulically connected) losing stream segments is dependent upon the hydraulic gradient between the stream and water table, and the wetted surface area of the stream. The flux [L/t] of water from disconnected stream segments is unaffected by the elevation of the water table.

Whether a stream is gaining or losing depends upon the hydraulic gradient between the stream and the local water table. The amount of water exchanged depends on several factors, including, the hydraulic conductivity and thickness of the streambed sediments, the wetted surface area of the streambed, and the hydraulic gradient. Water temperature also affects the amount of water movement between the streambeds and shallow groundwater systems. Although the change in viscosity is minimal, warmer water has less resistance to flow, allowing for a slightly greater flux to occur. Hydraulic conductivity of a streambed is very challenging to estimate, and may change over time due to sediment scour or deposition. The greatest flow rate [L^3/t] will occur when the wetted surface area is maximized and the hydraulic gradient is steepest.

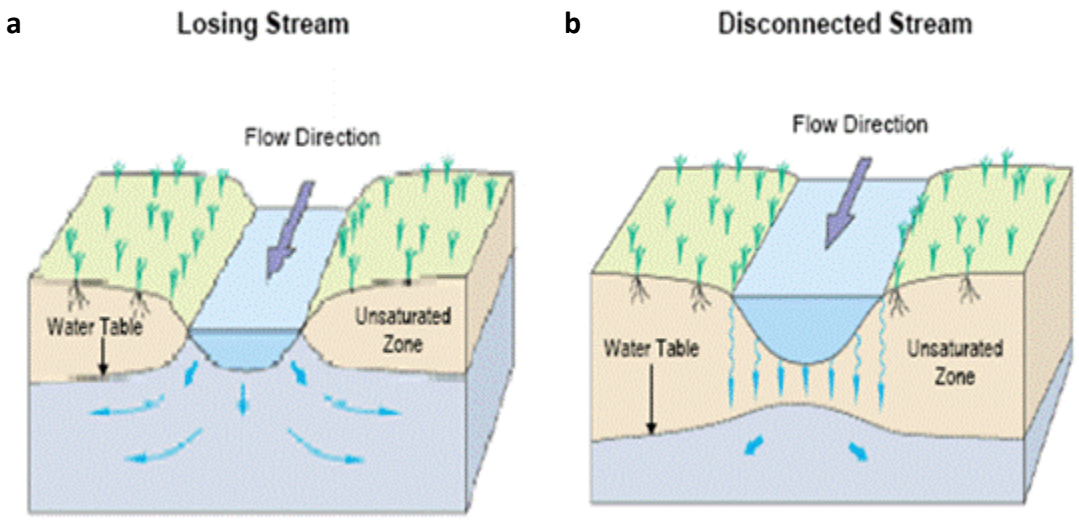

Figure 6. Losing streams are either a) interconnected with the shallow groundwater systems or b) disconnected from the local groundwater systems. Streams in hydraulic connection will be affected by local groundwater pumping (modified from Winter, 1998).

Conceptual Model for Groundwater - Surface Water Interactions

Groundwater and surface water interactions in the Moscow sub-basin are dynamic and site specific. Streams such as Paradise Creek, the South Fork of the Palouse River, and Missouri Flat Creek are generally in direct hydraulic contact with the sediments of Bovill. Most of the year, water levels in the adjacent geologic materials are at lower elevations than the elevations of the stream stages, and are thus potentially receiving water from the streams. Seasonally, however, some segments of these streams may receive baseflow (groundwater inflow) during the long and dry summers. Interactions between the streams and the aquifers greatly affect the volume of water available to recharge the Wanapum aquifer system.

Researchers have characterized two specific sites as locations where water is recharging the shallow aquifer system seasonally. Wright (1996) suggested water is moving from Paradise Creek into the groundwater systems at Sweet Avenue, in Moscow. However, Namick (1998) and Johnson (2003) both suggested that contaminated groundwater flows into Paradise Creek at Sweet Avenue at least seasonally. Li (1991),

Pardo (1993), and Kopp (1994) have all suggested that recharge to the shallow aquifer in the vicinity of the UIGFL occurs seasonally from Paradise Creek in that location as well. Hernandez (2007) performed multiple pumping tests in the shallow aquifer at the UIGFL; she noted groundwater level stabilization and groundwater temperature fluctuations during well pumping that were interpreted as surface water movement into the cone of depression.

Within the Moscow sub-basin, groundwater interaction between streams and the Wanapum aquifer system will largely be controlled by the hydraulic gradient between the streams and sediments of Bovill, as well as the hydraulic conductivity and saturated thickness of the stream channel and floodplain sediments. Stream channels in direct hydraulic connection with the sediments of Bovill allow direct interaction between the surface water in the streams and the shallow water tables adjacent to the streams. Then, groundwater flow within the sediments of Bovill redistributes the recharge water laterally across most of the Moscow sub-basin.

Water recharged seasonally from the streams into the sediments of Bovill is redistributed throughout the sub-basin making water available to percolate into the Wanapum basalt (Figure 7). Redistribution of water within the sediments of Bovill is controlled by the spatially variable hydraulic heads and hydraulic conductivities within the sediments. The greater the saturated thickness, the greater the potential volume of water stored within the sediments for eventual percolation into the Wanapum basalt, where the majority of the pumping occurs. Seasonal water infiltration, redistribution and storage within the sediments of Bovill increase the available hydraulic contact area for water to percolate into the fractured Wanapum basalt. In addition, as the water table in the sediments of Bovill rises during periods of high stream flow, hydraulic gradients between the sediments of Bovill and the Wanapum basalt become steeper, inducing greater rates of recharge.

Fracture systems control the movement of water from the sediments of Bovill to the producing zones in the Wanapum basalt. Hernandez (2007) outlined potential flow paths for water moving from the sediments of Bovill into the basalt. First, fractures (rubbled flow top) must occur near the contact with the sediments. These fractures are

then connected to deeper horizontal fractures (potential producing zones) via vertical fractures in the basalt. The presence and connectivity of fractures control the amount of water entering the basalt from overlying sediments or from stream flow in direct contact with basalt. Fairley et al., (2006) concluded that many shallow fractures in the Wanapum basalt are filled with clay derived from weathering of the basalt. Clay filled fractures will retard the flow of water into the basalt. However, it is obvious that significant recharge does make its way into the basalt producing zones and the Vantage on an annual time frame. Although it is impossible to evaluate the abundance and connectivity of these fracture systems throughout the sub-basin, it is unlikely the UIGFL and Sweet Avenue sites are the only locations where streams are losing water to the Wanapum aquifer system.

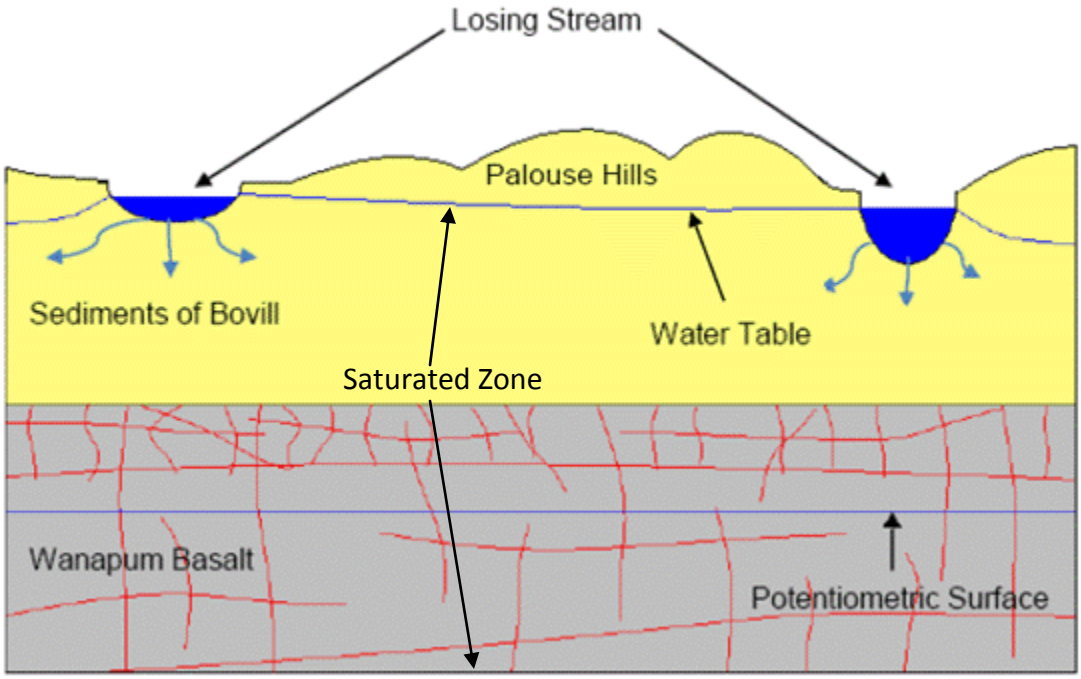

Figure 7. Illustration of groundwater surface water interactions in the Palouse Basin. Water lost to the sediments of Bovill is then distributed throughout the unit. Water is then allowed to percolate into the producing zones of the Wanapum basalt through fractures.

Conceptual Model for Aquifer Analysis

When simplified, the geology of the Moscow sub-basin is a series of sediment and basalt formations (Figure 5). Very little in the way of structural deformation has occurred. In the Moscow sub-basin, the Wanapum basalt dips slightly eastward and is fairly uniform in thickness. Sediment layers above and below the basalt are hydraulically connected to the fracture systems. Several outcrops of the Wanapum basalt occur within the Moscow sub-basin; these outcrops and those located just west of the Idaho-Washington state line contain abundant open fractures, many of which seep groundwater seasonally. The upper portion of Wanapum basalt containing clay filled fractures, together with fine grained layers within the sediments of Bovill, are believed to form an aquitard above the fractured, producing zones in the Wanapum aquifer system. Li (1991) found that several fractured producing zones occur at different depths within the Wanapum basalt at the UIGFL. The fracture zones were found to be hydraulically connected during long-term aquifer pumping tests. Kopp (1994) recorded a hydraulic connection between wells completed in the Wanapum basalt and the Vantage interbed below the basalt. Hernandez (2007) recorded drawdown in the sediments of Bovill while pumping the Wanapum basalt at the UIGFL.

For the purpose of aquifer test analyses (Chapter 4), the Wanapum aquifer system will be considered an equivalent porous medium. Assuming fractured basalt will respond as a porous medium is common. Several researchers, including Kopp (1994), Owsley (2003), McVay (2007), Badon (2007), and Hernandez (2007) have used the Theis (1935) equation (a solution developed for confined homogeneous and isotropic porous medium aquifers) to analyze aquifer tests in the Palouse Basin. In order to do so, several assumptions are made about the fractured rock, including: it is highly fractured, fracture apertures are relatively constant, and the orientation of fractures is random. The volume of aquifer sampled must also be taken into consideration; if pumping is small and/or of short duration, it may not be appropriate to apply a porous medium analysis. Aquifer tests conducted for this study stressed a large volume of the aquifer for a long period of time.

Chapter 4 – Hydrogeologic Data Collection and Analysis

Introduction

As part of this thesis research, two aquifer tests were conducted between November 2007 and July 2008. The tests were conducted using municipal wells in Moscow with help from the city of Moscow Water Department. Observation wells consisted of the 19 wells continually monitored as part of the PBAC groundwater monitoring network. The pumping period for the first aquifer test was 68 days, conducted using Moscow #2 as the pumping well. The pumping period for the second aquifer test was 70 days, and pumped Moscow #3 to stress the aquifer. Both wells are Wanapum aquifer system wells, but are completed at different depths (Table 1). Pumping during the tests was designed to stress the aquifer system significantly more than normal (typical years). Aquifer tests were conducted to achieve several goals: observation of new hydrologic connections, evaluation of compartmentalization within the Wanapum aquifer system, estimation of the physical properties of the aquifer system, and evaluation of the feasibility of inducing additional, controlled recharge to the Wanapum aquifer system, based on the conceptual model, outlined in Chapter 3.

Water Level Data - Barometric Pressure Effects

Water level data and barometric pressure measurements were collected at one-hour intervals during both long-term aquifer tests. Barometric changes can mask the pumping effects at an observation well if the changes in water level due to barometric pressure changes are greater than those caused by pumping (Toll and Rasmussen, 2007). Generally, aquifer tests are of relatively short duration, and changes in barometric pressure during the tests are minimal. During long-term, aquifer pumping tests, such as those in this study, barometric pressure can have a significant impact on water levels. In order to effectively determine the magnitude of water level changes (if any) due to Moscow #2 and #3 pumping, barometric pressure effects were removed from the data.

A software program, BETCO©, was used to remove water level fluctuations in the groundwater level data due to barometric pressure changes. Groundwater levels were corrected using barometric pressure data collected at the same time as the water level data. BETCO©, a software package developed by Nathaniel Toll of Sandia National

Laboratories and Dr. Todd Rasumssen of the University of Georgia, applies regression deconvolution to remove barometric effects (Toll and Rasmussen, 2007). Additional information on BETCO© is available in Appendix C. Water level data corrected by BETCO© showed apparent drawdown effects between the PCEI well and the pumping of Moscow #2 and #3 that otherwise would have been masked by fluctuations in barometric pressure. Figure 8 compares the PCEI water level data prior to and after the removal of barometric pressure effects. Barometric pressure effects masked the drawdown that was apparently caused by pumping. After the barometric pressure effects were removed, it was concluded that PCEI responded to Moscow #2 and #3 pumping. In other instances, the removal of barometric pressure effects allowed for more accurate drawdown measurements to be used in the aquifer analyses.

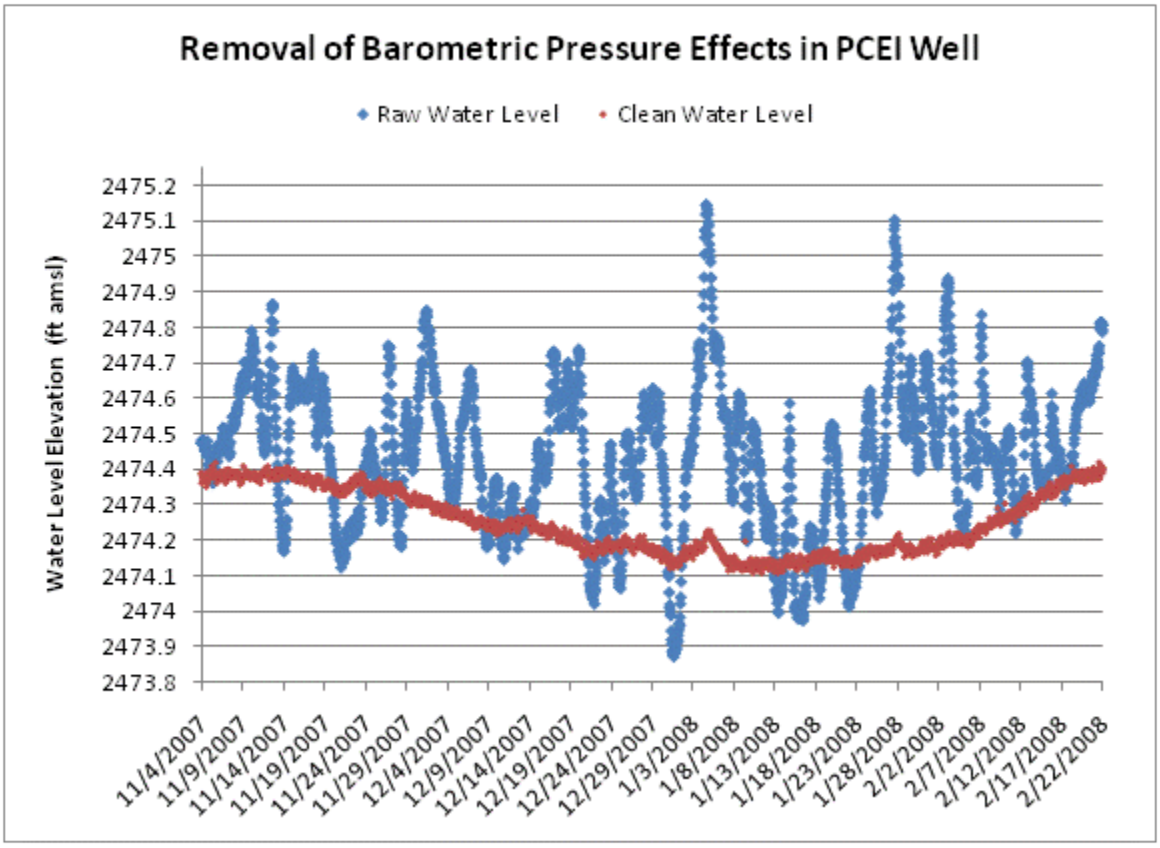

Figure 8. Barometric pressure effects in the PCEI well were large enough to mask drawdown during the aquifer test that occurred between November 14th and January 20th, 2008. Barometric corrections made using BETCO© allowed for evaluation the hydraulic connections between the wells.

Boundary Analysis

The Moscow sub-basin is bounded to the north, south and east by low permeability basement rocks. Due to the relatively small size of the Moscow sub-basin, it is believed that these boundaries affect the drawdown observed during aquifer tests. AQTESOLV® is a commercially available, aquifer testing, software program. It was used for all aquifer test analyses performed as part of this thesis research. AQTESOLV® allows the user to include boundaries as part of the analysis; however, boundaries must be represented by straight lines that intersect at right angles. It was uncertain whether this oversimplification of the actual Moscow sub-basin boundaries would induce significant errors during analysis. Therefore, a numerical model was used to assess the ability of AQTESOLV® to adequately represent the geological boundaries for hydrogeologic conditions believed to be representative of the Wanapum aquifer system in the Moscow sub-basin. A Visual MODFLOW™ (Modflow, 2000) Palouse Basin model originally developed in UTM coordinates by Holom (2006) was modified to simulate geologic conditions of the Wanapum aquifer system as conceptualized in this thesis. The model domain consisted of a rectangular grid of dimensions x=165,712 ft by y=238,554 ft with variable cell spacings. The model grid consisted of 826 rows and 499 columns. Uniform, square model cells of dimensions $\Delta x=\Delta y=166.5$ ft were placed over the entire area of the Moscow sub-basin to closely approximate the actual locations of wells used in the Moscow #2 Test. Impermeable boundaries were placed around the perimeter of the model grid (Modflow default condition) beyond the influence of pumping. The initial drawdown everywhere in the aquifer was zero. Figure 9 shows the impermeable boundaries of the Moscow sub-basin as simulated in the numerical model.

A pumping well was placed in the model at the appropriate surveyed coordinates for Moscow #2, and a monitoring well was added at the coordinates for the Brandt observation well, which was determined by Badon (2007) to be in direct hydraulic connection with Moscow #2. A preliminary model consisting of five one-day pumping periods separated by five one-day recovery periods was run to test model boundary effects on drawdown and recovery. The model was run to simulate several on-off pumping periods for idealized, homogeneous and isotropic, confined aquifer with

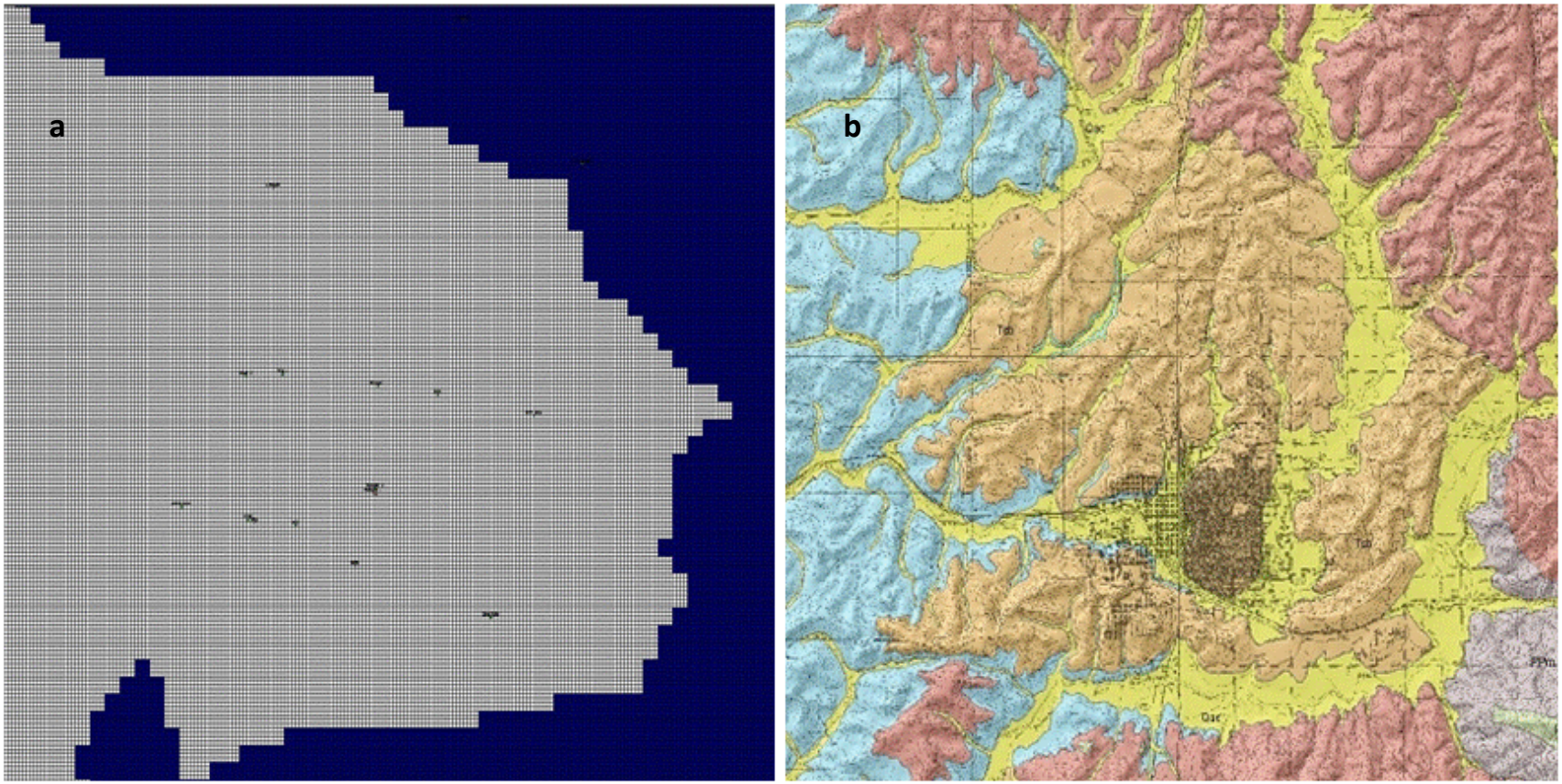

Figure 9. Comparison of Moscow sub-basin geologic boundaries (refer to Figure 3 for more details) and representative inputs placed into Visual MODFLOW™. The model was used to evaluate the hydraulic effects of boundaries on drawdown at the Brandt well. Figure 9a presents a small portion of the entire model grid and shows the simulated crystalline rock boundaries in dark blue. Figure 9b shows the crystalline rock boundaries (pink and gray), sediments of Bovill (tan), recent alluvium (yellow), and Wanapum basalt (light blue) as mapped by Bush et al. (2007).

arbitrarily chosen values of transmissivity (6,236 ft^2/day) and a storativity (0.00067). The irregular crystalline rock boundaries that form the eastern perimeter of the Moscow sub-basin were represented using arbitrarily chosen values for transmissivity (1 E-25) and specific storage (1E-5). Simulated drawdown observations for the Brandt observation well were imported into AQTESOLV® and plotted as a log-log graph of drawdown versus time. The simulated pumping schedule for Moscow #2 used in the model was used in AQTESOLV® to create a type curve based on the Theis (1935) equation (Appendix D) for confined aquifers with boundaries simulated by image wells based on the principle of superposition. Three, right angle, intersecting straight line boundaries representing the horseshoe-shaped outcrops of basement rocks were adjusted by trial-and-error calibration until the best visual curve match (Figure 10) yielded the exact values for transmissivity and storativity, simulated by Visual MODFLOW™. These straight line boundaries, illustrated in Figure 11, are believed to effectively represent the hydraulic effects of the irregular crystalline rock boundaries of the Moscow sub-basin, and were used for the analysis of field drawdown data collected during the actual long-term aquifer pumping tests.

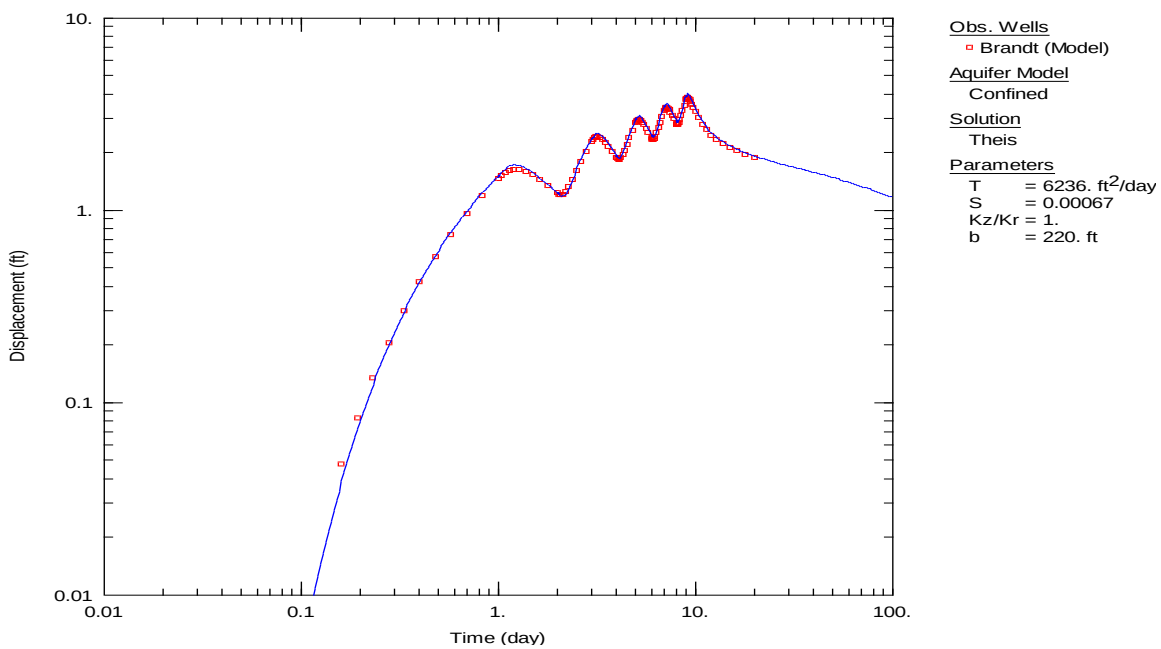

Figure 10. Theis (1935) analysis with the method of superposition for multiple pumping rates and boundaries (image wells) for a simulated aquifer test. Red squares represent synthetic aquifer test data derived from Visual Modflow™. The blue type curve represents the drawdown predicted by AQTESOLV® for the identical T and S values as used in the numerical model, but for the simplified straight line boundaries shown in Figure 11.

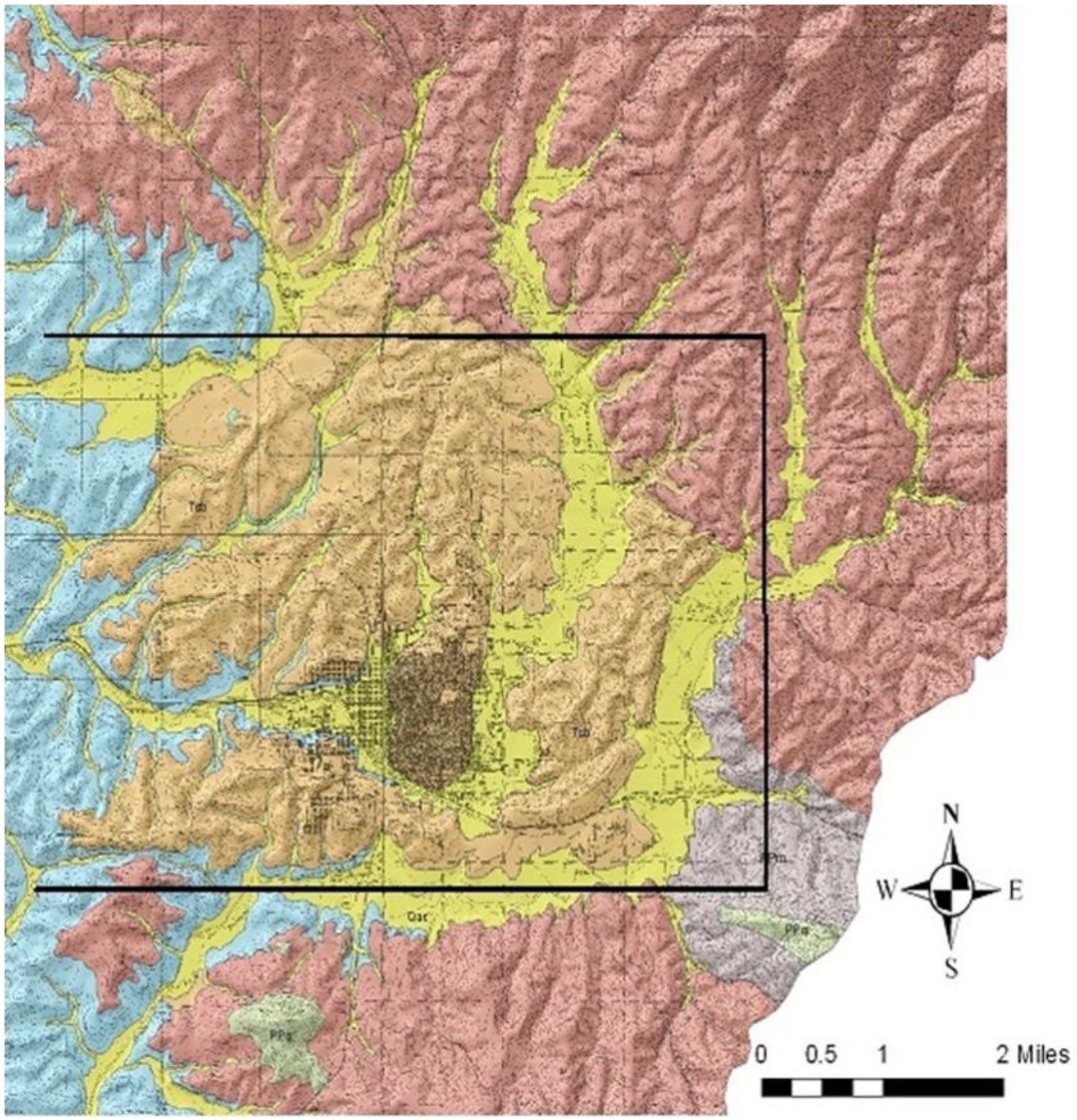

Figure 11. Straight line boundaries used in aquifer test analyses with AQTESOLV®. Refer to Figure 3 for further details on Moscow sub-basin geology (modified from Bush et al., 2007).

Moscow #2 Aquifer Test

Originally, the Moscow #2 Aquifer Test was the only aquifer test planned for this thesis investigation. The test was designed to begin in November 2007 during the wet season and run until approximately May 2008. The test was designed to pump a greater volume of water from Moscow #2 in five to six months, than is normally pumped during an entire year. Increased pumping began November 14, 2007. Due to mechanical failure of the pump, the test was cut short on January 20, 2008. The increased pumping period lasted for 68 days. Daily pumping volumes were dependent upon the municipal supply demands, and all water was pumped into the city distribution system. The total volume of water pumped during this test period was more than twice the total volume pumped for the corresponding time period during each of the previous three years.

The Moscow Water Department collected pumping records during the aquifer test as they do normally throughout the year. Ideally, complete on/off records for Moscow #2 pumping would have been recorded in order to eliminate errors in the test analyses. Unfortunately on/off records were only sporadically recorded by the water department (Appendix E) during the test. For analysis purposes, daily pumping averages had to be used instead of actual pumping rates and times. The water department recorded the volume of water pumped during the previous day every morning, so the volume (in gallons) pumped during the previous day was divided by 1440 minutes to estimate the daily average gpm. Averaging of pumping over a 24-hour period induced error into the analyses; however, this circumstance could not be avoided. Averaged pumping caused AQTESOLV® forward modeling to generate smoothed type curves compared to the actual field measured drawdown values that were directly affected by daily, short-term (<24 hours), pumping variations. Due to the use of a log-log scale in the analyses, the significance of averaging errors decreased as time of pumping increased.

Pumping of Moscow #2 was significantly increased on the morning of November 14th 2007 as scheduled for this investigation. According to the Moscow Water Department record (Appendix F), Moscow #2 pumping started and pumping continued uninterrupted for approximately 26 consecutive hours; however, the exact time that pumping began was not recorded by Moscow Water Department personnel. An accurate

t=0 (pumping start time) is critical to the analysis methods used in this investigation. During a previous Moscow #2 aquifer pump test (Badon 2007), it was discovered that the Brandt observation well responds directly to Moscow #2 pumping within 200 minutes. Based on this information, and the observations of drawdown in the long-term Brandt hydrograph (Figure 12), an estimate of t=0 was made. Pumping was estimated to begin on November 14th 2007 at approximately 0700 hours. To honor the recorded Moscow #2 pumping records (Appendices E and F) in the aquifer test analyses, the initial pumping period were considered to have lasted 1560 minutes (26 hours); each of the subsequent pumping periods was considered to be 1440 minutes per day. The actual time and duration that pumping occurred each day is not known. Therefore, total pumping volumes per day were divided by 1440 minutes per day to derive average pumping rates in gpm.

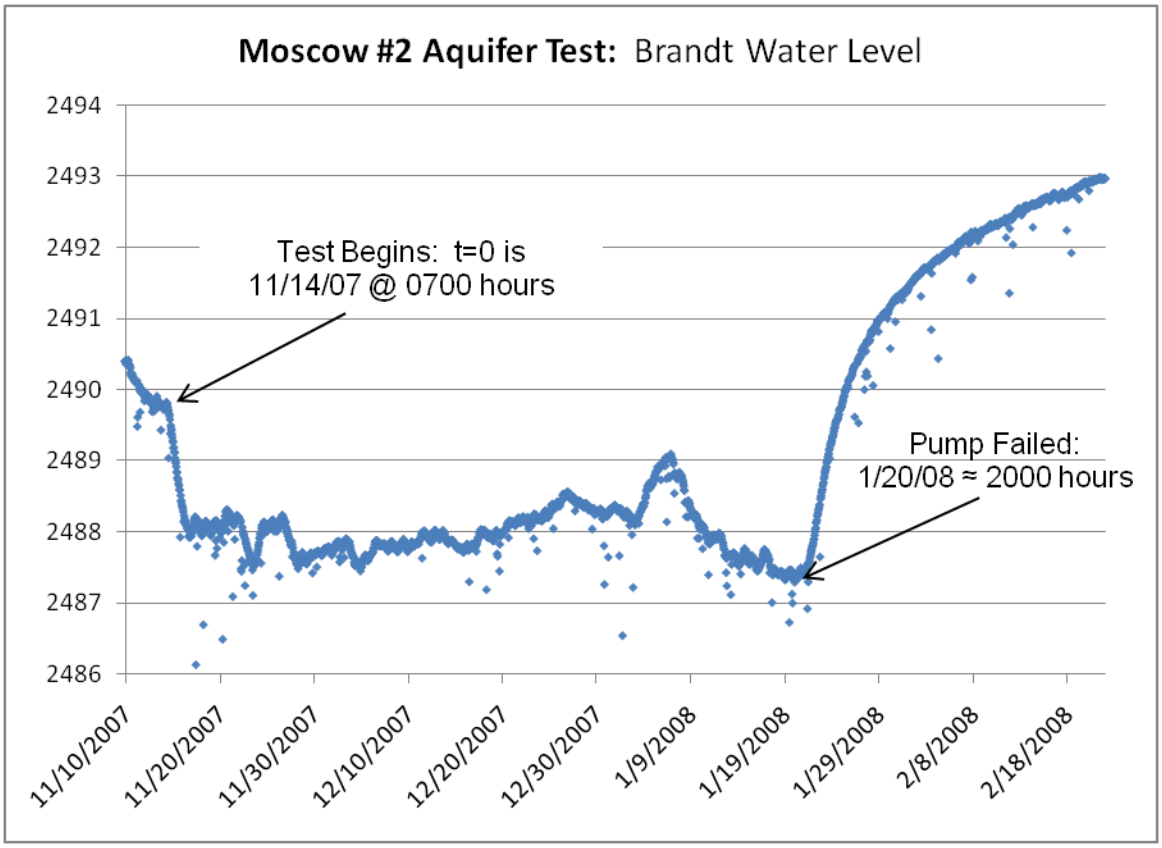

Figure 12. Arithmetic Plot of drawdown vs. time in the Brandt observation well for the Moscow #2 Aquifer Test.

Moscow #2 was chosen as the primary pumping well in this investigation because it was the only municipal well completed within the Wanapum aquifer system known to cause drawdown in surrounding wells. Using the majority of the same observation wells as used in this investigation, Badon (2007) ran relatively short-term aquifer tests using both Moscow #2 and Moscow #3 as pumping wells. She found that pumping of Moscow #2 caused measurable drawdown in the Brandt and Bond wells (Figure 2). The Bond well is no longer monitored by PBAC (at the request of the well owner). Figure 13 presents well construction details for Moscow #2. A recently recorded, downhole video log for Moscow #2 by the city of Moscow suggests that the majority of water is produced from the bottom five to ten feet of the well, approximately 230-240 feet bgs. Ain total 19 observation wells were monitored during the 138.89-day drawdown and recovery periods of the aquifer test. After barometric pressure effects were removed from the data, measurable drawdown, defined as decreasing water levels due to pumping, was observed in only three of the 19 observation wells: the Brandt, Mountain View Park, and PCEI observation wells. Prior to the aquifer test, relatively stable water levels were observed in the three responding observation wells. All other wells monitored during this period showed increasing water level trends during the aquifer test period, a normal seasonal response in the Wanapum aquifer system. Rising water levels in the observation wells suggest little or no hydraulic connection with Moscow #2. Water level hydrographs were analyzed to determine if any pumping effects, (i.e. abrupt water level changes coinciding with Moscow #2 pumping) could be seen in the wells showing water level rises during the aquifer test; however, no evidence for hydraulic connections was found. Water level hydrographs for the observation wells were corrected for barometric effects, and are presented in Appendix C.

Moscow #2 Aquifer Test Analyses

Once it was determined that only the Brandt, Mountain View Park, and PCEI wells responded to pumping during the Moscow #2 Aquifer Test, the barometrically corrected drawdown data were plotted as a log-log graph of drawdown versus time in AQTESOLV®. AQTESOLV® uses several published aquifer test solutions combined with aquifer property information such as aquifer thickness, boundary locations, and well completion information, to develop a unique type curve (expected aquifer response) for

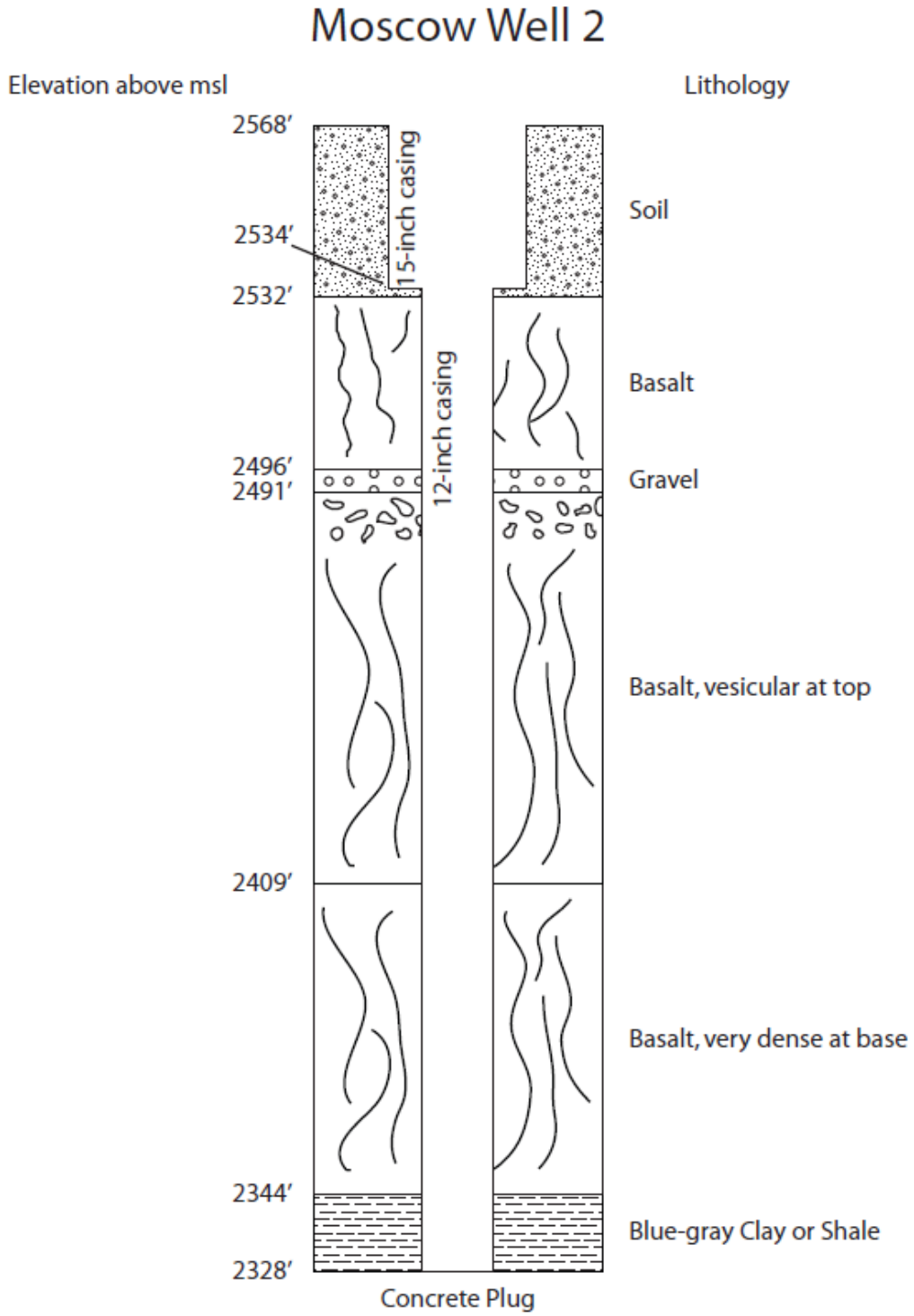

Figure 13. Moscow #2 geology and well completion details (modified from Badon 2007). Elevations and lithology are shown.

the pumping rates and times entered into the software. The type curve represents the predicted aquifer response for the specific boundary and initial conditions for the method of analysis (i.e., analytical model) selected. If none of the limiting assumptions of the method are violated, actual drawdown should fall directly on the type curve generated during the curve matching process. Values for aquifer coefficients such as transmissivity and storativity are calculated for the curve match.

The response measured in the Brandt well (Figure 12) suggests that an excellent hydraulic connection exists with Moscow #2. While Mountain View Park and PCEI also show distinct hydraulic connections (Figure 14) with Moscow #2, the connection with the Brandt well appears to be the strongest and most visually pleasing of the group. Moscow #2 and the Brandt well share the most similar stratigraphic conditions and well completion intervals of the four wells, as indicated in the well logs (Appendix G). Because the well shows such a good hydraulic connection, the Brandt well observations were given the greatest credence and thus, aquifer test analyses were focused on those observations.

Type curve matching began with an attempt to match the drawdown response (after removing barometric pressure effects) measured at Brandt with the type curve predicted by the Theis (1935) equation with the method of superposition for variable pumping rates and no boundaries (Figure 15). The Theis solution represents a fully confined aquifer, infinite areal extent with no source of recharge (Appendix D). The type curve match to the observation well drawdown data shows several obvious deviations. Averaging of pump on/off periods over 24-hour periods during the development of the type curves caused the type curve to be smoothed significantly compared to the observed drawdown curve. A major deviation also occurs during the period of recovery. The type curve predicted by the Theis equation with the method of superposition for variable pumping rates indicates that the water levels should not have recovered as abruptly as the actual measured water levels (Figure 15). However, because the boundaries are known to be real, the effective impermeable boundaries as calibrated with the Palouse Basin Visual

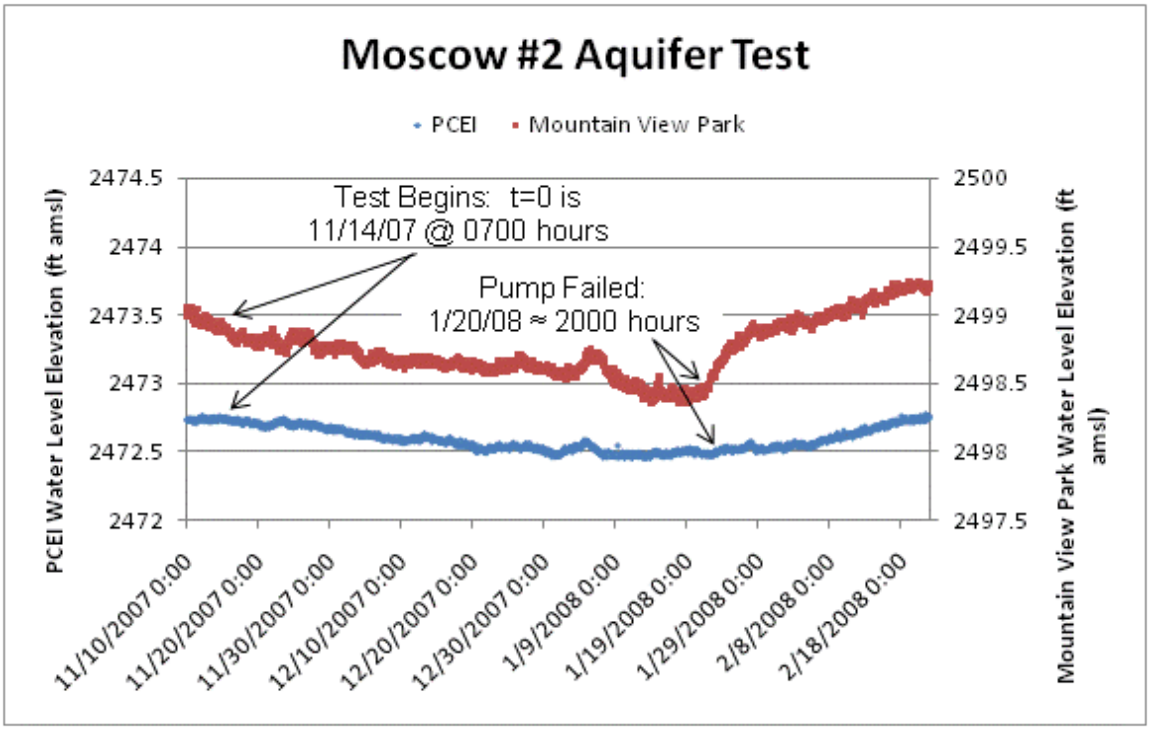

Figure 14. Arithmetic plots of the Mountain View Park and PCEI water level (corrected for barometric pressure effects) vs. time during the Moscow #2 Aquifer Test. Water level elevations are plotted at different scales.

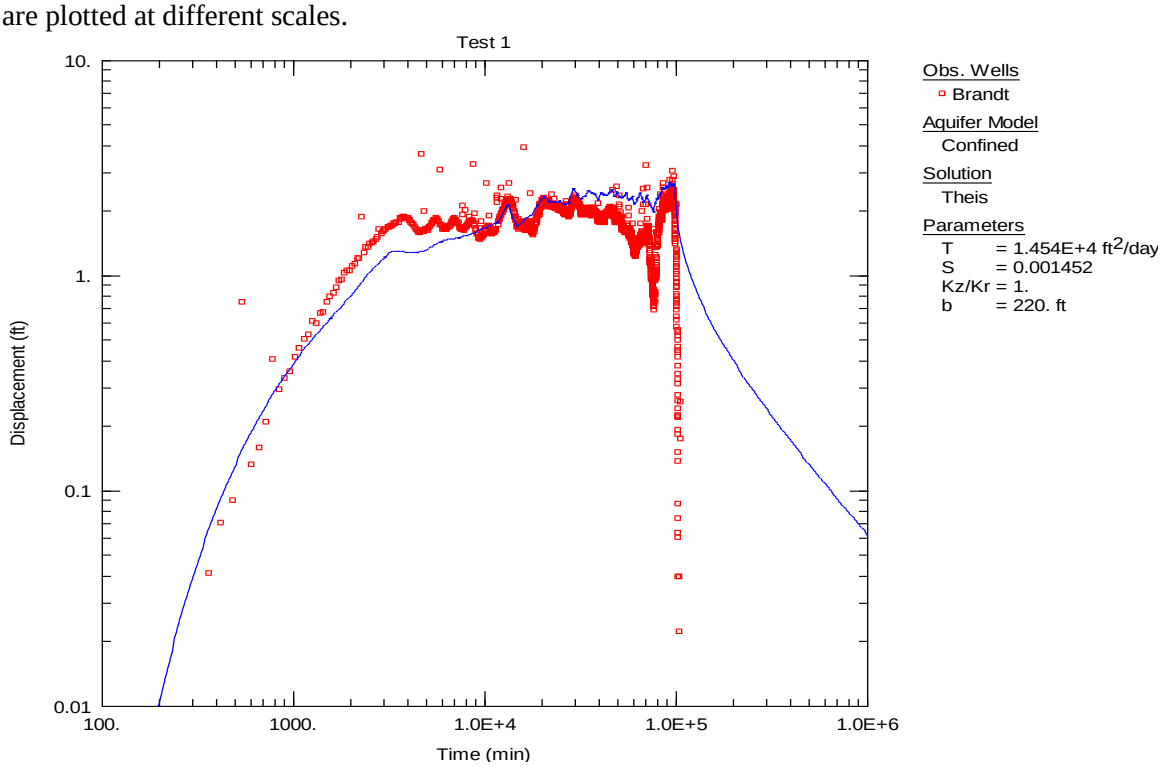

Figure 15. Theis (1935) analysis with the method of superposition for variable pumping rates for the Brandt well drawdown data collected during the Moscow #2 Aquifer Test.

MODFLOW™ model, were added to develop a new type curve based on the Theis equation with the method of superposition for variable pumping rates and boundaries (image wells) (Figure 16). This type curve significantly overestimates drawdown in the Brandt observation well. The type curve in Figure 16 predicts that groundwater inflow into the Moscow sub-basin, from the west, is insufficient for drawdown to stabilize during pumping of Moscow #2 as reflected in the estimated drawdown curve. Therefore, it was concluded that water must be derived from a source bed located above the producing zone in the Wanapum aquifer system. As discussed in Chapter 3, the sediments of Bovill have been shown (Li, 1991; Kopp, 1994; Hernandez, 2007) to be in direct hydraulic connection with some basalt producing zones in the Wanapum aquifer system. Based on the conceptual model for the Wanapum aquifer system as presented in this thesis, the Cooley-Case (1973) analytical model was selected as the method of choice to analyze the observed aquifer test drawdown data. The Cooley-Case method of analysis provides a solution for a semi-confined aquifer with an overlying leaky water table aquitard. A detailed discussion, including equations and assumptions, of the Cooley-Case method is presented in Appendix D.

The type curve predicted by the Cooley-Case (1973) equation with the method of superposition for variable pumping rates and boundaries (image wells) closely matches the drawdown measured in the Brandt observation well (Figure 17). The shape of the type curve is based on four aquifer/aquitard coefficients: transmissivity (T), storativity (S), β, and r/B. Each of these coefficients influences the solution. T and S are aquifer properties, while β and r/B represent leakage properties of the aquitard, such as the hydraulic conductivity, saturated thickness, and storage (both Sy and Ss). Rapid recovery is predicted by the Cooley-Case (1973) equation with the method of superposition for variable pumping rates and boundaries. The rate of recovery is dependent upon the values of β and r/B. Deviations from the type curve early in the test can be attributed to the use of averaged early-time pumping rate variations in lieu of exact on/off times and rates. However, late-time data plot very close to the predicted type curve (Figure 17).

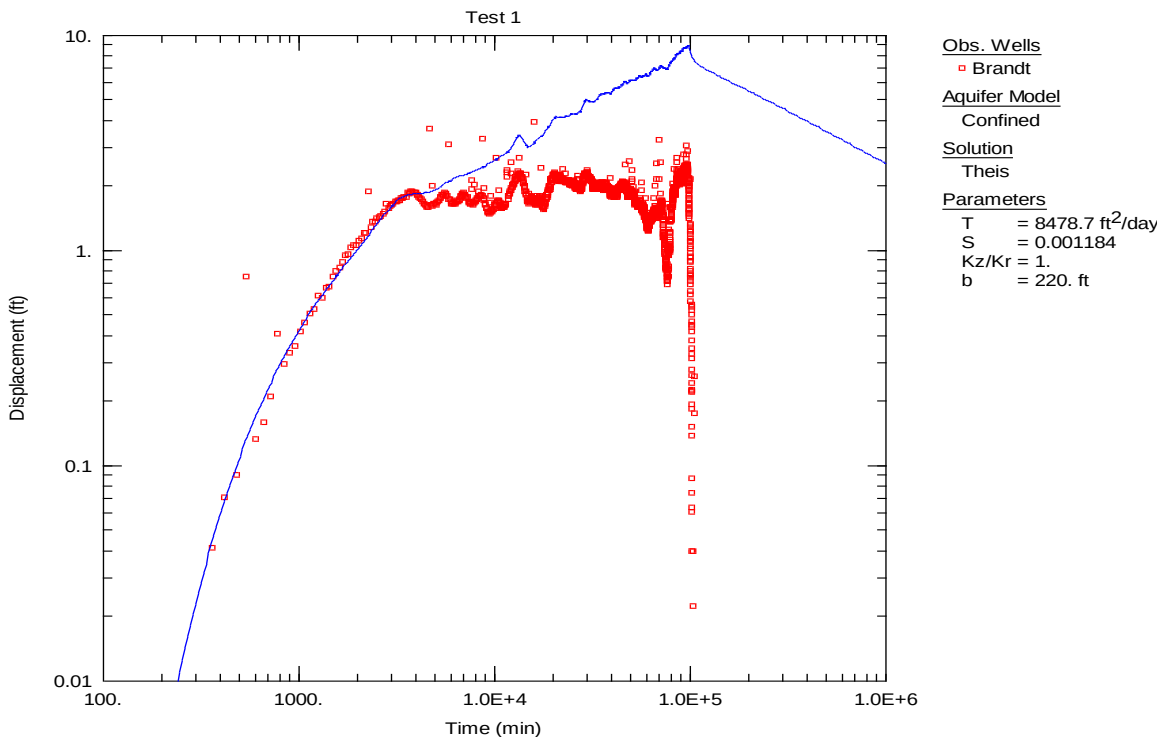

Figure 16. Log-Log plot of drawdown versus time for the Brandt well collected during the Moscow #2 Aquifer Test matched to the type curve derived by the Theis (1935) method with the principle of superposition for variable pumping rates and boundaries**.**

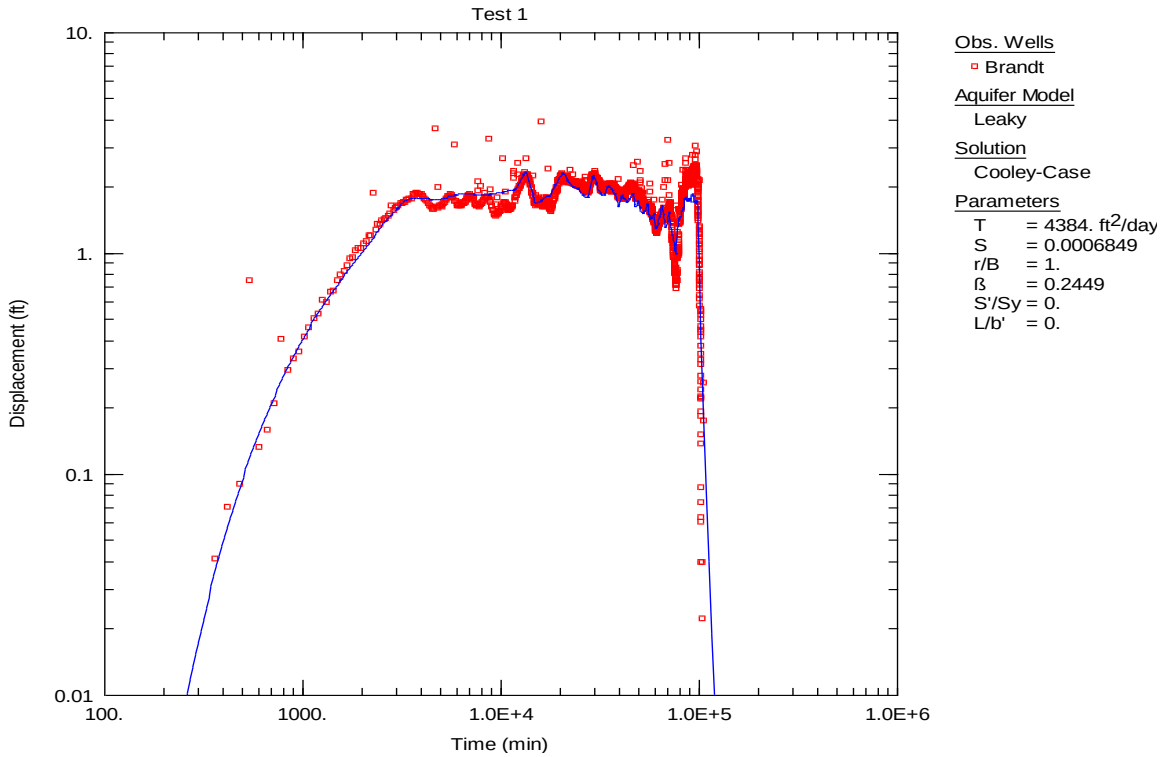

Figure 17. Log-Log plot of drawdown versus time for the Brandt well collected during the Moscow #2 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries.

After concluding that the Cooley-Case (1973) model is an appropriate method available to analyze the Moscow #2 aquifer test, both the Mountain View Park and PCEI wells were plotted (as log-log graphs of drawdown versus time) for analysis (Figures 18 and 19). The quality of the curve matches for the Mountain View Park well and the PCEI well drawdown data are not nearly as good as for the Brandt well. The drawdown responses are not the same shape as those observed in the Brandt well. Shapes of the drawdown curves are distinctive both from each other and from the Brandt well; T, S, r/B, and β were adjusted by trial-and-error to obtain a best visual fit for each well. Fluctuations in the actual drawdown data can be attributed to pumping variations of Moscow #2, but the overall shape of the curves cannot be matched (using the Cooley-Case (1973) or any other available method). Both wells show a small recovery period due to a decrease in aquifer pumping at approximately 10,500 minutes. A time lag appears to exist between the type curve and water level responses in the PCEI well, especially for the recovery portion of the test. This apparent time lag may be a remnant of the time lag used in BETCO© to remove the barometric pressure effects in the water levels. However, because the total drawdown is small (less than 0.5 feet), no definitive drawdown is observed without removing the barometric effects from the PCEI water level record (Figure 8).

Deviations from the type curves are most likely due to a combination of factors, including, heterogeneity and anisotropy within the Wanapum aquifer system, differences in completion zones, small errors associated with removal of barometric pressure effects, and/or the oversimplification of geologic boundaries. Both wells experienced more drawdown than is predicted by the Cooley-Case (1973) method, with the major deviation occurring at approximately 11,000 minutes. This could be due to the cone of depression reaching a boundary that is not properly simulated by the right angle boundaries used in AQTESOLV®. Differences in completion zones may also explain the drawdown responses. Mountain View Park is believed to be completed in the Vantage sediments below the producing zones in the Wanapum basalt, while PCEI is completed in basalt approximately 100 feet higher than the major producing zone tapped by Moscow #2. Despite the relatively poor type curve fits for the aquifer test drawdown data, both the

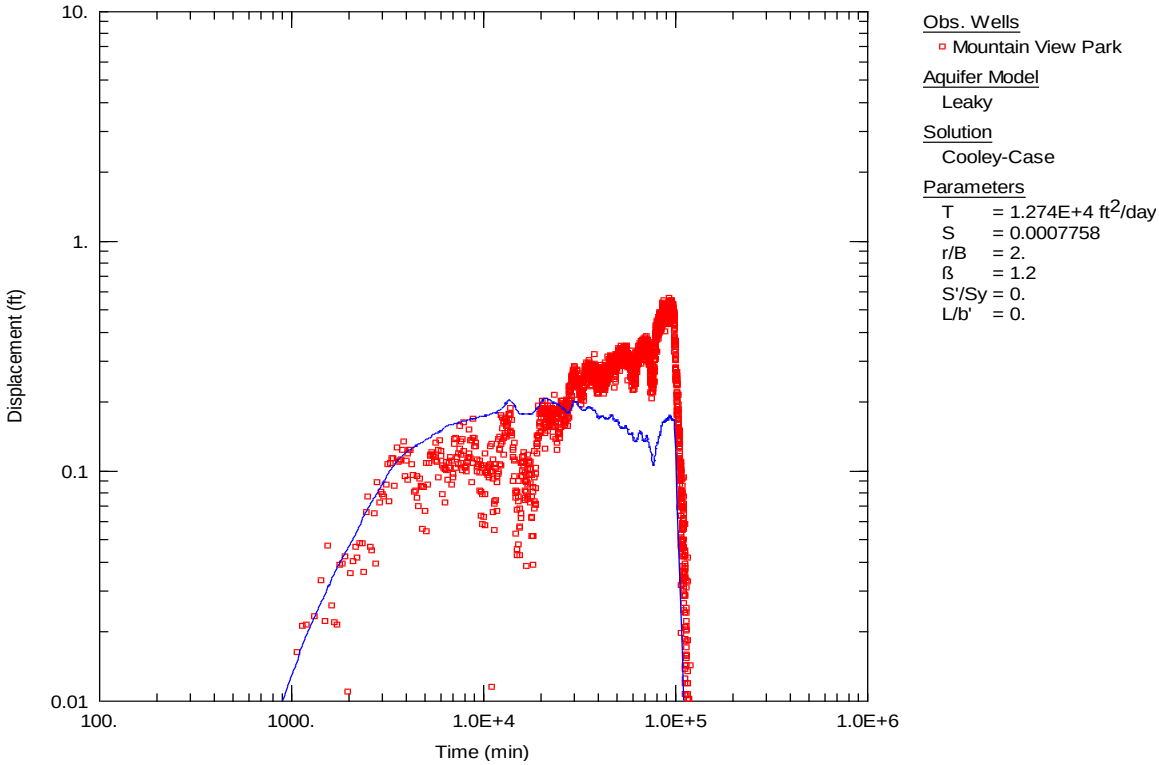

Figure 18. Log-Log plot of drawdown versus time for the Mountain View Park well collected during the Moscow #2 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries.

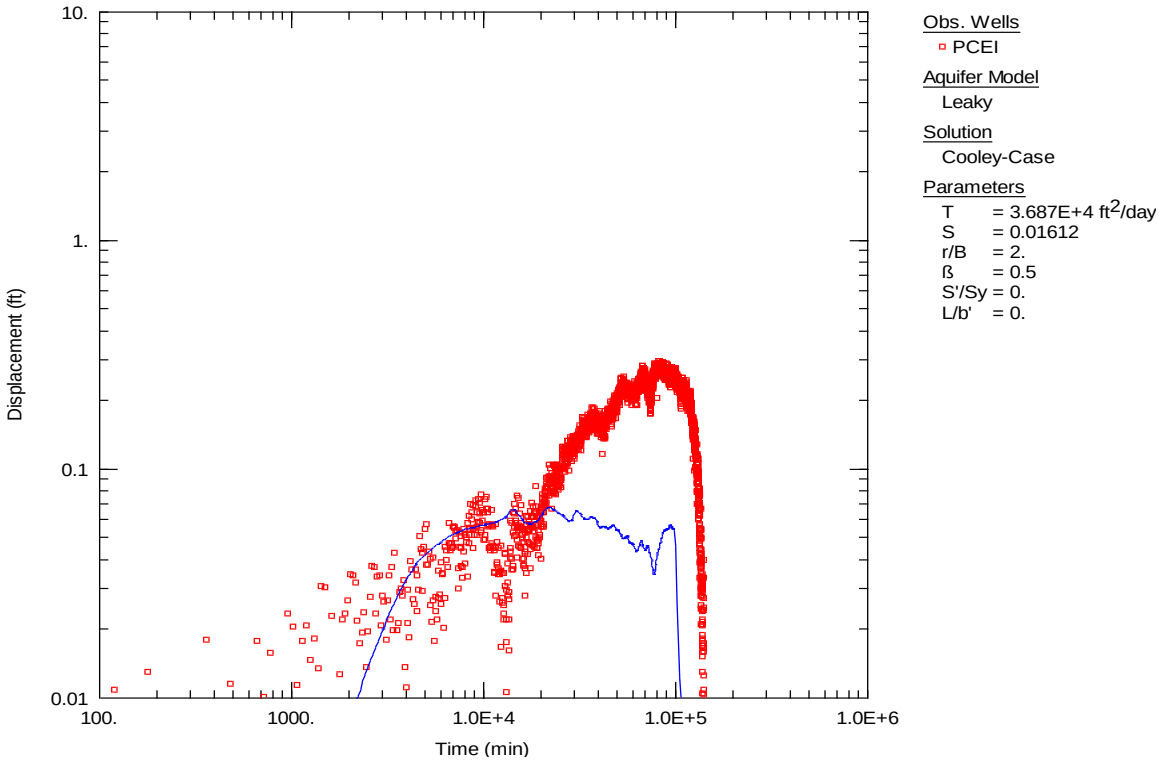

Figure 19. Log-Log plot of drawdown versus time for the PCEI well collected during the Moscow #2 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries.

Mountain View Park and PCEI wells experienced very rapid recovery, indicative of vertical leakage, and predicted by the Cooley-Case (1973) method.

It must be noted that, due to the large number of independent variables that influence groundwater flow between the pumped aquifer and the non-pumped aquitard, a unique solution is not possible by curve matching methods. Estimated drawdown can be affected by adjusting any of the variables used in the solution (T, S, r/B, and β). The aquifer characteristics estimated by these curve matches cannot be considered unique because the curve could, theoretically, be reproduced by many different combinations of values for T, S, r/B and β. Non-uniqueness is due to the fact that drawdown in the aquifer is affected by not only the transmissivity and storativity of the aquifer, but also the hydraulic conductivity and storage capabilities of the aquitard; large amounts of drawdown in the aquifer could be caused by many factors, including, a low aquifer transmissivity, a low value of storativity, or very little leakage from the overlying aquitard. The violation of some limiting assumptions, and issues related to non-uniqueness of the type curve matches affect the values for T and S derived herein; therefore, values presented must be considered estimates only. The T and S, r/B and β values that yield the best type curve fit for each well are presented in Table 2. The values of r/B and β needed to derive the closest type curve matches fall within a reasonable range of values for hydraulic conductivity (.008-.049 ft/day) and specific storage (.00007-.0026) for the sediments of Bovill aquitard.

Aquifer Characteristics Yielding Best Curve Match of Moscow #2 Aquifer Test			
Aquifer Parameter	**Well**		
	Brandt	**Mountain View Park**	**PCEI**
Transmissivity (T)	4384 ft^2/day	12,740 ft^2/day	36,870 ft^2/day
Storativity (S)	0.00068	0.00078	0.016
r/B	1	2	2
β	0.2449	1.2	0.5

Table 2. Estimates of aquifer coefficients based on curve matching. Type curves were derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Note: values must be considered to be estimates only and to be non-unique.

Moscow #2 Aquifer Test Numerical Model

To evaluate the applicability of the Cooley-Case (1973) analytical model as a method for analyzing the Moscow #2 Aquifer Test data, several Modflow simulations of the Moscow #2 Aquifer Test were performed. The model was calibrated to reproduce the actual, field measured, Brandt well drawdown/recovery response for specific aquifer/aquitard hydraulic properties (i.e., model input data). The Visual MODFLOW™ (Modflow 2000) Palouse Basin model used in the boundary analysis was modified to include an aquitard layer overlying the confined aquifer. Table 3 lists the aquifer/aquitard/boundary (aquiclude) property values as simulated in the model. The aquitard layer was given approximately the same lateral dimensions as the sediments of Bovill (Figure 20). The values, T=4384 ft^2/d and S =0.0006849 as estimated for the Brandt observation well in the AQTESOLV® analysis were used for aquifer properties in the model. Aquitard hydraulic properties and saturated thickness were selected subjectively. Differences between the model conditions and the actual geology are known to exist. For example, the exact saturated thickness of the sediments of Bovill is unknown and varies both spatially and temporally. The model aquitard is, therefore, only an approximate representation of the sediments of Bovill. The 138.89-day aquifer test period was divided into 72 pumping stress periods with a variable number of time steps per stress period, and with a time-step multiplier of 1.2 allowing for model simulation of the exact pumping schedule used in AQTESOLV® to generate the type curve for the Brandt observation well. Simulated drawdown and recovery data for the Brandt observation well were imported into AQTESOLV®, plotted as a log-log graph, and matched the type curve predicted by the Cooley-Case (1973) equation with the method of superposition for variable pumping rates and boundaries (image wells).

Figure 21 compares the Visual MODFLOW™ simulated aquifer test drawdown/recovery data and the actual field aquifer test drawdown/recovery data for the Brandt observation well. It should be noted that, in order for the model to accurately simulate the recovery portion of the aquifer test, recharge had to be added to the model to maintain adequate heads in the aquitard. Based on trial-and-error calibration, a recharge rate between 20 mm/yr and 50 mm/yr distributed uniformly over the simulated sediments

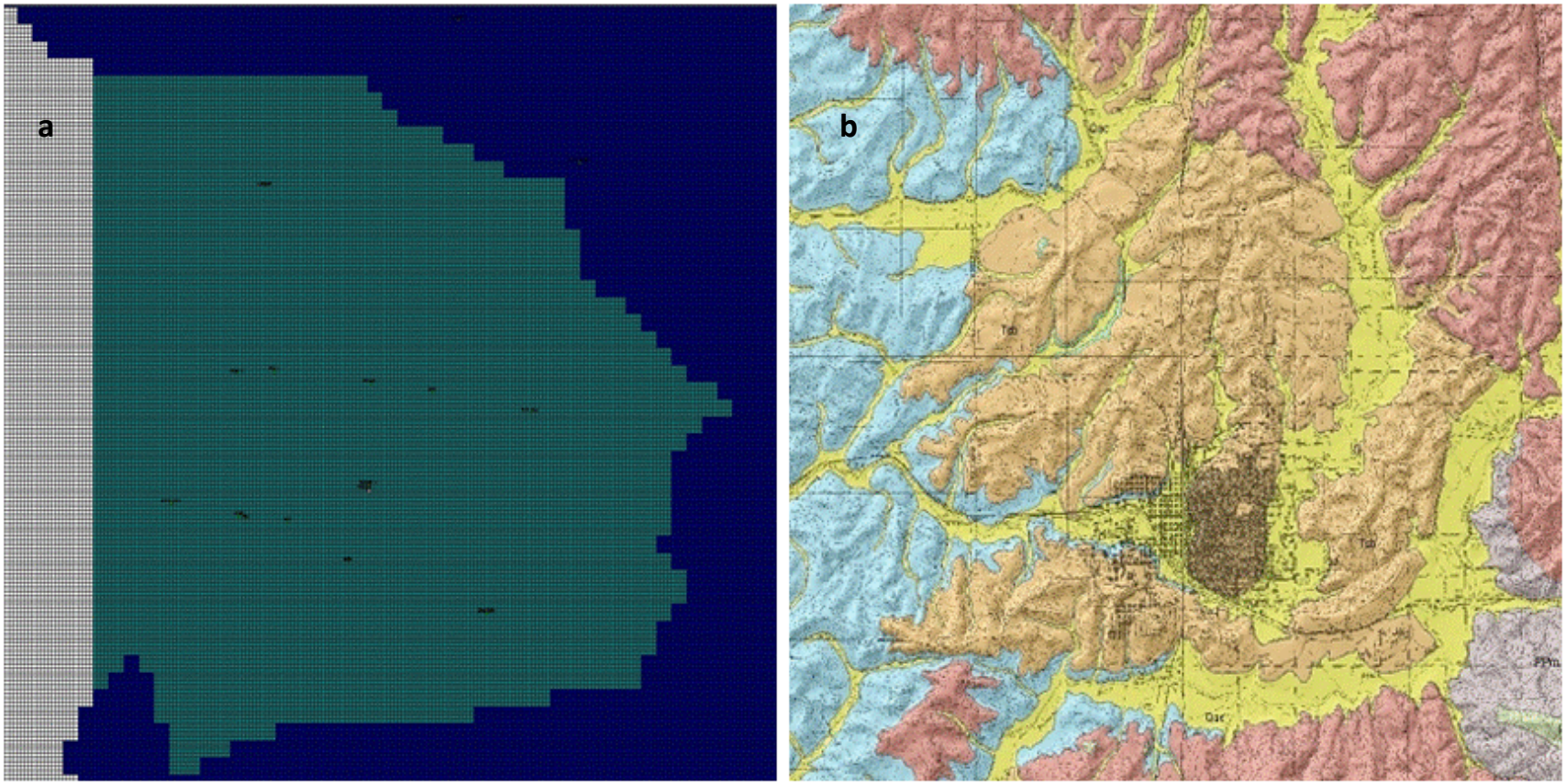

Figure 20. Comparison of Moscow sub-basin geologic boundaries (refer to Figure 3 for more details) and representative inputs placed into Visual MODFLOW™ for determining applicability of Cooley-Case (1973) model in Moscow #2 Aquifer Test analysis. Figure 20a presents a small portion of the entire model grid and shows the simulated crystalline rock boundaries (dark blue) surrounding the sediments of Bovill (green). Figure 20b shows the crystalline rock boundaries (pink and gray), sediments of Bovill (tan), recent alluvium (yellow), and Wanapum basalt (light blue) as mapped by Bush et al. (2007).

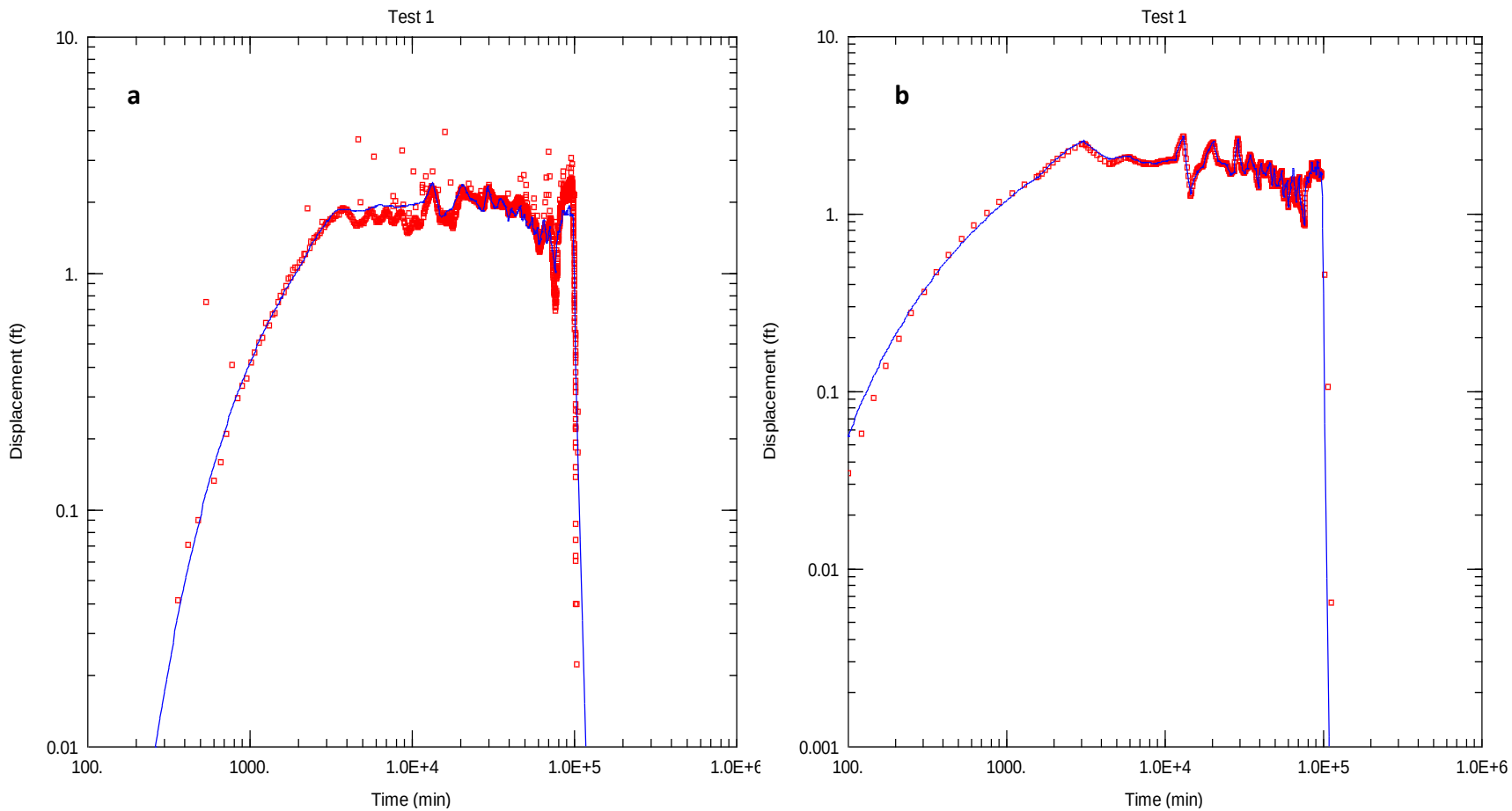

Figure 21. Comparison of a) actual drawdown and recovery observed at the Brandt observation well, and b) Visual MODFLOW™ simulated drawdown and recovery in the Brandt observation well during the Moscow #2 Aquifer Test. The Visual MODFLOW™ model utilized a 10-meter (30-ft) thick layer to simulate the sediments of Bovill.

Model Properties for Aquifer Test Simulation			
Model Parameters	Aquifer	Aquitard	Aquiclude
K (ft/day)	19.92	0.008	3.28 X10 -25
Ss	3.1318×10^{-5}	2.0 x 10-5	1×10^{-5}
Sy	0.2	0.2	0.2
b (ft)	220	32.8	252.8

Table 3. Aquifer/aquitard properties used in the Visual MODFLOW™ simulated aquifer test. The simulated aquifer consisted of 61 meters (200-ft) of Wanapum basalt plus 6 meters (20-ft) of Vantage sediments; the aquitard represented the sediments of Bovill, and the aquiclude represented the basement boundary rocks.

of Bovill was needed (greater recharge makes the recovery curve more vertical). Overall, the simulated and actual data plots are very similar. However, drawdown occurs sooner and increases more rapidly in the model simulation data than for the actual field data suggesting that the simulated cone of depression reaches the basin perimeter boundaries sooner than in the real cone of depression. This may be due to heterogeneity and/or anisotropy (e.g., compartmentalization) in the Wanapum aquifer system that was not simulated. In early time, the actual leakage to the Wanapum aquifer system appears to be greater than leakage in the model simulation. Fluctuations in drawdown and recovery between 12,000 minutes and 100,000 minutes are much less variable in the model output than in the actual field data. Averaging of the pumping rates over 24-hour periods resulted in fewer pumping periods in the model simulation than occurred in reality. At the end of the pumping portion of the test, more drawdown was measured in the real Brandt well than in the model simulation. This is most likely due to periodic pumping of the Brandt well for domestic uses (floating bubble effect in Figure 17) combined with heterogeneity and/or anisotropy that were not simulated. While not exactly the same, the shape of the drawdown curves strongly suggest that the Cooley-Case (1973) model is a reasonable method for analyzing the Moscow #2 Aquifer Test.

Moscow #3 Aquifer Test

After mechanical pump failure abruptly ended the Moscow #2 Aquifer Test, a second test using Moscow #2 was planned. However, it became apparent that Moscow #2 would not be repaired in time for a second test, planned to occur in spring 2008. Therefore, Moscow #3 (a well approximately 200 feet north of Moscow #2) was used to conduct the second aquifer test. A data logger was placed in Moscow #2 for a portion of the test to determine if there is any hydraulic connection between the two wells. Pumping of Moscow #3 during an aquifer test conducted in May 2005 did not cause measurable drawdown in Moscow #2 (Badon, 2007). Drawdown was not observed in any Grande Ronde aquifer system observation wells or Wanapum aquifer system observation wells during the May 2005 aquifer test. The primary producing zone for Moscow #3 has never been delineated. However, a borehole video log of the well (city of Moscow) suggests that at least some water may enter the well through the Wanapum basalt. The well log (Appendix G) indicates that Moscow #3 is completed through the Vantage sediments and into the uppermost Grande Ronde basalt flows. Static water levels in Moscow #3 are the same as Moscow #2, suggesting that Moscow #3 draws water from the Wanapum aquifer system.

After the end of the pumping period for the Moscow #2 Aquifer Test, no municipal pumping of the Wanapum aquifer system occurred for 80 days. The 80-day recovery period allowed water levels in the Wanapum aquifer system to approach as close to a non-pumping condition as could be expected. On April 16, 2008, Moscow #3 began pumping to start the Moscow #3 Aquifer Test. In a manner similar to the Moscow #2 Aquifer Test, the volume of water pumped per day was dependent upon the water needs of the city of Moscow, and volumes of water pumped daily were recorded. The pumping period for the aquifer test lasted 70 days until June 24, 2008. A 12-day recovery period followed before pumping of Moscow #3 resumed. On/off records (Appendix E) were only recorded periodically throughout the duration of the test, and therefore, daily averaged pumping rates were used in the aquifer test analysis instead of actual pumping rates and times. Averaging the pumping rate over a 24-hour period is a known source of error in the analysis. The start of the aquifer test was accurately recorded, and t=0 occurred April 16, 2008, at 0930 hours.

Water levels in the Wanapum aquifer system are dynamic and vary seasonally. During the late spring and early summer, water levels begin to decline and generally continue to decline until early fall. Almost the entire Moscow #3 Aquifer Test was completed during a period of continual, seasonally declining water levels in the Wanapum aquifer system. However, water levels in the aquifer had been rising since the pump failure on January 20th ended the Moscow #2 Aquifer Test, (Figures C2 through C19 in Appendix C). The rising water level trends in the aquifer were taken into consideration and will be discussed further in the Moscow #3 Aquifer Test Analyses section. Water levels in all the observation wells began to decline shortly after pumping of Moscow #3 began and continued to decline during the rest of the 70-day pumping period. This placed a greater significance on the 12-day recovery portion of this aquifer test to rule out coincidence in timing of the water level declines due to some cause other than direct pumping of Moscow #3. Barometric pressure effects were removed from the water levels measured in the observation wells; arithmetic plots of these data are presented in Appendix C. In contrast to the drawdown measured during the Moscow #2 Aquifer Test, drawdown during the Moscow #3 Aquifer Test was not recorded immediately in any of the observation wells. However, after a time lag of approximately two weeks, water levels in most wells began to decline. By the end of the test period, water level declines were measured in every Wanapum aquifer system observation well. The only way to ascertain whether water levels were falling due to Moscow #3 pumping or some other unknown cause was to analyze water level data for the 12-day recovery period following the test. Four wells showed recovery during the 12-day recovery period (Brandt, Mountain View Park, PCEI, and Moscow #2). Water levels in the other wells declined continually during the recovery portion of the test, so no other positive hydraulic connections could be identified.

Moscow #3 Aquifer Test Analyses

At the beginning of the Moscow #3 Aquifer Test, water levels in the Wanapum aquifer system appeared to be recovering from the seasonal pumping of the summer and/or the Moscow #2 Aquifer Test. Water levels for the Brandt well were plotted for the period between January 21, 2008, (the end of the Moscow #2 Aquifer Test) and the end of the Moscow #3 Aquifer Test recovery period (Figure 22). The water level rise

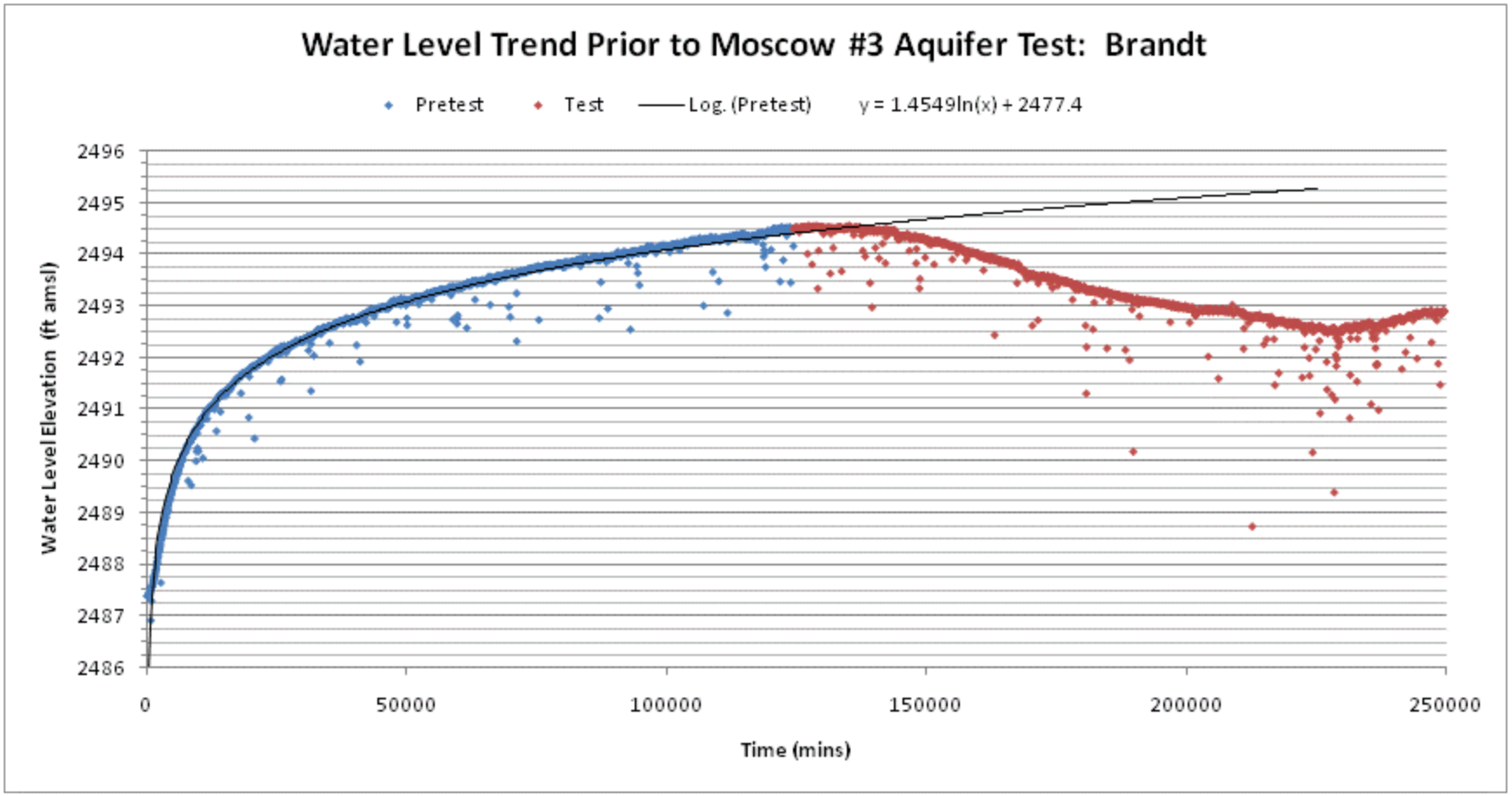

Figure 22. Rising water level trend (blue) in the Brandt well prior to the Moscow #3 Aquifer Test. The trend began when a pump failure ended the pumping portion of the Moscow #2 Aquifer Test. It is impossible to know how long the rising water level trend would have continued, or if it would have continued throughout the period of Moscow #3 Aquifer Test (red).

in the Brandt well appears to be a recovery curve. Because the data appear to represent a recovery curve, the water level data between the aquifer tests was fit to a logarithmic trendline using Excel. To determine the effects of the trend on the aquifer test, the drawdown data were analyzed with and without the trend added to the data. It is impossible to know how long the trend would have continued, so, to be conservative, the trend was projected to continue throughout the duration of the Moscow #3 Aquifer Test. Accounting for the trend, drawdown was considered to be the difference between the observed drawdown and the projected water level, assuming the trend continued throughout the test. When the trend was taken into consideration, approximately one foot of additional drawdown was calculated for the Brandt well. The projected drawdown with the trend considered (Figure 23) and the observed drawdown (Figure 24) were plotted on log-log scales as drawdown versus time. The type curve predicted by the Cooley-Case (1973) equation with the method of superposition for variable pumping rates and boundaries (image wells) was matched to the drawdown and recovery data. After establishing the best visual curve match, it was determined that although incorporation of the trend causes greater apparent drawdown and shifts the location of the drawdown curve, the shape of the drawdown curve was unaffected. It is unknown whether the trend would have continued throughout the duration of the aquifer test, and thus, the differences between the estimated aquifer characteristics were not considered significant enough to warrant adjusting for the trend in all other monitoring wells. The estimated T and S when the trend was considered were T=3166ft^2/d and S=0.01185. When the trend was ignored, the T and S estimates were slightly larger, T=3745ft^2/d and S=0.0185.

During the Moscow #3 Aquifer Test, more water was pumped from the aquifer system than during the Moscow #2 Aquifer Test. The average amount of water pumped each day was also slightly greater during the Moscow #3 Aquifer Test. All four wells that responded to Moscow #3 pumping did so in similar ways. Observation well drawdown responses were delayed and gradual in contrast to the nearly immediate responses observed during the Moscow #2 Aquifer Test. Water level measurements were plotted on log-log scales as drawdown versus time. The type curves predicted by the

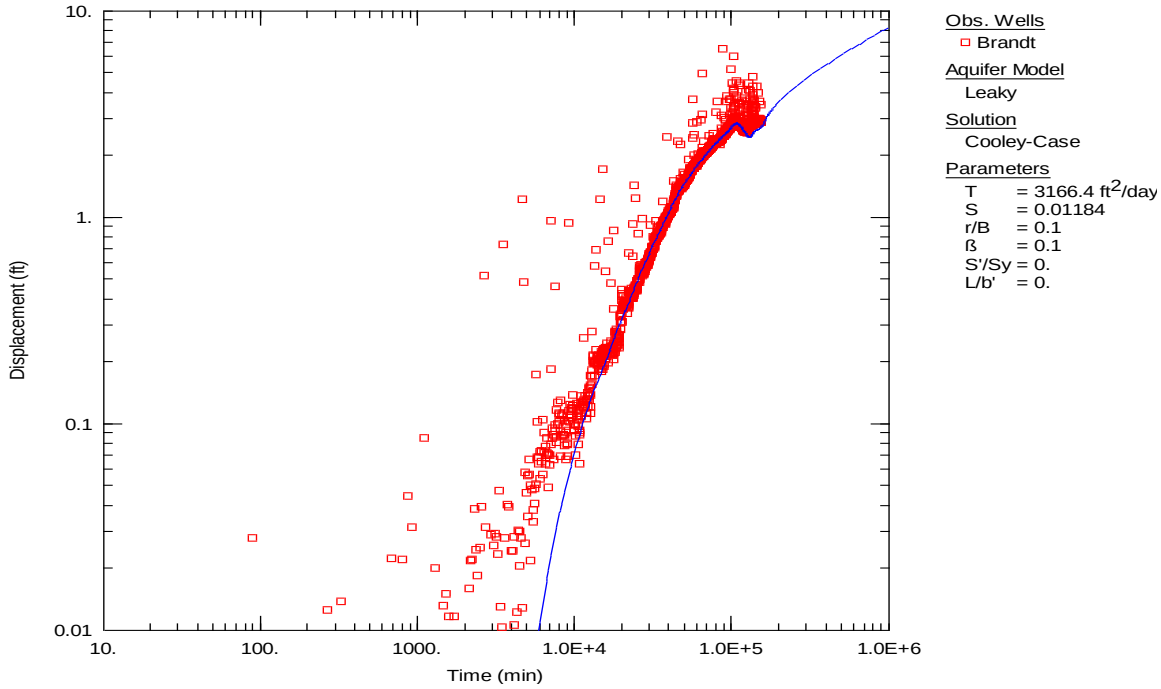

Figure 23. Log-Log plot of drawdown versus time for the Brandt well collected during the Moscow #3 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Plotted data incorporate corrections for the rising water level trend throughout the duration of the Moscow #3 Aquifer Test.

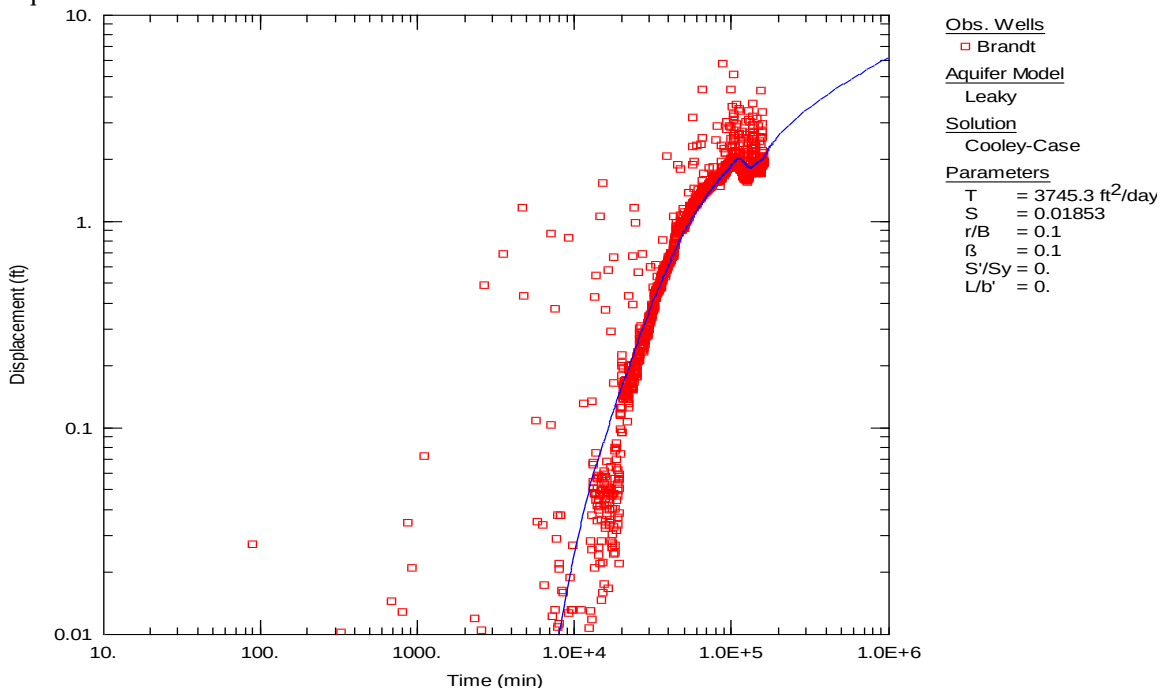

Figure 24. Log-Log plot of drawdown versus time for the Brandt well collected during the Moscow #3 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Plotted data do not incorporate corrections for the rising water level trend prior to the start of the Moscow #3 Aquifer Test.

Cooley-Case (1973) equation with the method of superposition for variable pumping rates and boundaries (image wells) were also matched to the drawdown and recovery data for observation wells, PCEI, Mountain View Park, and Moscow #2 (Figures 25, 26, and 27). Drawdown is delayed approximately 10,000 minutes at the Brandt well, approximately 11,000 minutes in the PCEI and Mountain View Park wells. Mountain View Park was used for irrigation pumping during the aquifer test, causing a great deal of noise in the drawdown curve for the Mountain View Park well. A data logger was not placed in well Moscow #2 until approximately 21 days after the start of the test. A depth to water measurement taken the morning of April 16th by the city of Moscow Water Department was considered to represent the pre-pumping static condition (t=0) and was used to calculate the amount of drawdown in the well prior installation of the data logger. The drawdown curve for Moscow #2 shows a slight blip at approximately 40,000 minutes; this is believed to be the result of a two-day period of reduced pumping of Moscow #3. The blip recovery period does not appear in the Brandt or PCEI water level records, and the Mountain View Park record is too noisy to resolve either way. All wells

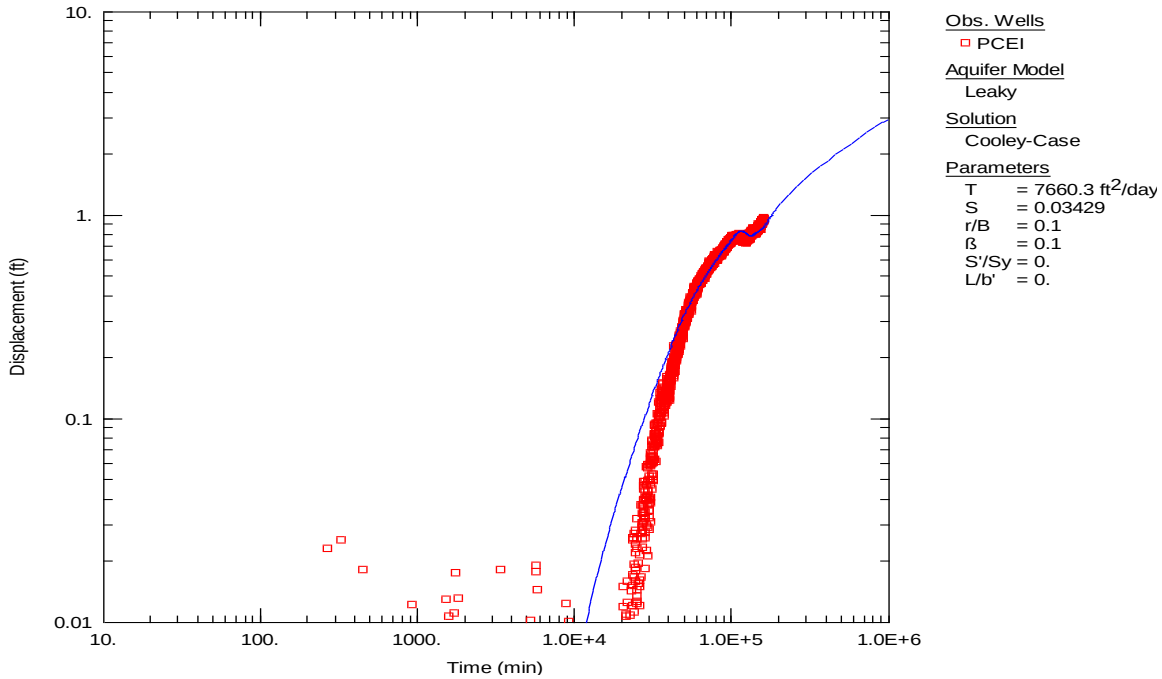

Figure 25. Log-Log plot of drawdown versus time for the PCEI well collected during the Moscow #3 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Plotted data do not incorporate corrections for the rising water level trend prior to the start of the Moscow #3 Aquifer Test.

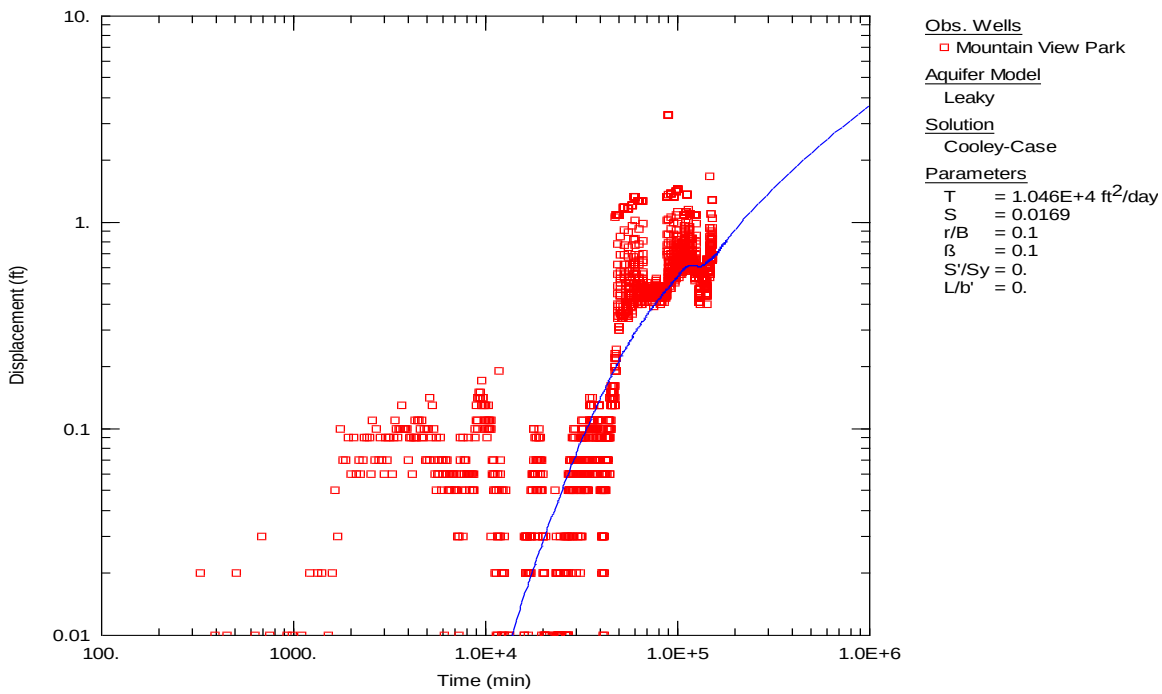

Figure 26. Log-Log plot of drawdown versus time for the Mountain View Park well collected during the Moscow #3 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Plotted data do not incorporate corrections for the rising water level trend prior to the start of the Moscow #3 Aquifer Test.

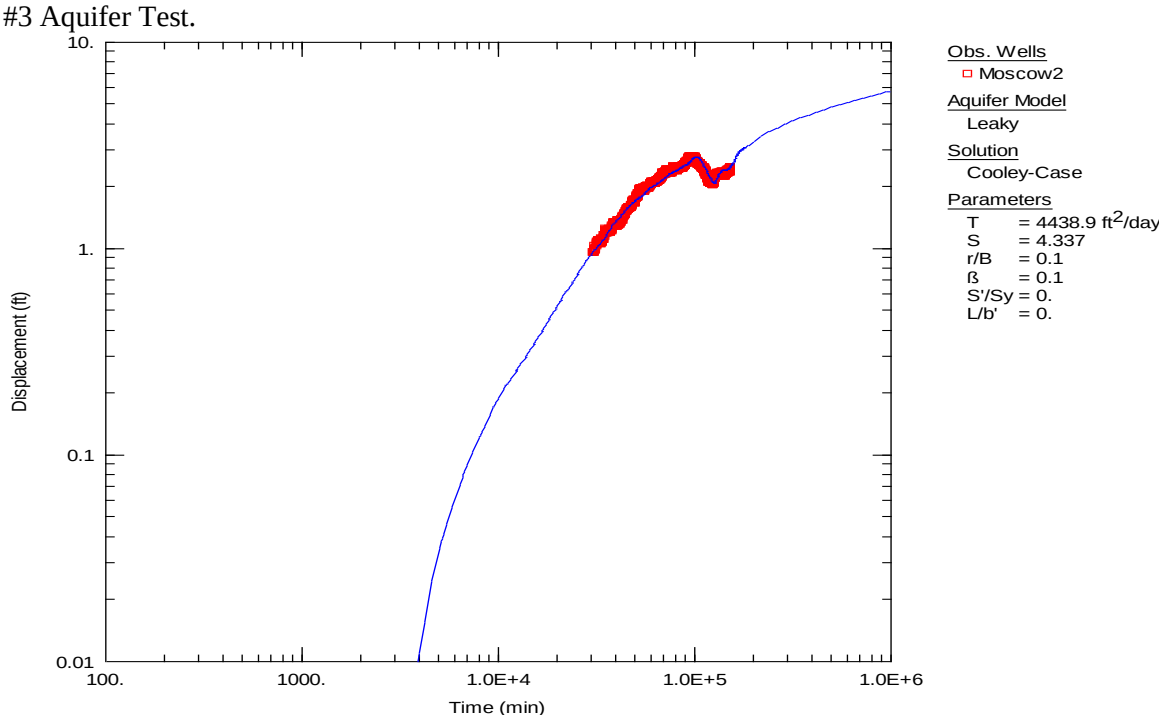

Figure 27. Log-Log plot of drawdown versus time for the Moscow #2 well collected during the Moscow #3 Aquifer Test matched to the type curve derived by the Cooley-Case (1973) method with the principle of superposition for variable pumping rates and boundaries. Plotted data do not incorporate corrections for the rising water level trend prior to the start of the Moscow #3 Aquifer Test.

show a period of recovery at approximately 100,000 minutes; this corresponds to a 12-day recovery period where Moscow #3 was not pumping.

Moscow #2 is less than 200 feet away from Moscow #3 (Figure 2), and although drawdown was recorded, the drawdown appears to be an atypical aquifer response. Drawdown closest to the pumping well should be much greater than drawdown observed farther from the well. Drawdown in Moscow #2 was only about 0.5 ft greater than the drawdown measured in the Brandt well, almost one mile to the north of Moscow #3. After curve matching was completed for Moscow #2 (Figure 27), the estimated value of storativity (S=4.337) is far greater than the maximum possible storativity of one. The Brandt, Mountain View Park, and PCEI curve matches yield apparent storativity values indicative of unconfined aquifers; however, the Moscow #2 Aquifer Test analysis of the Brandt and Mountain View Park data yielded estimates of storativity that suggest the aquifer is confined. Moscow #3 is completed below the completion zone of Moscow #2 (a confined aquifer) and withdraws groundwater from a deeper portion of the Wanapum aquifer system. The apparent discrepancy between the storativity values derived for the two aquifer tests is believed to reflect the condition that the observation wells are completed in different aquifers (producing zones) than the aquifer pumped during the Moscow #3 Aquifer Test.

Responses to Moscow #3 pumping are delayed and appear to be dampened. The shape of the drawdown curves observed for the Brandt, Mountain View Park, PCEI, and Moscow #2 wells are similar in character to those predicted by Neuman and Witherspoon (1969) for wells completed in an overlying aquitard or aquifer. Vertical separations between the producing zone for Moscow #3, and the completion zones for the observation wells can be explained hypothetically. Moscow #3 water may be derived from a producing zone that is separated stratigraphically from the rest of the overlying strata by a laterally continuous clay layer. Well logs for the Moscow #2 and Moscow #3 wells (Appendix G) describe several layers that could potentially be responsible for retarding hydraulic responses between the potential producing zones, including a 30-ft thick layer of clay/shale directly below the Wanapum basalt. Bush (2006) describes several five to ten foot thick clay layers, discovered in the well cuttings for the Vantage

sediments collected during drilling of the IDWR well nest. A potential clay layer(s) may separate the completion zones of the responding observation wells from the producing zone of Moscow #3. However, this is only a hypothetical explanation for the lack of strong and immediate hydraulic connection to Moscow #3 pumping, because the clay layer has not been delineated. Other observation wells in the Wanapum aquifer system monitoring network (OldCemetery, UI #2, and IDWR 3) are completed in similar geologic units and at similar depths as Moscow #3. However, no definitive hydraulic connection to any of these wells is apparent in the water level hydrographs (Figures C2 through C19 in Appendix C).

Implications of Aquifer Test Results

Results of both the Moscow #2 Aquifer Test and the Moscow #3 Aquifer Test have important implications for management of the groundwater resources within the Moscow sub-basin. The Wanapum aquifer system is thought to consist of the sediments of Bovill, Wanapum basalt, and Vantage sediments. Observed drawdown during the two tests suggests that the aquifer system is composed of a leaky aquitard overlying at least two leaky aquifers or producing zones, which are separated by a horizontal aquitard. The results (i.e., no observed hydraulic connections to Moscow #3) of the previous aquifer tests conducted by Badon (2007) can be explained by the presence of an aquitard between Moscow #2 and Moscow #3. Previous aquifer pumping tests using Moscow #3 as the pumping well were of relatively short duration (14 hours) when compared to those conducted during this investigation.

Compartmentalization of the Wanapum aquifer system is prominent, as has been hypothesized previously. After two, long-term (68 and 70-day) aquifer pumping tests, drawdown was observed in only four wells. Because the aquifer was stressed for such long durations, the cones of depression should have propagated throughout the Moscow sub-basin. However, observed drawdowns from the Moscow #2 and Moscow #3 Aquifer Tests, suggest that the aquifer compartmentalization is not just a short-term phenomenon. The extent of the aquifer compartment penetrated by Moscow #2 and Moscow #3 is unknown; however, aquifer test results suggest that the compartment extends in a north-south direction between the Brandt well and the Bond well (Badon, 2007). Results of

this investigation indicate that the compartment also extends eastward to at least the Mountain View Park well (Figure 2). It appears the compartment does not extend to the Old Cemetery well, southeast of Moscow #2 and Moscow #3 (Figure 2). The western extent of the compartment is difficult to delimit, because no drawdown was measured west of Moscow #2 or Moscow #3; however, it must be assumed that the compartment does not extend westward to the IDWR monitoring well network, or to well UI #2. Several factors likely affect aquifer compartmentalization, including the lack of fracture continuity, and/or the clay filling of fracture zones. It is unclear what could cause the compartmentalization within the Vantage sediments. One potential explanation is the existence of paleo-stream channels (Bush, 2005); these heterogeneities may form preferential flow paths between different locations within the Moscow sub-basin. Additionally, the propagation and shape of the cone of depression may depend on the spatial distribution of leakage from the overlying sediments of Bovill into the major producing zones at the base of the Wanapum basalt and throughout the Vantage sediments.

Seasonal water level fluctuations throughout the Wanapum aquifer system have been considered the result of added stresses on the aquifer system due to landscape irrigation occurring in summer months. Results of long-term aquifer tests suggest there is little hydraulic connection between most wells in the Wanapum aquifer system monitoring network and the municipal pumping centers in the Wanapum aquifer system. Several feet of drawdown are observed in most Wanapum aquifer system wells during the summer months (Figure B3 to B21 Appendix B). However, if the aquifer is compartmentalized, most water level declines may not be directly attributable to additional seasonal pumping of Moscow #2 or Moscow #3. Therefore, some unknown discharge might account for the water level declines. No major pumping wells are known to exist in the Wanapum aquifer system, other than the municipal wells in Moscow. Potential explanations for the seasonal water level fluctuations include groundwater discharge to streams or springs west of the Moscow sub-basin, and domestic pumping of the Wanapum aquifer system. Another possibility is that all wells (in the Wanapum aquifer system) are connected over an annual time frame even though direct hydraulic connections have not been observed.

Observed drawdown recorded in the Wanapum aquifer system observation wells due to pumping of Moscow #2 suggests that leakage through the sediments of Bovill most likely plays an important role in the total annual recharge that occurs annually. Based on the pumping responses observed, and the rapid recovery of water levels in the system, it is feasible that recharge is being supplied from streams in the Moscow sub-basin. Calibration of the Visual MODFLOW™ (Modflow 2000) Palouse Basin model required between 20 and 50 mm of recharge over the sediments of Bovill annually. The rapid recovery of the groundwater levels can only be explained if hydraulic heads in the aquitard are not drawn down. In order for the hydraulic heads to be maintained, the aquitard must receive at least as much water as it loses to the underlying aquifer.

Chapter 5 – Water Level Records for 2007-2008

Introduction

As part of this thesis research, data loggers in Wanapum aquifer system monitoring wells were downloaded and reset approximately every three months. Downloading for this project began in October 2007. Water level hydrographs for 2007 and 2008 have been plotted for all the wells in the monitoring network (Appendix B). Hydrographs have been compared to evaluate potential hydrologic connections between wells and/or to identify long-term trends in the data. This chapter compares water level hydrographs based on well locations, trends, and well completion depths. Water level elevations in the hydrographs represent raw data, and thus only the approximate total heads measured in the wells over time. The effects of barometric pressure variations over time have not been filtered from the data presented in the hydrographs; however, the data logger data have been converted to elevations above mean sea level based on the surveyed (GPS) elevation of the top of each well casing (measurement reference point).

Pumping Conditions

Many domestic (includes lawn irrigation) wells draw water from the Wanapum aquifer system. However, municipal pumping of Moscow #2 and Moscow #3 is believed to constitute the major groundwater withdrawals from the system. Municipal pumping must be taken into consideration in order to understand any trends in the hydrographs. The amount of water pumped from each well is recorded daily by the city of Moscow Water Department. Table 4 shows the volume of water pumped from Moscow #2 and Moscow #3 in 2007 and 2008. In 2007, Moscow #2 was pumped significantly more than Moscow #3. However, in 2008 Moscow #2 was offline for the majority of the year, and Moscow #3 was pumped significantly more than the previous year. Total pumping from the Wanapum aquifer system was down by 34% in 2008.

Theoretically, the decrease in pumping, and the shift from Moscow #2 to Moscow #3 should be seen in the hydrographs. Although not all the wells in the monitoring network responded during aquifer tests, changes in pumping may be detectable in the water level data when viewed over a longer period of time. Water levels should increase slightly from 2007 to 2008, based solely on the total amount of pumping each year.

However, if Moscow #3 draws water from a deeper aquifer or producing zone than Moscow #2, water levels might be expected to have declined more in deeper wells than in shallow wells because of the increased pumping of Moscow #3 and decreased pumping of Moscow #2.

Volume of Municipal Water Pumped from the Wanapum Aquifer System			
Year	Gallons Pumped From Each Well		Combined Total (Gallons)
	Moscow #2	Moscow #3	
2007	216,013,300	18,156,000	234,169,300
2008	15,061,600	138,486,000	153,547,600

Table 4. Municipal pumping of the Wanapum aquifer system in the Moscow area for 2007 and 2008.

Hydrograph Comparisons

Several observations can be made when all the wells in the Wanapum aquifer system are plotted on the same chart (Figure 28). Water level elevations in the wells vary widely (between 2470 and 2670 feet above mean sea level), and temporal water level fluctuations within different wells vary greatly. Overall, between 2007 and 2008, water levels neither declined nor rose significantly (Figure 28). The wells showing hydraulic connections to both Moscow #2 and Moscow #3 during the aquifer tests exhibit similar seasonal water level trends (Figure 29). However, water levels in the PCEI and Mountain View Park wells declined in 2007, and rose in 2008, while water levels in the Brandt well have risen since the beginning of 2007. The Brandt, Mountain View Park, and PCEI wells all responded to municipal pumping; however, the magnitudes of the fluctuations were not the same. Brandt showed the largest fluctuations, while Mountain View Park and PCEI exhibited smaller water level changes between 2007 and 2008. Water levels in the hydraulically connected wells varied by about 22.5 feet over the time period of the hydrographs. Unlike some other locations within the Wanapum aquifer system, the deepest well (Mountain View Park) had the highest groundwater level, while the shallowest well (PCEI) has the lowest water level. It should be noted that the Moscow #2 Aquifer Test was conducted in December 2007 and January 2008. Water level recovery from that test may be the cause of the rising water levels during 2008.

Long-Term Water Level Hydrograph for Monitored Wanapum Aquifer System Wells

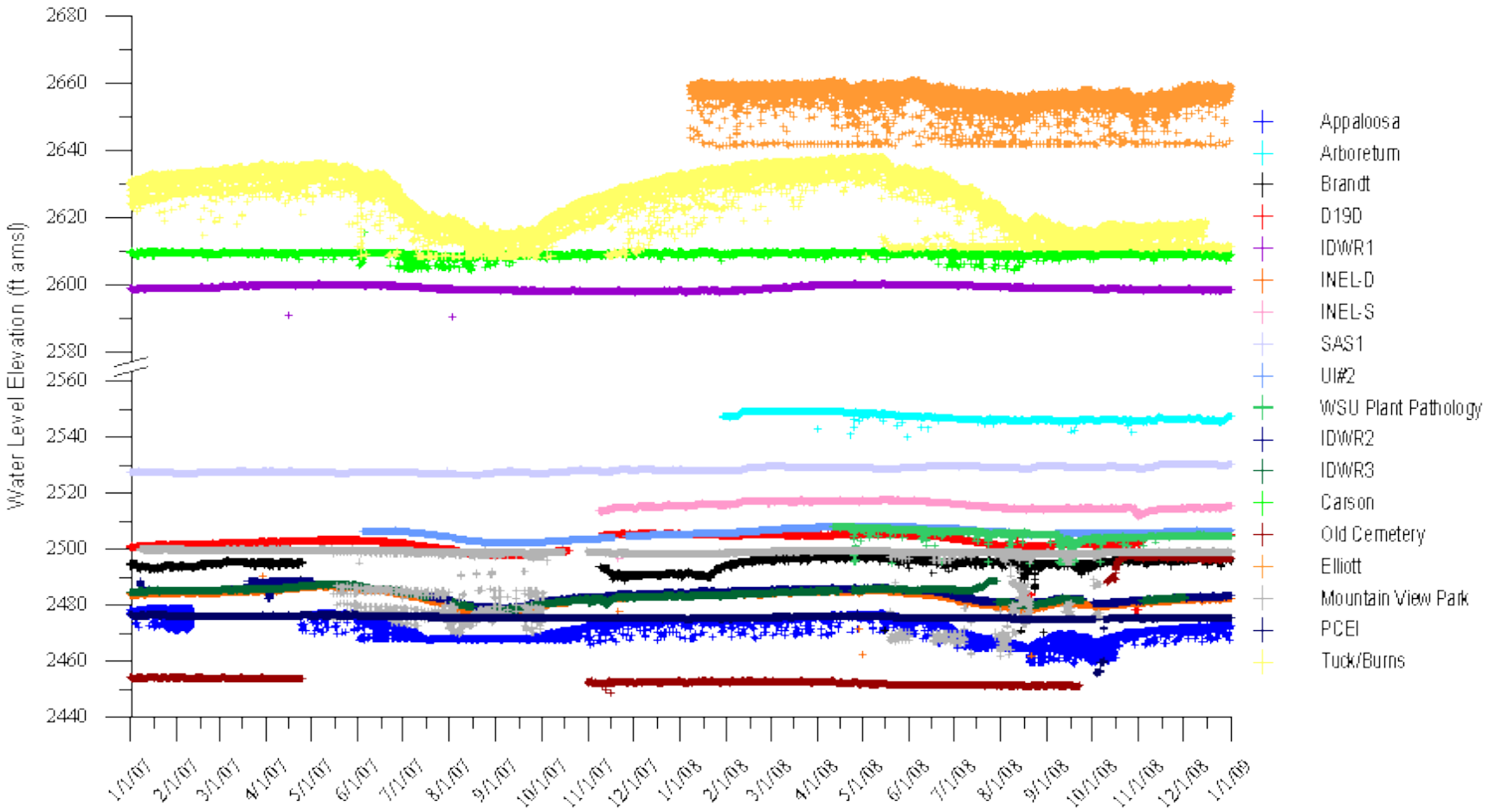

Figure 28. Water level hydrograph representing all wells monitored in the Wanapum aquifer system. There is a large range of hydraulic heads in the system. Water levels vary seasonally in most wells, but no alarming water level declines have occurred within the system. Note: the Carson well is a seasonal flowing artesian well. Therefore, water levels for that well are accurate only during July and August each year when the head falls below the casing collar.

Long-Term Water Level Hydrograph for Monitored Wanapum Aquifer System Wells
Showing Hydraulic Response to Moscow Municipal Pumping

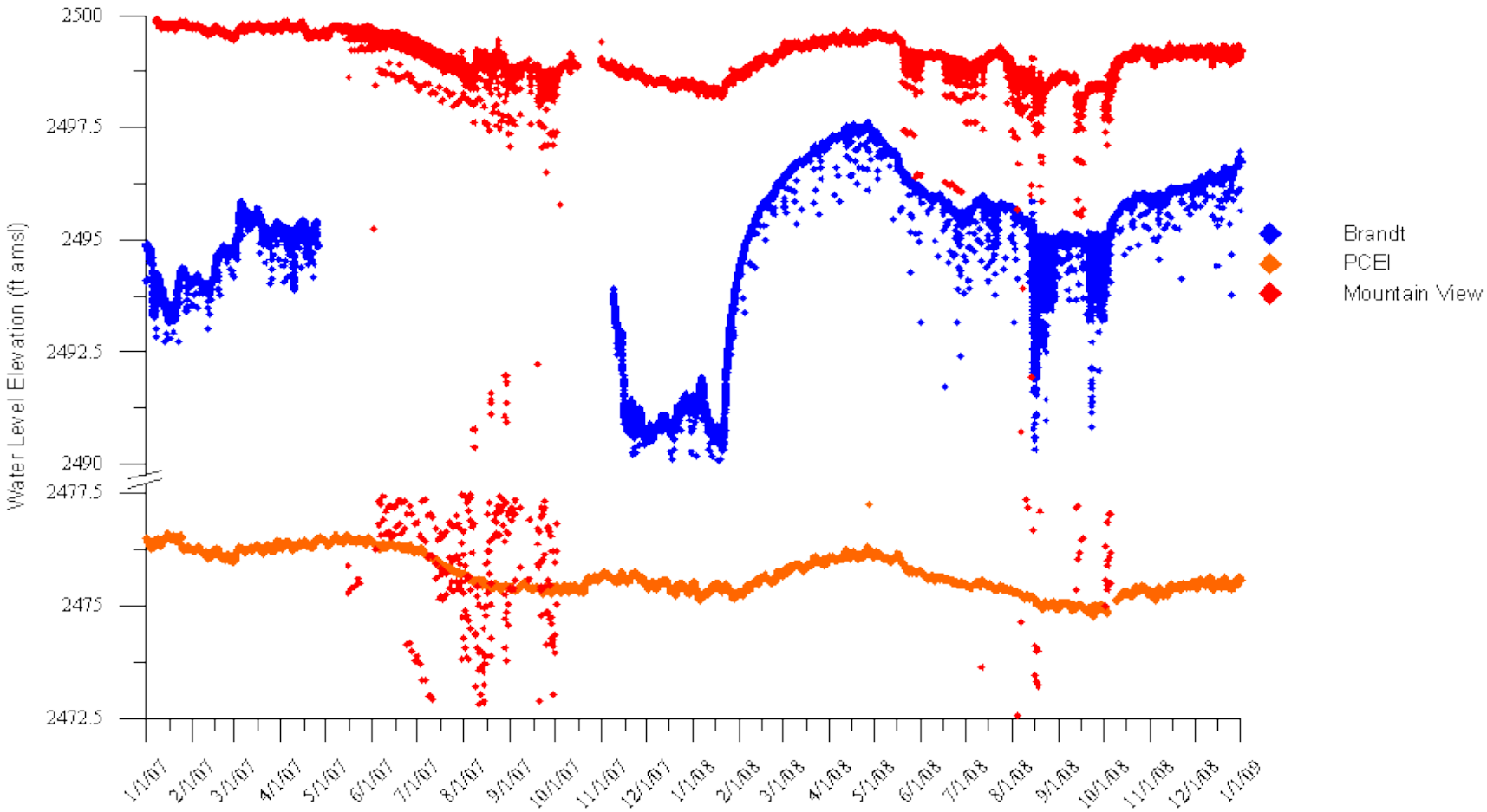

Figure 29. Water level hydrographs for Wanapum aquifer system observation wells which showed hydraulic responses to Moscow #2 and Moscow #3 pumping.

Water levels in wells on the University of Idaho campus (Figure 30), generally indicate a local downward gradient (i.e., decreasing head with depth of well). Seasonal trends were similar in the UIGFL wells (INEL-D, INEL-S, and D19D), and in well UI #2. However, the deepest well at the UIGFL (INEL-D), completed in the Vantage sediments, experienced a water level decline during 2008 while water levels in wells completed in the Wanapum basalt rose during 2008. Water levels in shallow wells on campus (SAS1 and Arboretum) appear to have risen slightly between 2007 and 2008 (Figure 30). Water level hydrographs for the Idaho Department of Water Resources monitoring wells (IDWR1, IDWR2, and IDWR3) located north of the University of Idaho (Figure 2) illustrate typical seasonal water level changes in the Wanapum aquifer system (Figure 31). IDWR 1 is completed above the Wanapum basalt in the sediments of Bovill; IDWR 2 and IDWR 3 are completed below the Wanapum basalt in the Vantage sediments. Although completed at different depths (282 ft and 355 ft, respectively) water levels in IDWR 2 and IDWR 3 are almost exactly the same, indicating no vertical gradient. However, when water levels were rising, they rose more rapidly in IDWR 2 than in IDWR 3, suggesting downward movement of water. Water levels in IDWR 2 and IDWR 3 during the summer 2007 were slightly lower than during the 2008 summer. This condition may reflect the decrease in total pumping from summer 2007 to summer 2008 (Figure 32). However, water levels in IDWR 2 and IDWR 3 were lower at the end of 2008 than they were at the end of 2007. Water levels in IDWR 1 were higher at the end of 2008 than in 2007. Water level fluctuations in IDWR 1 were smaller than the fluctuations in the deeper wells. The similarity of water level fluctuations in the IDWR wells compared to the UIGFL wells and the Appaloosa well (Figure 33), make it apparent that a hydrologic connection exists between these locations. Figure 34, illustrates the similarities between water levels in INEL-D, IDWR 2, and IDWR 3. Each of these wells is completed in the Vantage sediments, and water levels declined during 2008.

Only one well completed in the Vantage sediments has experienced rising water levels between 2007 and 2008 (Figure 35). Cleaning of UI #2 in 2006 ripped large holes in the inner steel casing, and allowed groundwater from the overlying units to enter into well and flow down the well bore (Opatz, 2007). Water level trends in UI #2 were similar to those of IDWR 2, IDWR 3, and INEL-D; however, water levels in UI #2 were

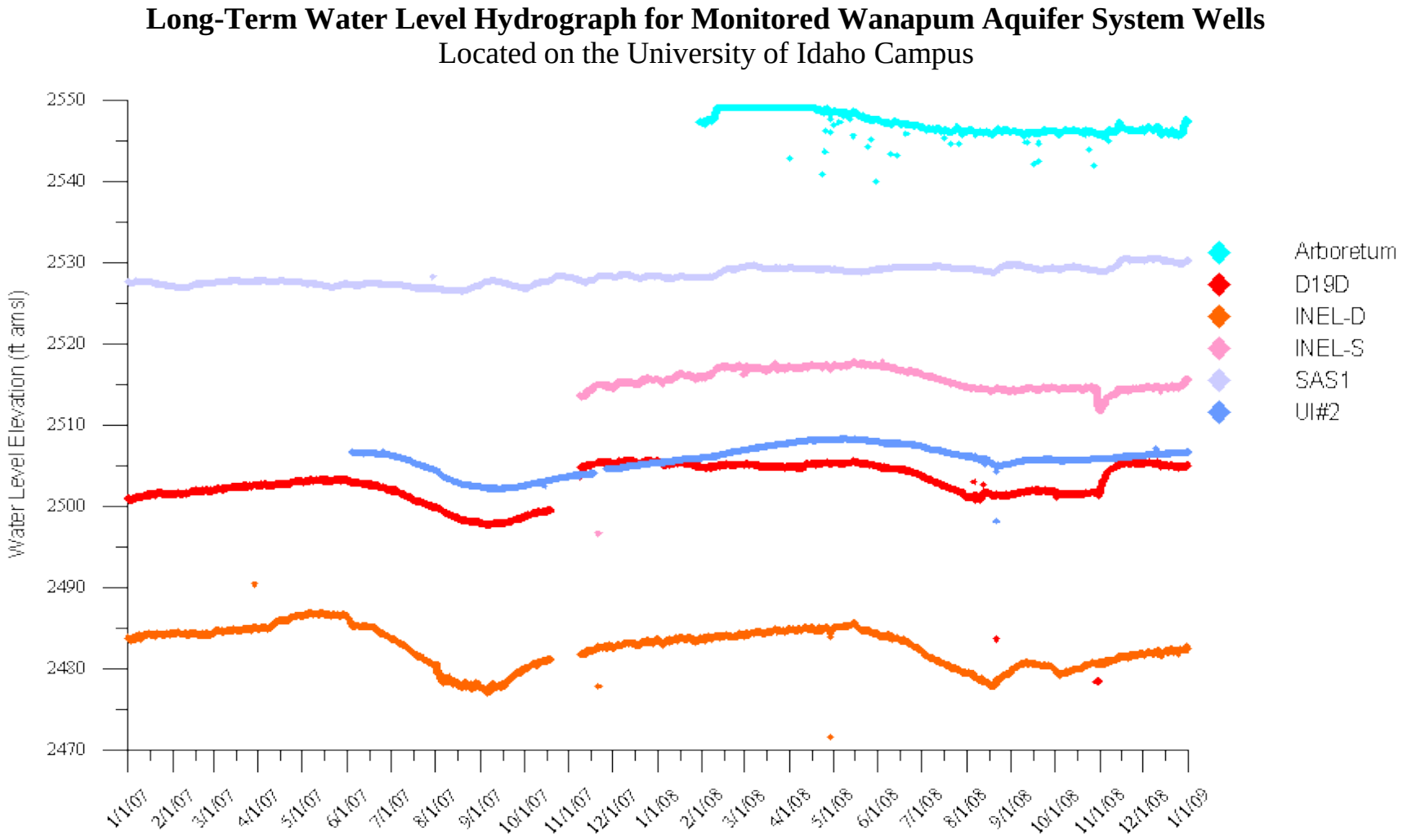

Figure 30. Water level hydrographs for Wanapum aquifer system observation wells on the University of Idaho campus. All wells exhibit similar seasonal water level responses. A downward gradient generally exists in the vicinity of the UIGFL wells

Long-Term Water Level Hydrograph for Monitored Wanapum Aquifer System Wells
at the Idaho Department of Water Resources Monitoring Nest

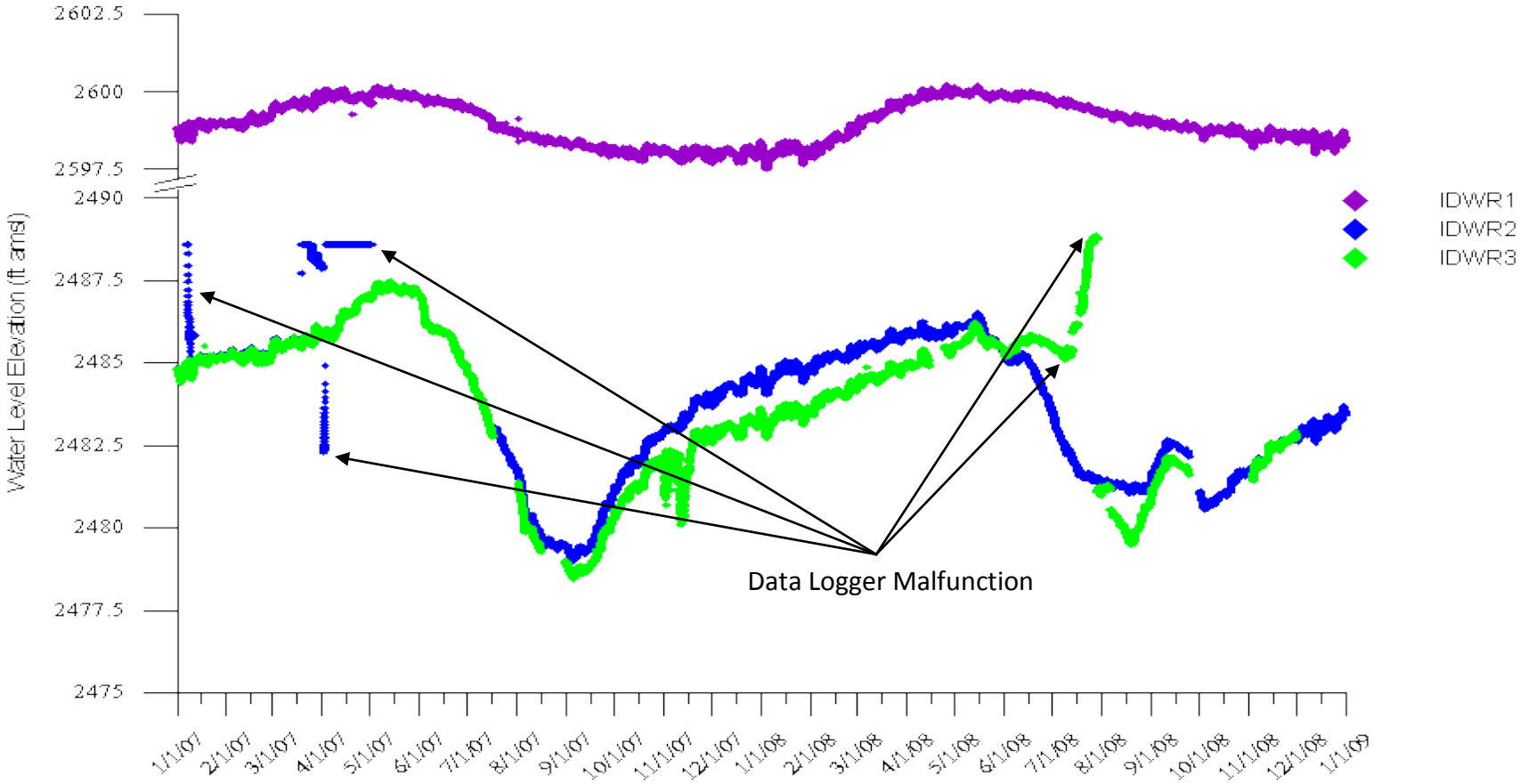

Figure 31. Water level hydrographs for Wanapum aquifer system observation wells at the Idaho Department of Water Resources (IDWR) monitoring nest. The Vantage wells (IDWR 2/3) exhibit similar seasonal water level responses. The sediment of Bovill well (IDWR 1) has a much higher hydraulic head, with smaller seasonal water level fluctuations.

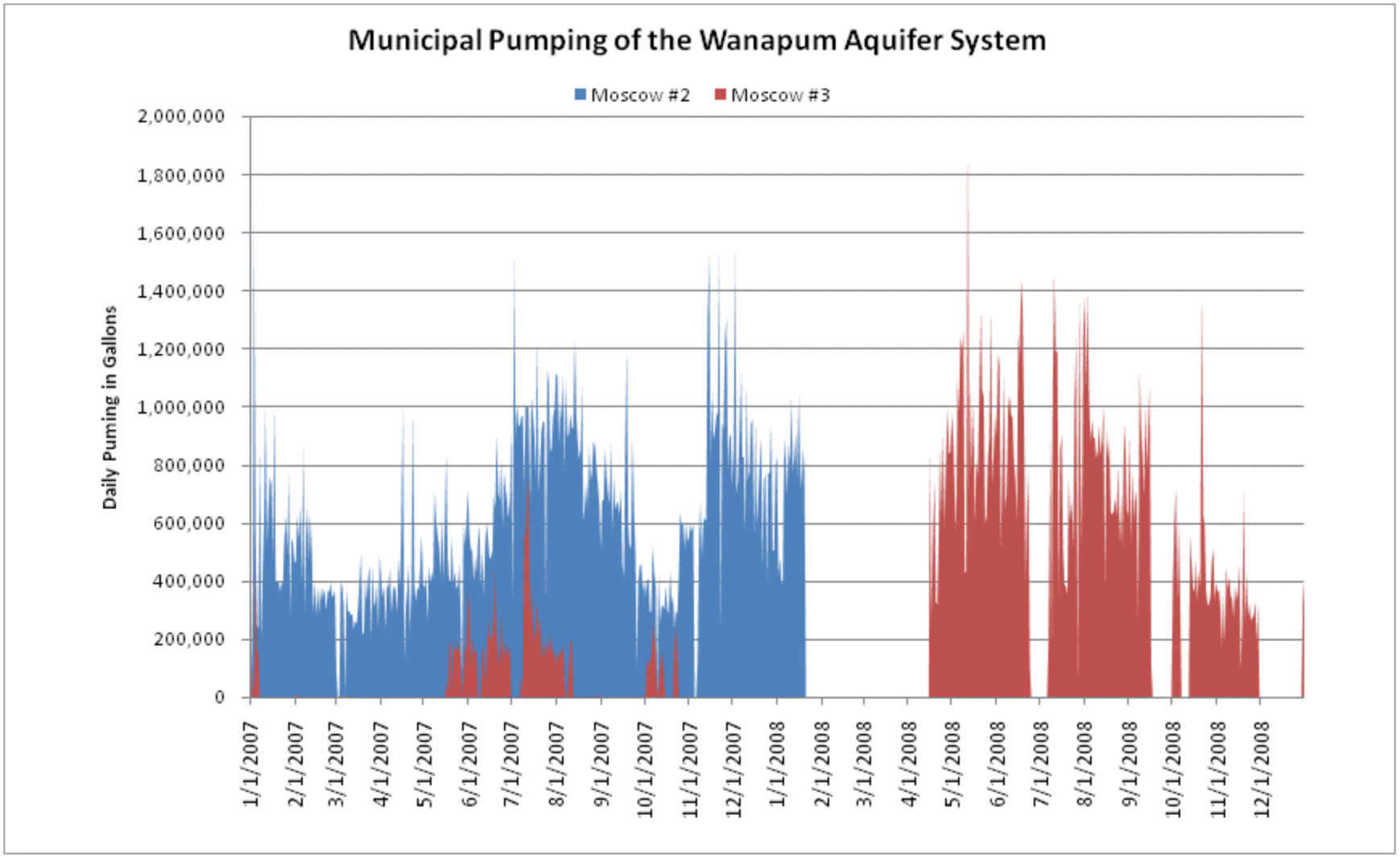

Figure 32. Daily volumes of water pumped from the Wanapum aquifer system by the city of Moscow municipal pumping wells (Moscow #2 and #3) for 2007 and 2008. The major shift in pumping from Moscow #2 to Moscow #3 is due to mechanical failure of the pump in Moscow #2.

Long-Term Water Level Hydrograph for Monitored Wanapum Aquifer System Wells
Comparison of the IDWR Monitoring Nest Wells, UIGFL Wells, and the Appaloosa Wells

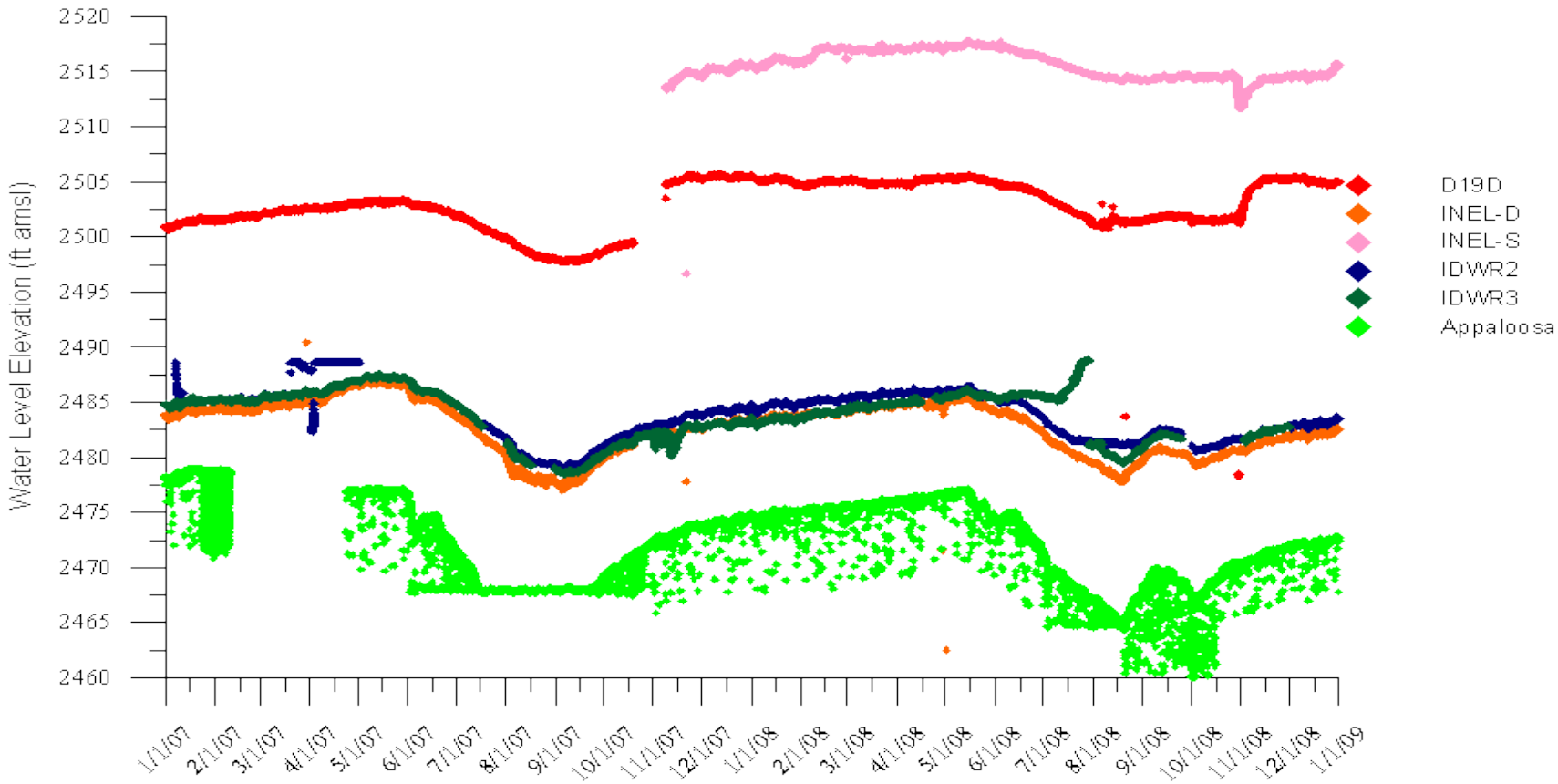

Figure 33. Water level hydrographs for Wanapum aquifer system observation wells completed in the Wanapum basalt or Vantage sediments at the Idaho Department of Water Resources (IDWR) monitoring nest, the University of Idaho Groundwater Field Lab (UIGFL) , and in the Appaloosa well. The deepest wells (IDWR 2, IDWR 3, INEL-D, and Appaloosa) exhibit nearly identical seasonal water level responses. Appaloosa is the only pumping well of those wells plotted.

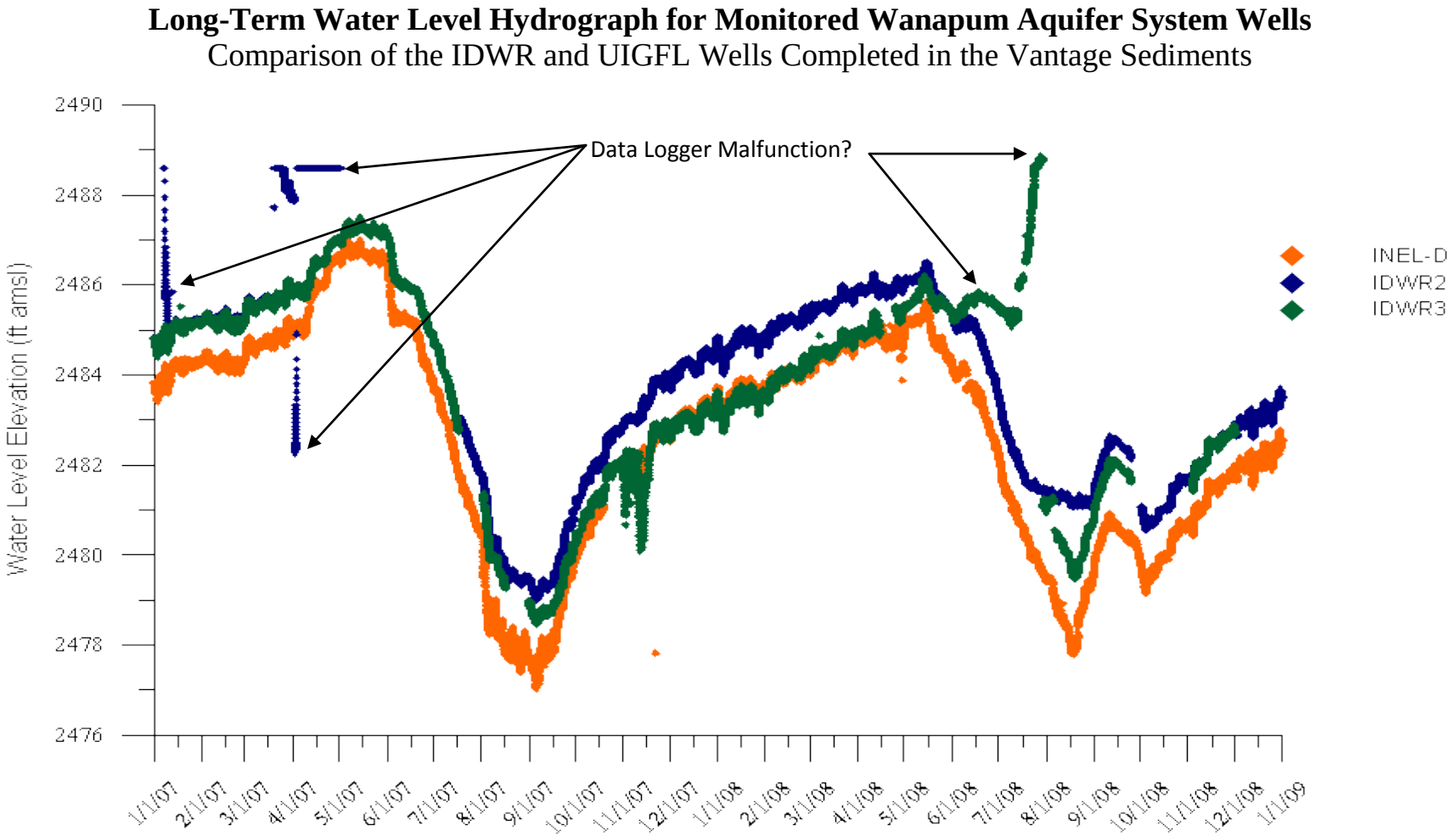

Figure 34. Water level hydrographs for Wanapum aquifer system observation wells completed in the Vantage sediments at the Idaho Department of Water Resources (IDWR) monitoring nest and at the University of Idaho Groundwater Field Lab (UIGFL). IDWR 2, IDWR 3, and INEL-D exhibit nearly identical seasonal water level responses.

Long-Term Water Level Hydrograph for Monitored Wanapum Aquifer System Wells
Comparison of the IDWR and UIGFL Wells Completed in the Vantage Sediments

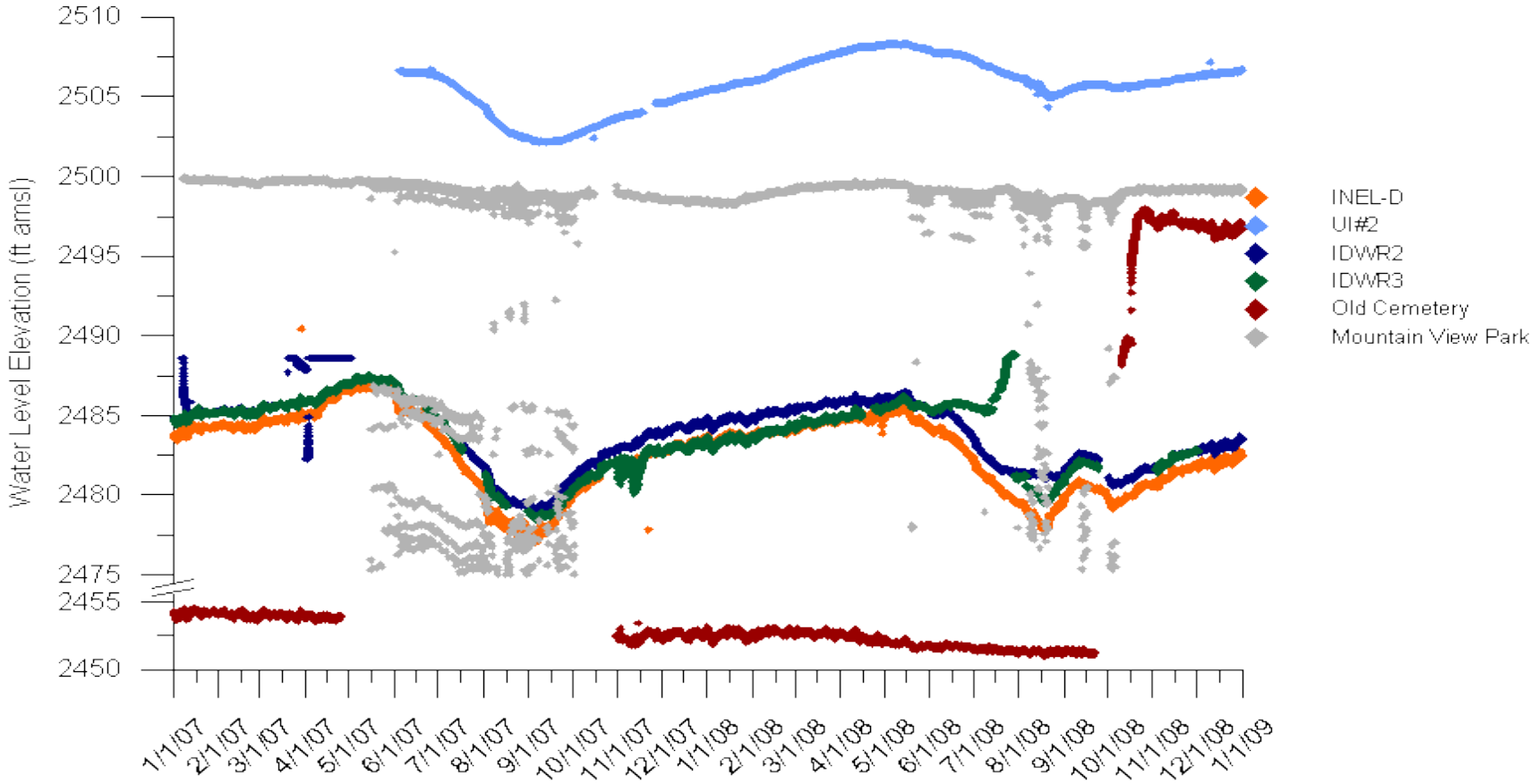

Figure 35. Water level hydrographs for Wanapum aquifer system observation wells completed in the Vantage sediments. UI #2 may be receiving some of its head from the sediments of Bovill or the Wanapum basalt. The Old Cemetery well had experienced a jump in water level after water was added to the well in September of 2008 as part of the well cleaning process (of a nearby well) contracted by the city of Moscow.

approximately 20 feet higher in elevation. The higher water level elevations in UI #2 are believed to be due to groundwater leakage through the corroded and damaged well casing from the sediments of Bovill and the Wanapum basalt. Water level elevations in the Old Cemetery well were the lowest of all Vantage wells. Water added to the well from the surface, to help identify the migration of sand in the area, caused the static water level to rise approximately 45 feet in September 2008 (Bailey and Allen, 2008). Since then, water levels have stabilized at the post investigation water level. The Mountain View Park well experienced smaller water level fluctuations, but had the highest water level elevation of all monitoring wells completed in the Vantage sediments. This well is closest to the eastern boundary of the Moscow sub-basin.

Overview of Hydrographs

Water level elevations and the magnitudes of seasonal fluctuations vary spatially from well to well in the Wanapum aquifer system. The UIGFL wells and the IDWR monitoring wells appear to be in hydraulic connection based on similarities between seasonal water level trends. Those observation wells that responded during aquifer tests exhibit similar water level fluctuations; however, they do not show any apparent connections to other wells in the Moscow sub-basin. Other anomalies exist within the basin. For example, the Carson well located approximately one mile northwest of the Brandt well (Figure 2) flows at the land surface seasonally even though the casing elevation is 2609.4 feet amsl. The water level in the Carson well is more than 100 feet higher than the water level in the Brandt well. The PCEI well had a lower static water level elevation than the deeper Brandt well; it is the only well completed in the Wanapum basalt to experience water level declines between 2007 and 2008. The Cemetery well, experienced a water level rise in September 2008 due to water being added, as part of an investigation of sand migration in the vicinity of the well. Since then, the water levels appear to have stabilized near that post-rehabilitation level. Apparent anomalies, and the lack of hydraulic connections between wells during aquifer tests (despite wells being completed in similar geology), suggest that aquifer compartmentalization is likely due to aquifer system heterogeneity.

Despite the apparent aquifer system compartmentalization, most water level hydrographs exhibit similar seasonal trends regardless of spatial well location or well completion interval. Water levels typically fall during long, dry summers and rise throughout the fall and into the spring months. Wanapum aquifer system pumping typically increases during the summer to help supply water for landscape irrigation. In general, the entire Wanapum aquifer system within the Moscow sub-basin appears to respond to pumping stresses on an annual time frame regardless of compartmentalization that may exist over a relatively short time frame.

In 2008, the Wanapum aquifer system was pumped at only 65% of the 2007 amount. Monitoring wells completed in the sediments of Bovill and the Wanapum basalt experienced a water level rise during 2008. Due to mechanical pump failure in Moscow #2, most of the groundwater withdrawn from the Wanapum aquifer system in 2008 was pumped from Moscow #3. Wells completed in the Vantage interbed experienced water level declines during 2008. Water level declines in the Vantage sediments were typically less than one foot. Moscow #2 is completed through the entire thickness of the Wanapum basalt and penetrates about ten feet of the Vantage sediments. The total volume of groundwater pumped from Moscow #2 in 2008 was only 8% of the volume pumped in 2007. Moscow #2 appears to withdraw only a small portion of its total discharge from the Wanapum basalt with the rest from the top of the Vantage sediments (Bailey and Allen, 2008). Moscow #3, however, is open to the Vantage sediments and appears to withdraw its water from the middle to lower portions of the unit. The increased pumping of Moscow #3 in 2008, (almost ten times the 2007 volume), is potentially responsible for the declining water levels measured in 2008 in wells completed in the Vantage sediments.

Chapter 6 – Potential for Induced Groundwater Recharge

Introduction

Prior to development of the groundwater resource systems in the Moscow sub-basin, streams and shallow aquifers in the sediments of Bovill and in the Palouse Formation loess were likely in a state of dynamic equilibrium with the deeper aquifers. Dynamic equilibrium occurs naturally when recharge at the water table is equaled by groundwater discharge. When equilibrium is established, inflow equals outflow and no change in storage occurs. Development of groundwater resources causes disequilibrium in the system by removing water from storage. When a well is installed and pumped at a certain rate, over time a new equilibrium may be established between recharge and discharge. This equilibrium will continue until further development of the aquifer system causes the balance to change again. Over time, variations in groundwater development can change the natural dynamics of the exchange between groundwater and surface water bodies. When pumping is greater than natural recharge, the cone of depression will grow until natural discharge from the aquifer system is captured and/or recharge is increased to form a new equilibrium. Induced groundwater recharge is the entry of surface water, in hydraulic connection with a water table, into the aquifer system as a system response to achieve balance between inflow and outflow.

Factors That Control Induced Groundwater Recharge

Induced groundwater recharge occurs in areas where streams are hydraulically connected to the groundwater system. The amount of water induced to recharge shallow aquifer systems depends on several factors, including surface water availability, area available for surface water/groundwater interactions, and hydraulic properties and gradients. Potential for induced groundwater recharge is greatest when surface water is readily available over large areas. Hydraulic conductivity and thickness of the streambed sediments are major controls on the amount of water flow between the streambed and aquifer (Winters, 1998). Of the factors that influence the amount of induced groundwater recharge to a shallow aquifer, only the hydraulic gradient can be influenced by groundwater pumping. If pumping creates a cone of depression that contacts a surface

water body while surface water levels are high, the hydraulic gradient between the aquifer and stream will be maximized spatially as a function of the drawdown.

During dry periods when surface water levels are lowest, there is less potential for induced groundwater recharge. Excessive pumping of shallow aquifers can cause water levels to fall, and streams to become hydraulically disconnected from the water table (Figure 6). In aquifers where the hydraulic connections to surface water bodies are in delicate balance, pumping during periods of low surface water flow increases the chances of hydraulic disconnection. Streams not hydraulically connected to groundwater systems will not be affected by groundwater pumping. Pumping cannot steepen the gradient between the water table and disconnected surface water bodies. Groundwater recharge cannot be induced from hydraulically disconnected streams; in these cases, the amount of water lost to the aquifer system is independent of pumping drawdown in the aquifer.

Conceptual Model for Induced Groundwater Recharge

Previous studies (Li, 1991; Pardo, 1999; Wright, 1996) have suggested that a recharge/discharge relationship exists between Paradise Creek and the sediments of Bovill. Hernandez (2007) reported that pumping from producing zones in the Wanapam basalt caused drawdown in the sediments of Bovill. She also observed temperature changes indicative of water movement from Paradise Creek into the sediments of Bovill and the Wanapum basalt at the UIGFL when basalt wells were pumped. This type of connection is assumed at other locations in the Moscow sub-basin as described in Chapter 3. Groundwater/surface water interactions play an important role in groundwater recharge to the Wanapum aquifer system.

In the months between November and May, the occurrence of surface water in the Moscow sub-basin is greatest (Figure 36). Major streams are at much higher stages than during summer months, and unnamed tributaries typically are also filled with water. The total head in the streams is greater than in the surrounding sediments during this period. Water moves into the uppermost portions of the aquifer system, spreading throughout the sediments as it moves away from the surface water bodies (Figure 7). Locally, shallow groundwater levels begin to rise when stream stages jump and remain elevated until stream stage begins to recede (Figure 36). SAS1, a shallow well, completed

approximately 40 feet bgs, mimics many of the stream stage fluctuations observed at Paradise Creek. IDWR 1 is further from local surface water bodies (Figure 2) and the observed water level fluctuates much less than in SAS1; however, a major rise in stream stage (around February 9th) appears to cause the significant increase in these water levels. These shallow groundwater levels are believed to represent the aquitard which overlies the producing zones of the Wanapum aquifer system. A relatively large number of streams and their associated alluvial floodplain deposits exist in the Moscow area. This condition, allows significant volumes of water to percolate into the underlying sediments of Bovill seasonally, increasing the amount of water stored in the sediments and increasing the head differential between the sediments and the underlying aquifers. During this time period, the greatest opportunity exists to control induced recharge to the Wanapum aquifer system.

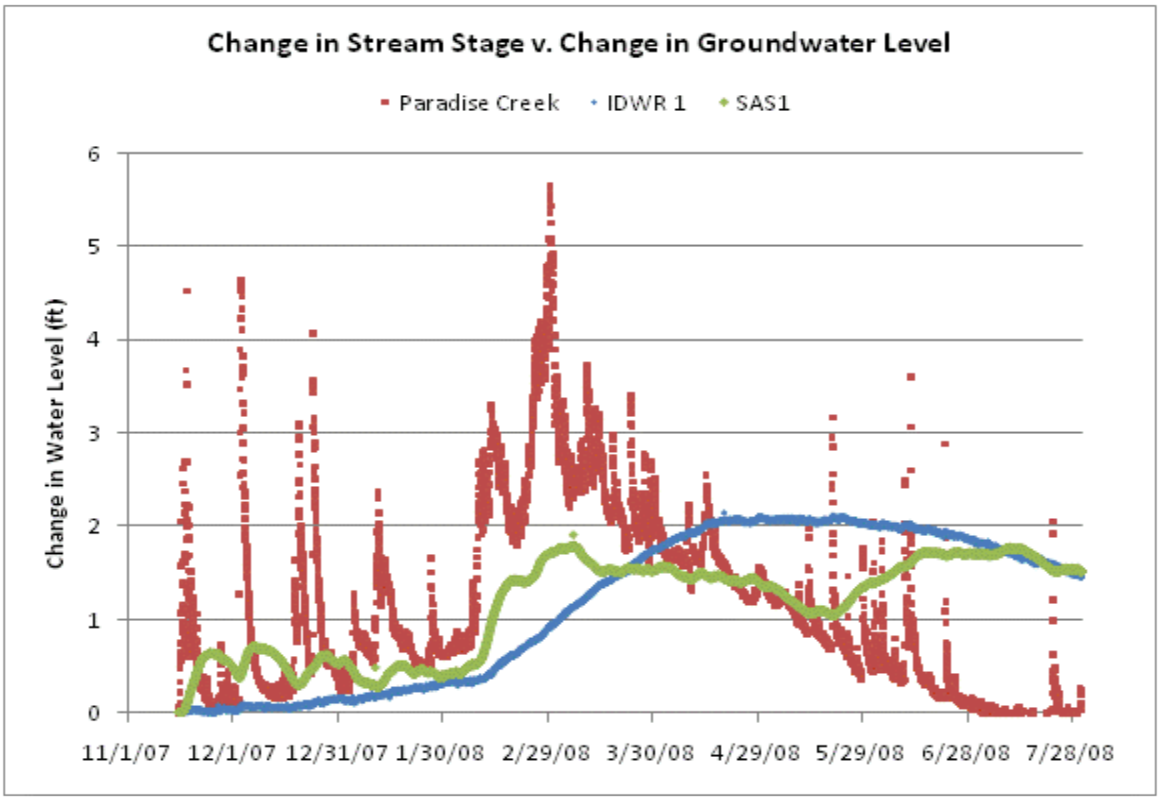

Figure 36. Comparison of changes in the Paradise Creek stream stage and water level changes in the shallow groundwater system. Water level changes in SAS1 and IDWR1 are thought to represent water level changes in the aquitard which overlays the producing zones of the Wanapum aquifer system.

The hydraulic heads everywhere in the sediments of Bovill are greater than the hydraulic heads in the underlying Wanapum basalt; therefore, water percolates from the sediments into the basalt wherever saturated hydraulic pathways exist. In order to maximize induced recharge, the hydraulic gradients between the sediments and producing zones must be maximized. Pumping of the Wanapum aquifer system will create a cone of depression maximizing the gradient between the sediments and basalt. Pumping induced gradients will cause water in the sediments of Bovill to leak into the pumped aquifers. This condition will maximize the hydraulic gradients between the sediments and the streams, allowing more water to percolate into the sediments. During the wet season, water that leaks from the sediments of Bovill to the Wanapum basalt can be replenished by water from Paradise Creek, the South Fork of the Palouse River, Missouri Flat Creek, and all of their tributaries. If pumping ceases with water still available in the streams, water levels should be able to recover. However, if pumping continues into the summer, there may not be enough water available to replenish the Wanapum aquifer system and water levels may not fully recover.

Chapter 7 – Conclusions and Recommendations

Conclusions

The complex nature of the geology in the Moscow sub-basin is a major factor in groundwater flow and recharge in the Moscow area. Hydrogeologic boundaries and heterogeneities within the Wanapum aquifer system make hydrogeologic characterization of the system difficult. The following conclusions are reached based upon data collected during the investigation:

Conclusions Based on Aquifer Test Data

1. Hydraulic connections exist between the Moscow #2, Moscow #3, Brandt, Mountain View Park, and PCEI wells during aquifer tests.
2. Hydraulic responses occur between wells completed in the Wanapum basalt and those completed in the Vantage sediments.
3. The Wanapum aquifer system is composed of multiple hydraulically connected (at least 2) aquifers separated by an aquitard(s).
4. Moscow #3 produces water from an aquifer (producing zone) below the producing zone for Moscow #2, there is a hydraulic connection between them.
5. Boundary effects in the Wanapum aquifer system caused by basin perimeter granites and metasediments are masked by leakage from a water table aquitard (sediments of Bovill) that overlies the Wanapum basalt.
6. Apparent aquifer compartmentalization may be influenced by spatially variable leakage rates within the Moscow sub-basin.
7. In order for the rapid recovery observed in the Brandt, Mountain View Park, and PCEI wells to occur, the saturated thickness of the sediments of Bovill must be maintained.
8. Recharge to the sediments of Bovill from streams influences the heads in the Wanapum aquifer system seasonally.
9. It is feasible to control seasonal groundwater/surface water interaction, to some degree, by controlling pumping strategically in time and space.
10. Maximizing the hydraulic stress in the Wanapum aquifer system during wet periods and periods of high stream flow will induce groundwater in the

sediments of Bovill to drain into open fractures in the top of the Wanapum basalt.

Conclusions Based on Water Level Data

1. Long-term water level records for 2007 and 2008 suggest Wanapum aquifer system wells at the UIGFL, the IDWR monitoring well nest, and the Appaloosa Horse Club are in direct hydraulic connection.
2. Wells completed at the same spatial location, but at different depths within the Vantage sediments such as IDWR 2, IDWR 3, Moscow #2, and Moscow #3, exhibit very similar water levels, indicating that little downward movement of water occurs in the Vantage. However, when water levels are rising, water levels in the deeper wells are slightly lower than those in the shallower wells, indicating that vertical gradients change seasonally.

Recommendations

Results from the Moscow #2 Aquifer Test suggest additional water may be induced to recharge the Wanapum aquifer system, if pumping occurs when water is available to recharge the sediments of Bovill. The following recommendations are offered to improve our understanding of groundwater flow and groundwater/surface water interactions in the Wanapum aquifer system, as well as to sustain the groundwater resources of the Wanapum aquifer system.

1. Instead of pumping the Wanapum aquifer system to mitigate the stresses placed on the Grande Ronde aquifer system during the summer irrigation season, pump from the Wanapum aquifer system during the wettest months of the year (November-May) when water is available to replenish water lost from the sediments of Bovill.
2. Find/drill a well to replace the previously monitored Bond well. Ideally, the non-pumping monitoring well would be completed to the bottom portion of the Wanapum basalt, in the proximity of Sweet Avenue.
3. Establish additional monitoring wells completed in the sediments of Bovill. Currently all sediment of Bovill wells are located at the groundwater field lab,

or the IDWR monitoring nest site. It would be beneficial to have sediment of Bovill wells located between the Brandt well and Moscow #2; as well as between Moscow #2 and Paradise Creek. Preferred sediment of Bovill well locations would be near to surface water bodies, and wells that respond to Moscow pumping (e.g., Mountain View Park, Sweet Avenue).

4. Aquifer tests conducted using either Appaloosa, the UI Aquaculture research wells, or IDWR wells, would help confirm a hydraulic connection between Appaloosa, the UIGFL, and the IDWR wells.
5. Establish additional Wanapum aquifer system monitoring locations approximately ½ a mile to the west and east of Moscow #2 and Moscow #3. Data for these wells would help to delimit the extent of the compartmentalization in the aquifer system. To date, no drawdown due to municipal pumping of the Wanapum aquifer system has been observed west of wells Moscow #2 and #3.
6. Install motor on/off data loggers to more accurately measure on/off times of municipal wells. These would provide for greater accuracy in pumping test analyses, and thus, more accurate estimations of aquifer characteristics.
7. If the Wanapum aquifer system proves to be a sustainable resource, additional city or university wells should be drilled/rehabilitated in areas that do not appear to be in hydraulic connection to the Moscow #2 and #3 "compartment". Ideal locations would be near Sunset Memorial Cemetery to the east, and between the UIGFL and the IDWR monitoring wells to the west. These locations do not appear to be in the same compartment as Moscow #2 and #3, but should be proximal to potential sources of recharge.

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Appendix A

Wanapum Aquifer System Groundwater Monitoring Database

Water level and temperature data collected as part of the Wanapum aquifer system monitoring project can be found in the DVD attached to the inside back cover of this thesis.

Appendix B

Water Level Records for 2007-2008

Long-Term Water Level Records

The PBAC Wanapum aquifer system monitoring network allows PBAC to monitor water level trends in the Moscow-Pullman area. Appendix B contains data collected from the monitoring network, displayed in arithmetic plots of water level elevation versus time. Plots for all wells monitored during this thesis project were created for 2007 and 2008. These plots were created from the original Solinst™ Levelogger (.lev) files which were downloaded from the data loggers. The pressure data were manipulated in order to present the data as water level elevations. Figures B1and B2 illustrate how the data logger, water pressure data were converted to water level elevations. First, the pressure of the water column above the data logger was plotted (Figure B1). Next, the dtw (depth to water) measurements that are collected before and after every download were subtracted from the elevation of the wellhead in order to determine the water level elevation. The dtw measurements were then used to "lock in" the elevation of the potentiometric surface by converting the water pressure measured by the data logger to the water level elevation taken at the time of download. From that point forward the changes in water pressure were equal to the changes in the water level. Occasionally, dtw measurements taken between download periods did not correspond to the water levels recorded by the data logger. These discrepancies most likely were due to changes in barometric pressure between download periods. In this appendix, any sudden jumps in water level or pressure (that are not believed to be real aquifer responses) (Figure B1) were adjusted upward or downward as needed so that the water levels before and after a measurement line up (Figure B2). The dtw measurements were honored as closely as possible without causing unrealistic jumps in the data.

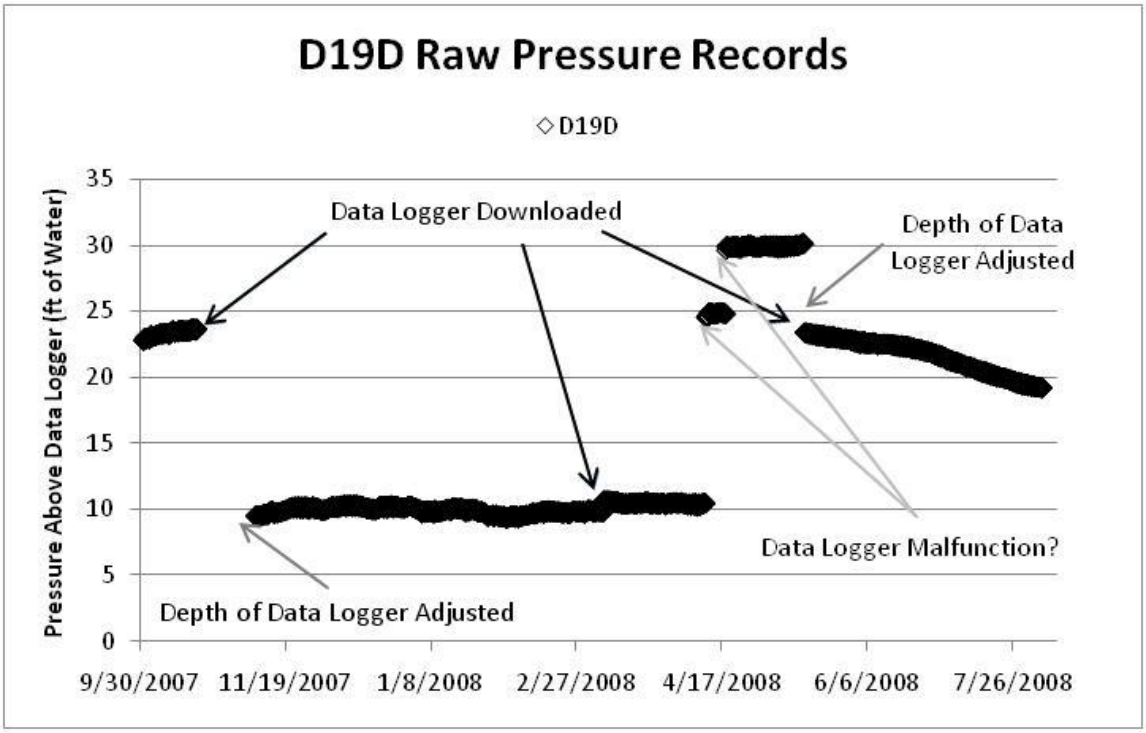


Figure B1. Example of raw water pressure (as feet of water) v. time as measured in a monitoring well.

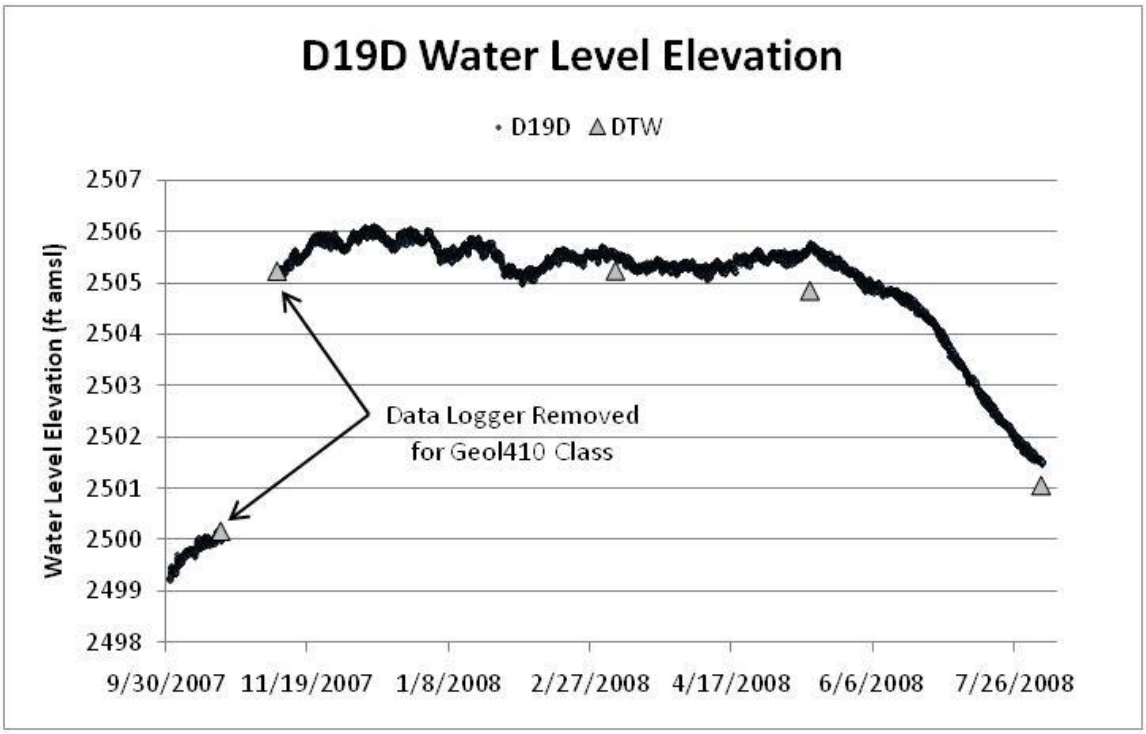


Figure B2. Raw data logger data converted to water level elevation (ft amsl) v. time. Dtw measurements and top of casing elevations were used to determine the water level elevations. Unreasonable sudden jumps in the data (data logger malfunction) have been removed from the data as they are not believed to be real. Note the scale in Figure B1 is different from Figure B2.

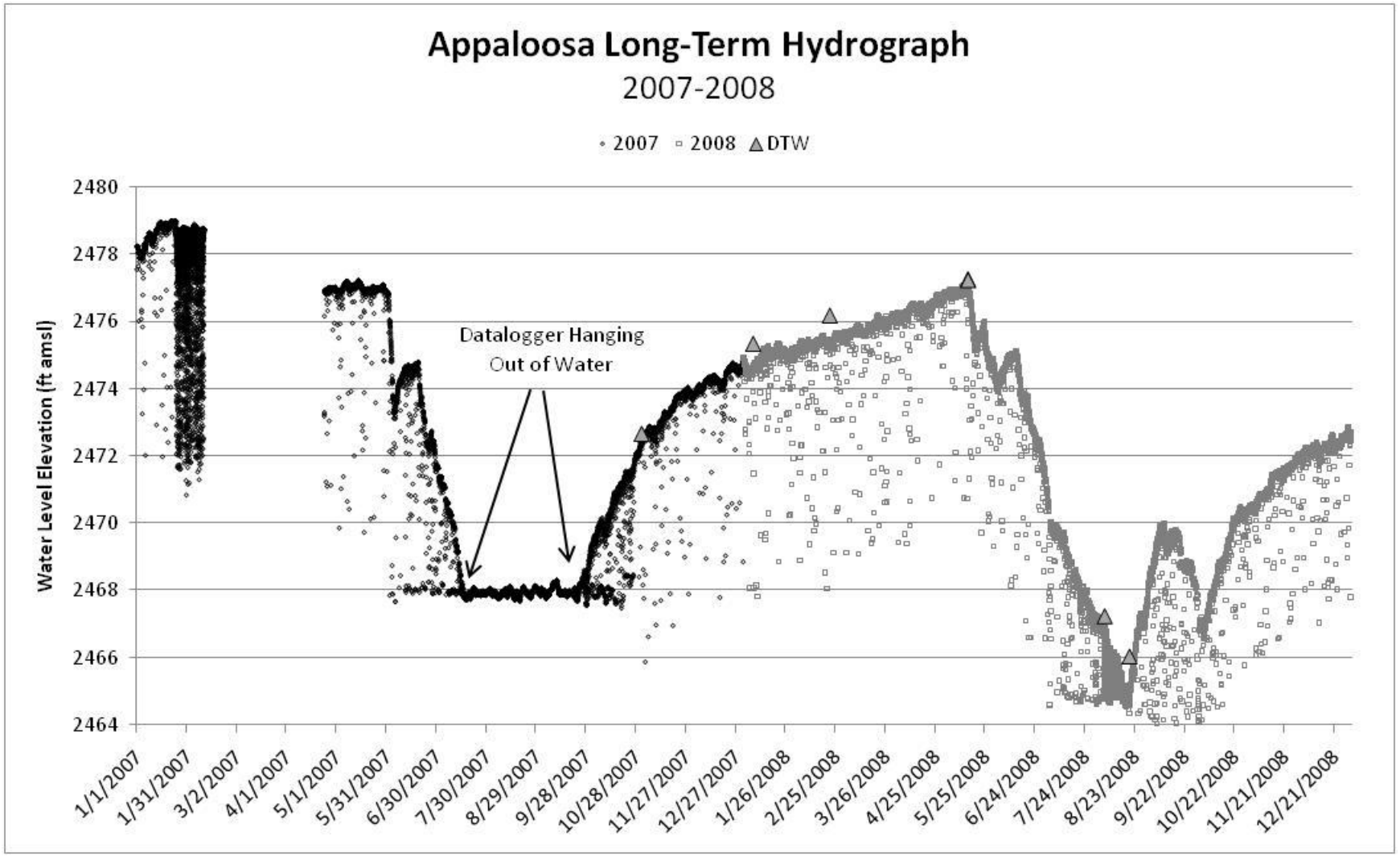


Figure B3. Long-term water level hydrograph for the Appaloosa well.

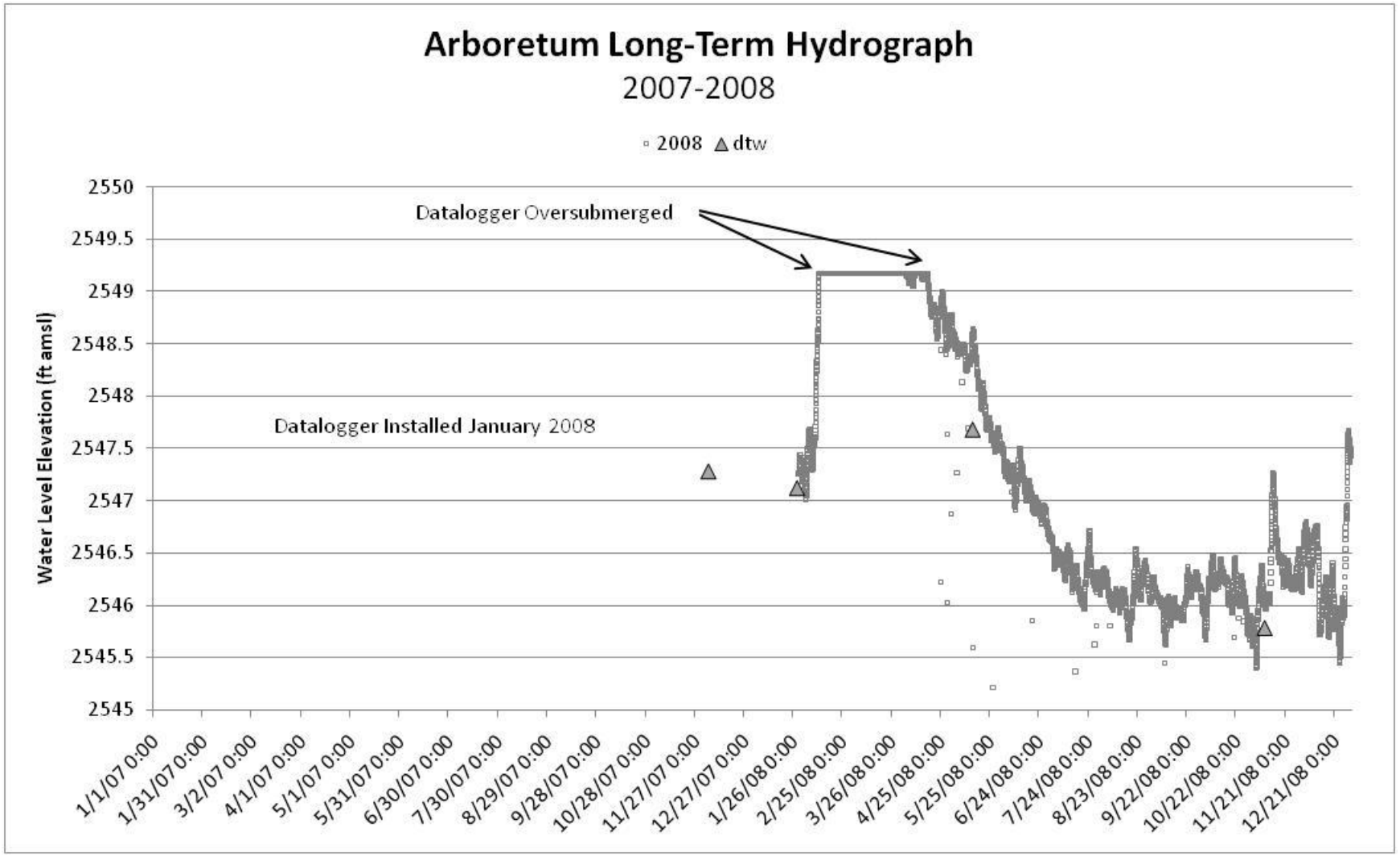


Figure B4. Long-term water level hydrograph for the Arboretum well.

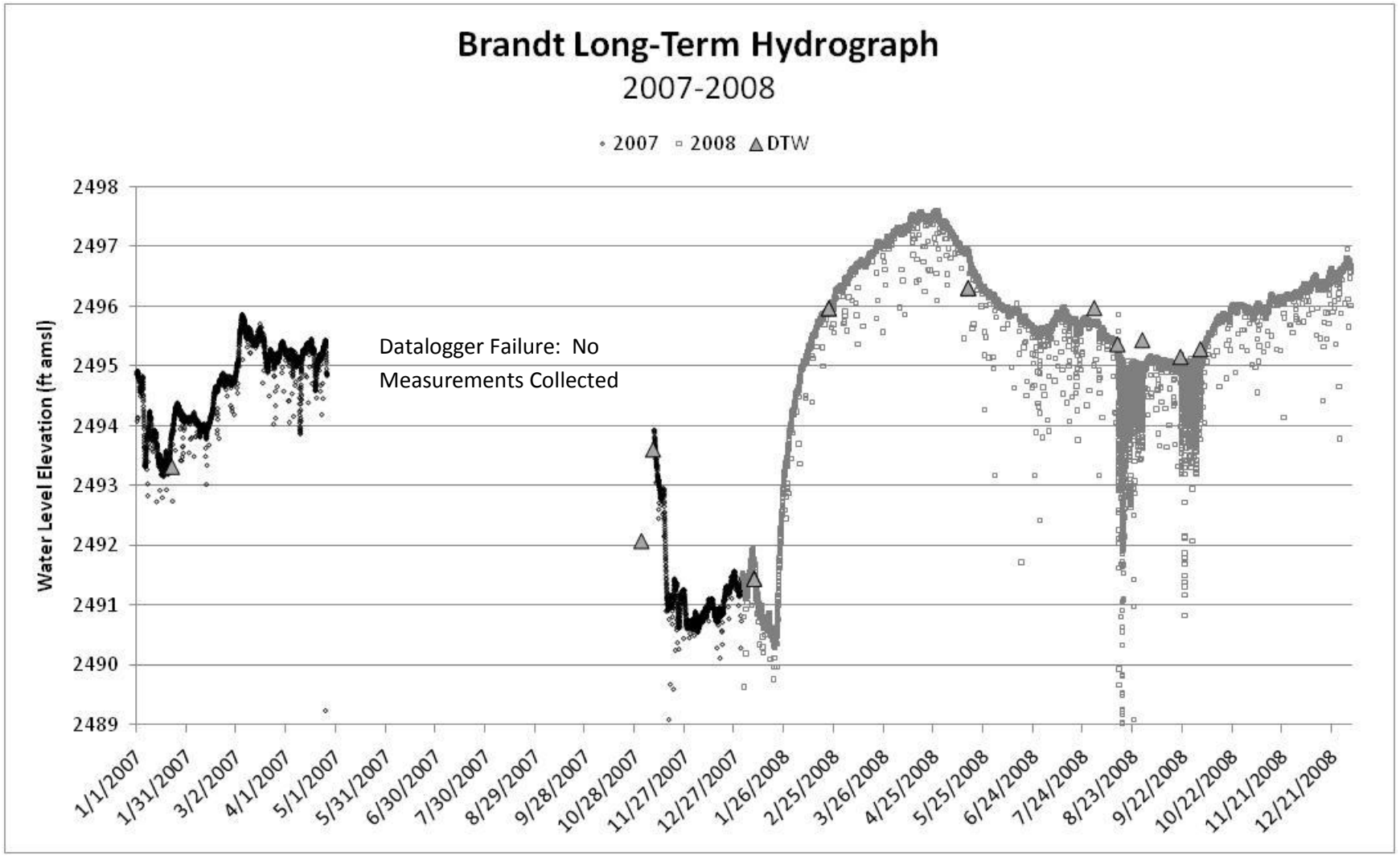


Figure B5. Long-term water level hydrograph for the Brandt well.

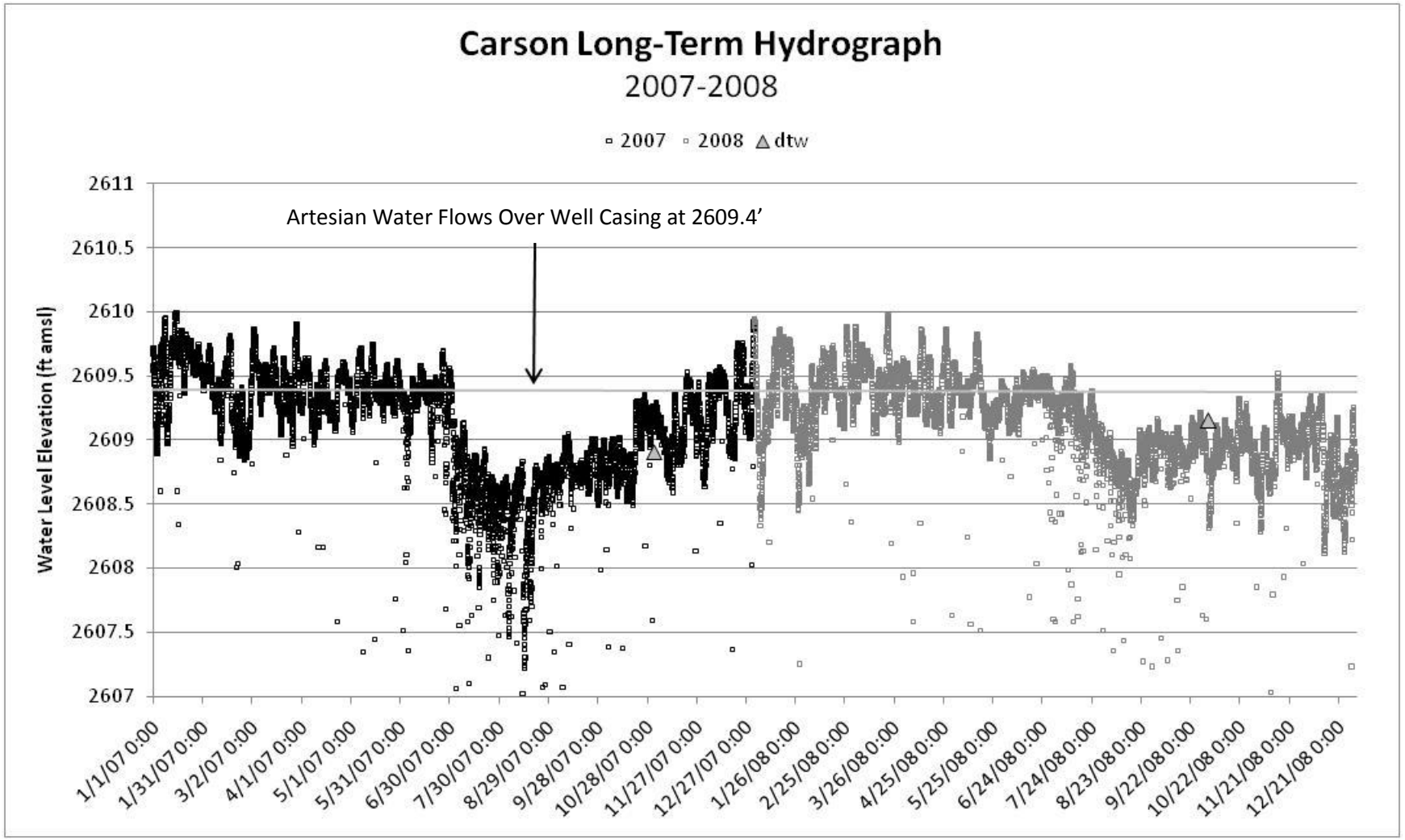


Figure B6. Long-term water level hydrograph for the Carson well. Water levels greater than 2609.4 represent changes in barometric pressure only, as water is flowing over the well at this elevation.

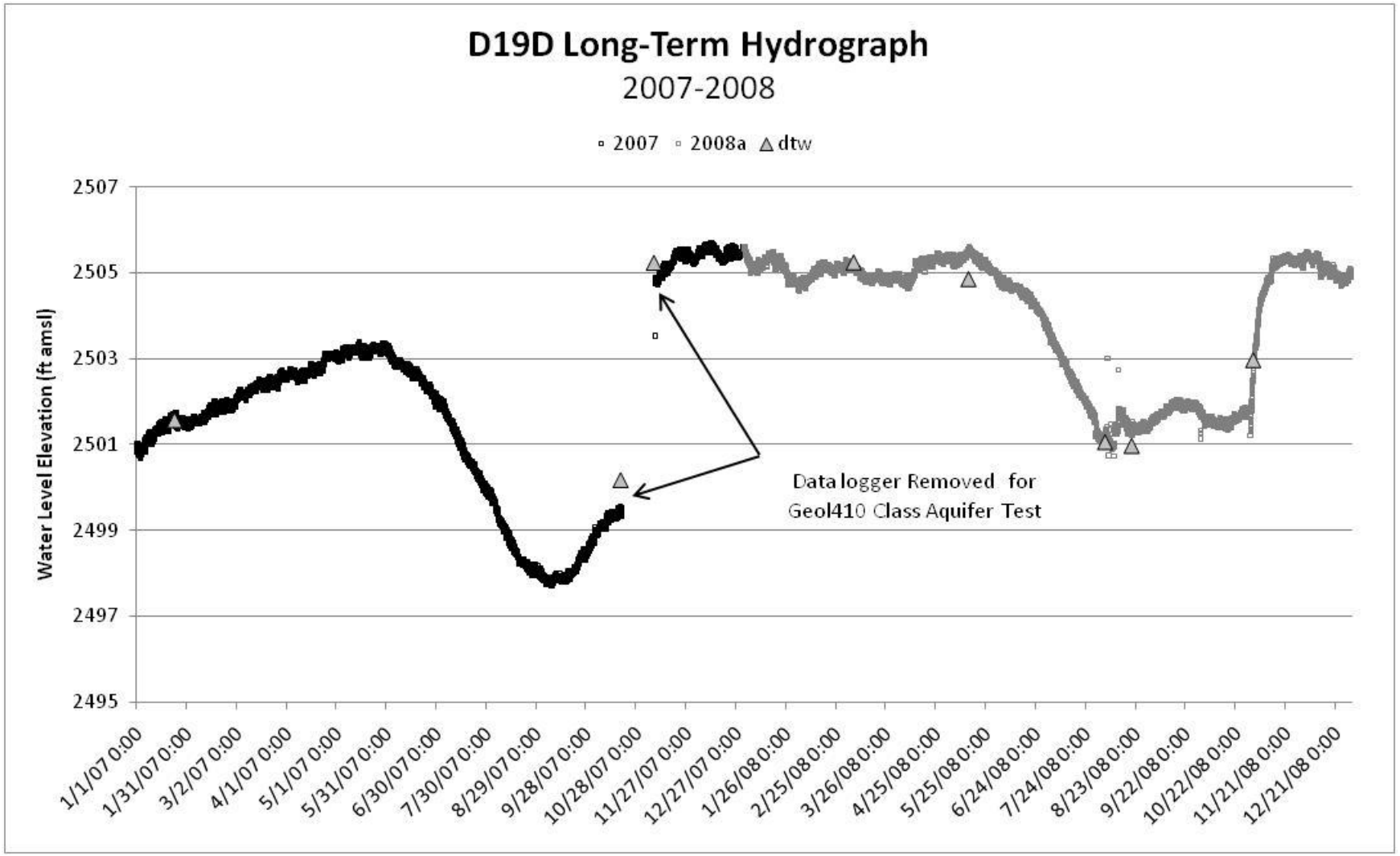


Figure B7. Long-term water level hydrograph for the D19D well.

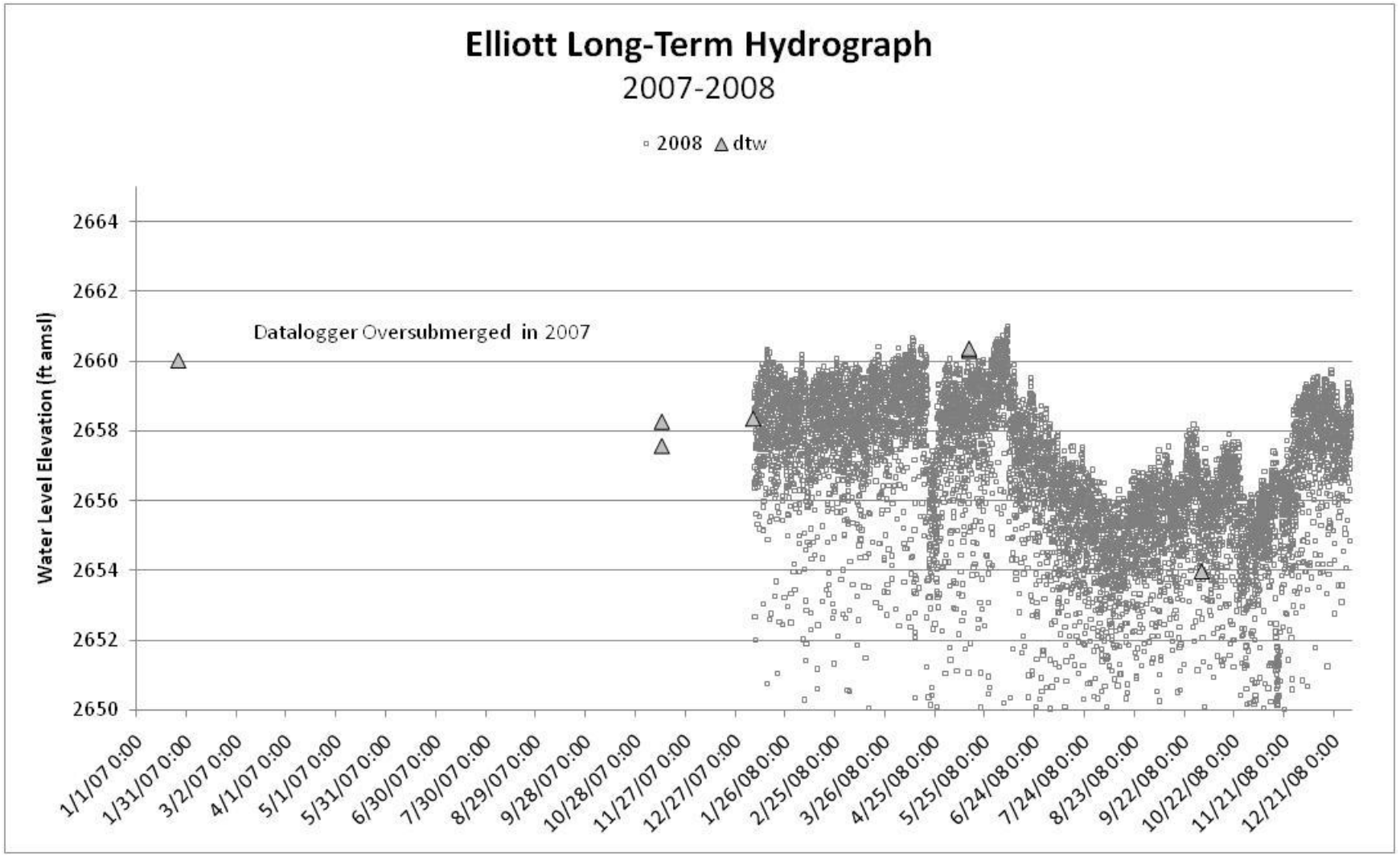


Figure B8. Long-term water level hydrograph for the Elliott well.

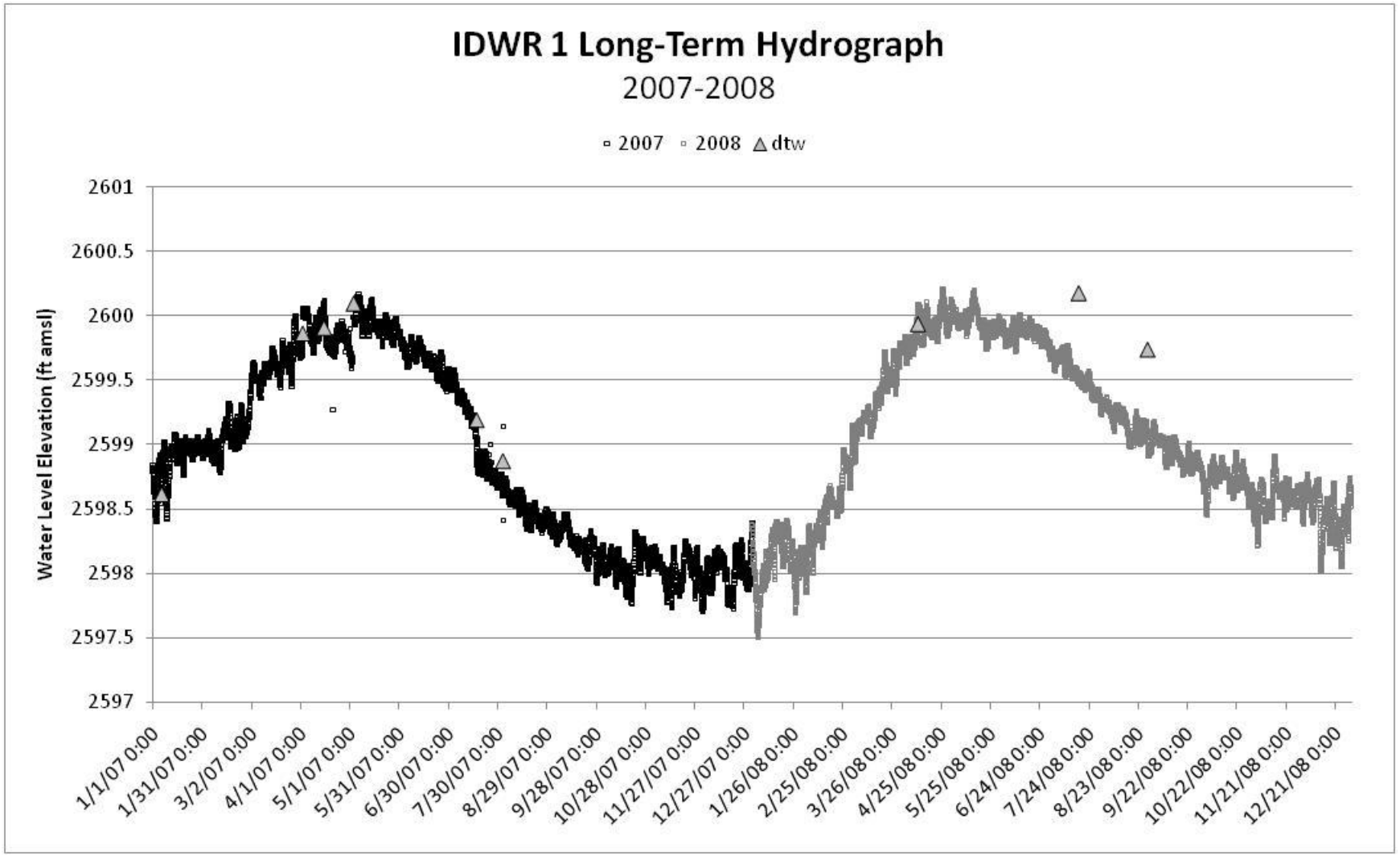


Figure B9. Long-term water level hydrograph for the IDWR1 well.

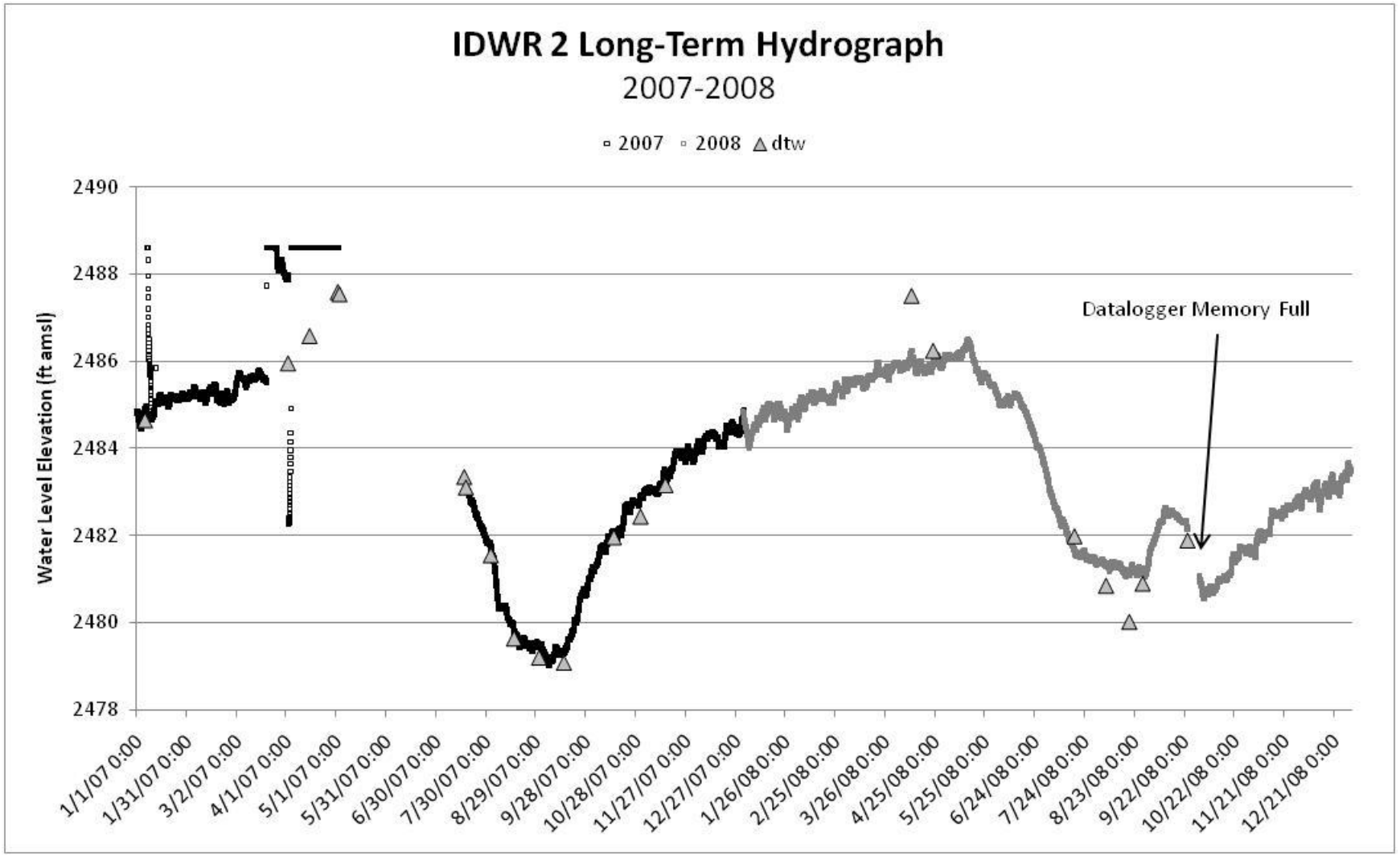


Figure B10. Long-term water level hydrograph for the IDWR2 well.

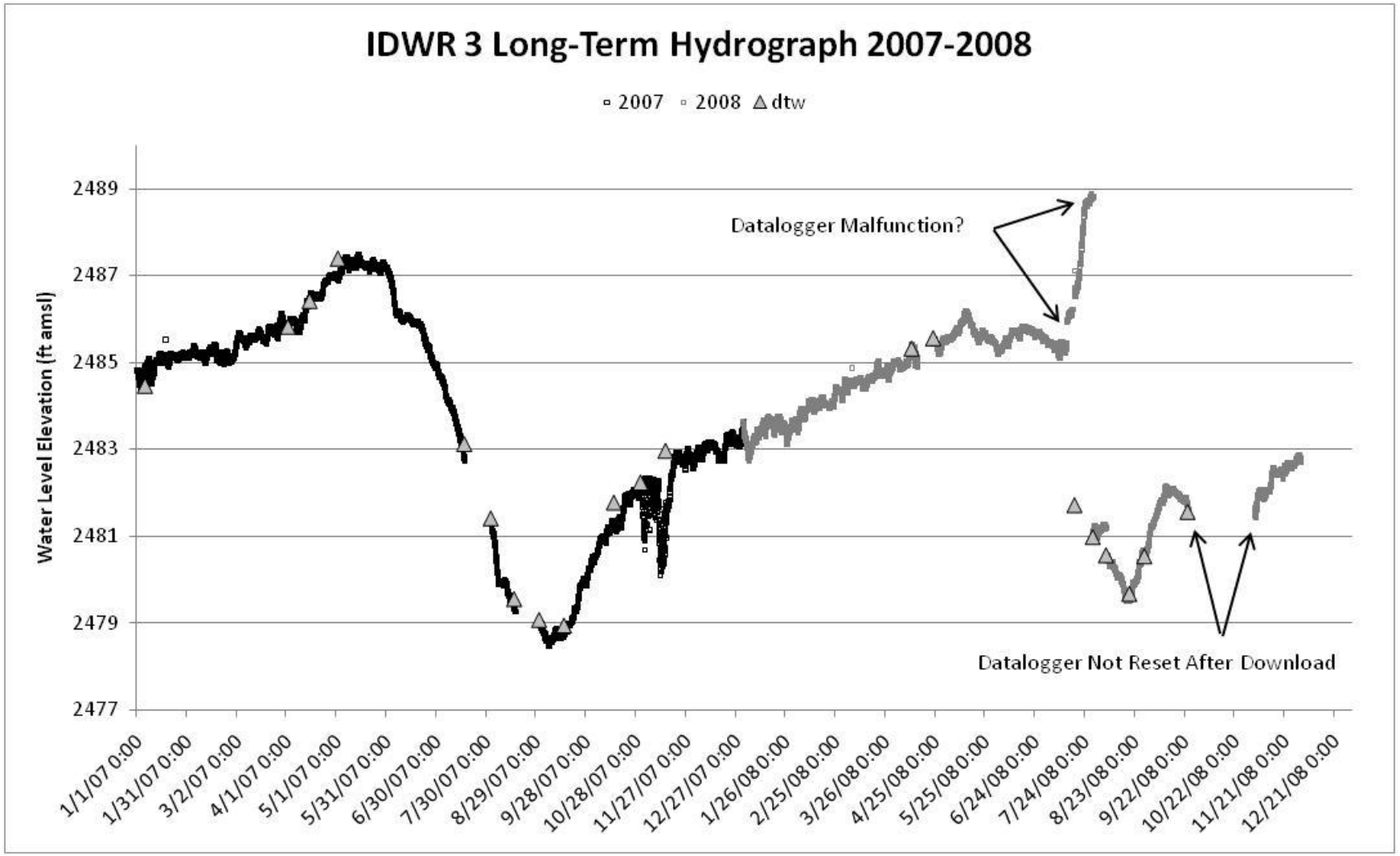


Figure B11. Long-term water level hydrograph for the IDWR3 well.

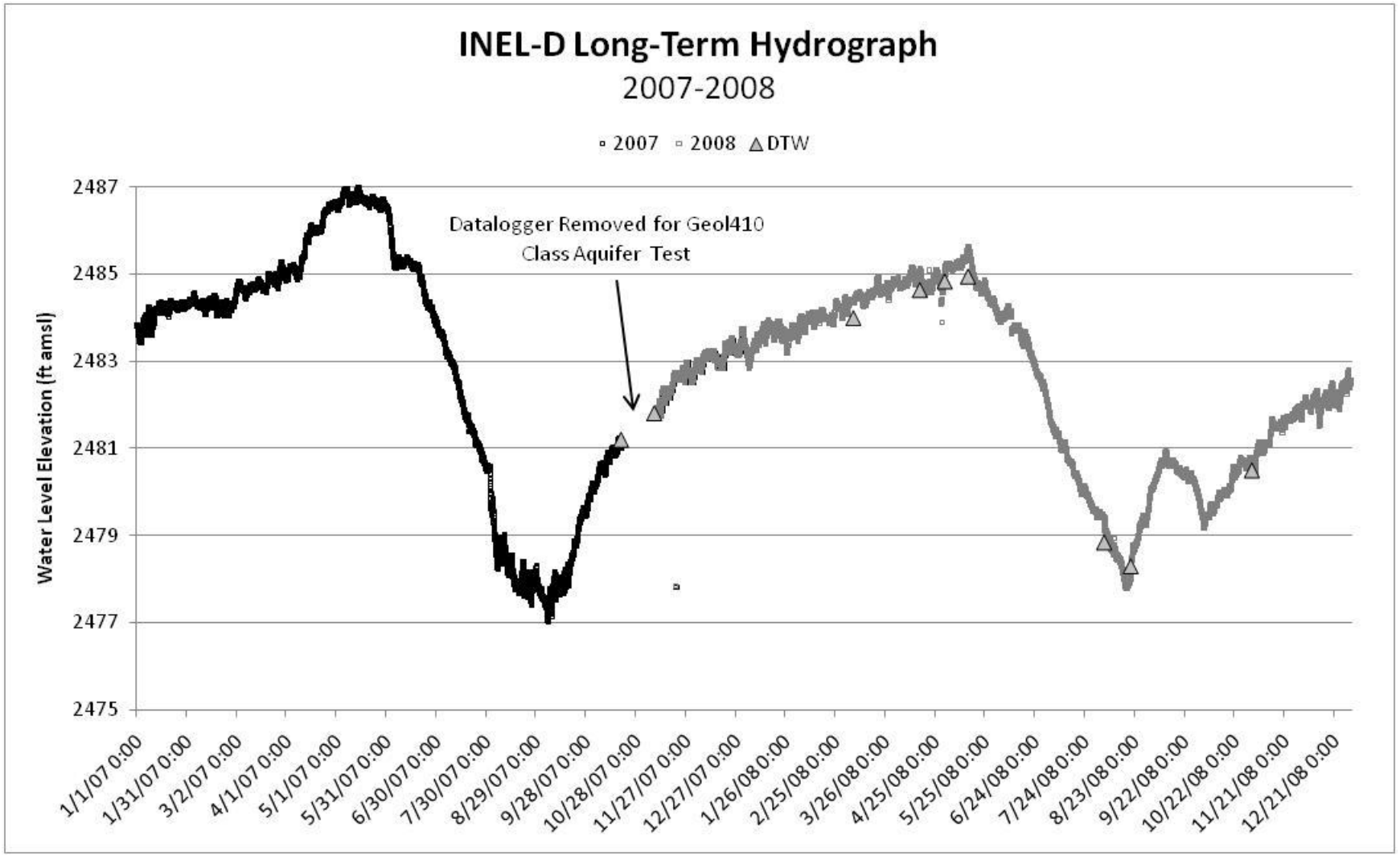


Figure B12. Long-term water level hydrograph for the INEL-D well.

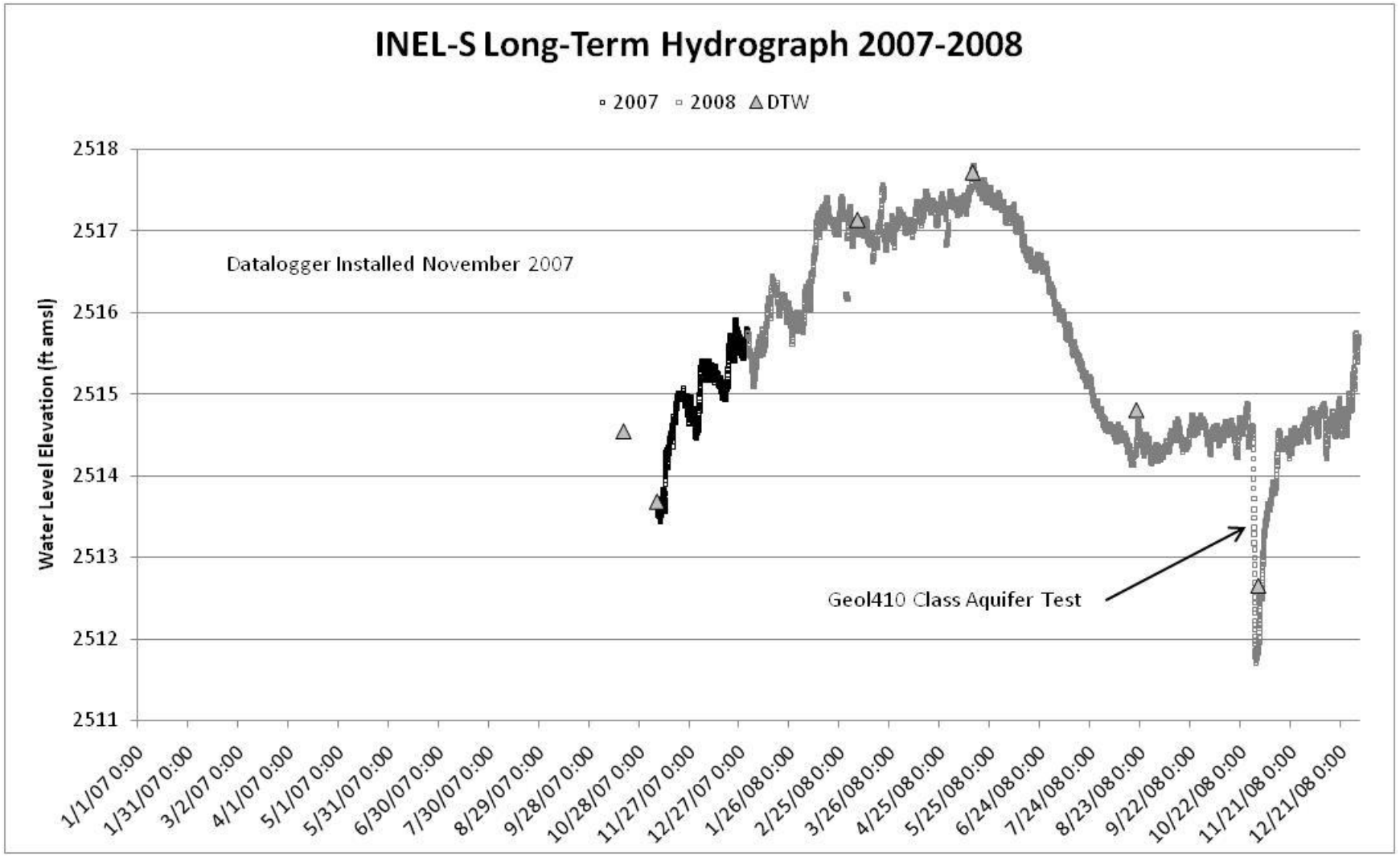


Figure B13. Long-term water level hydrograph for the INEL-S well.

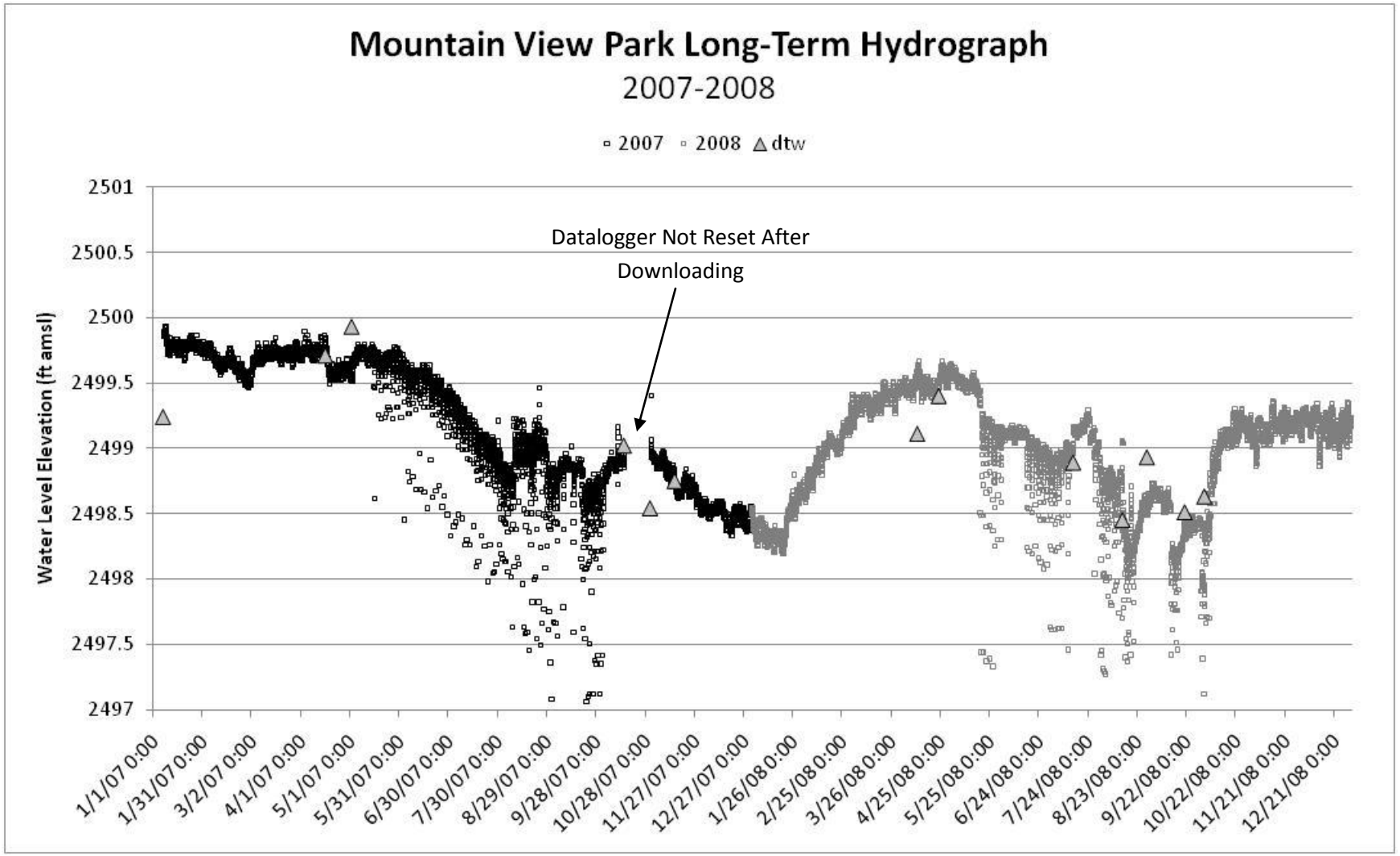


Figure B14. Long-term water level hydrograph for the Mountain View Park well.

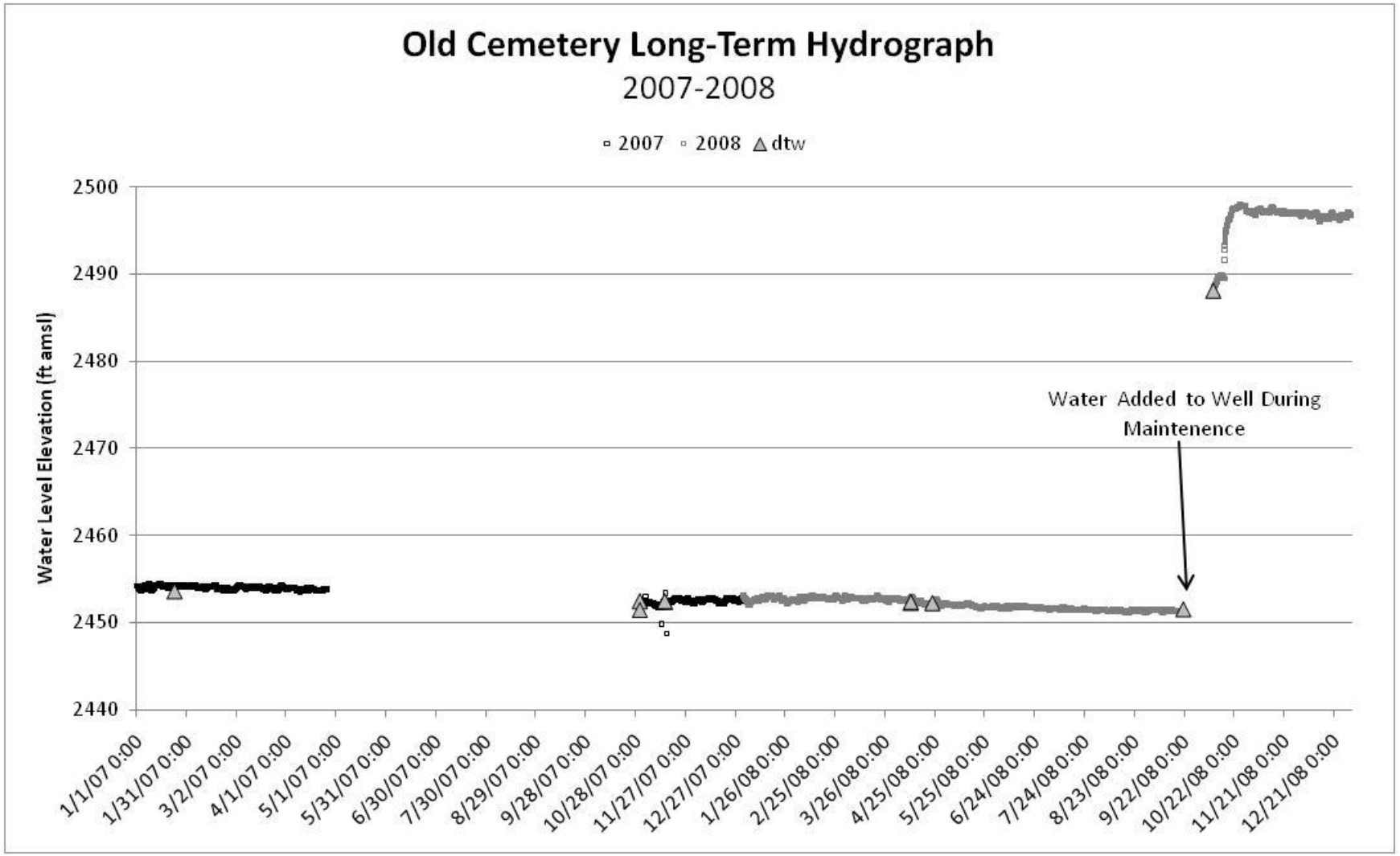


Figure B15. Long-term water level hydrograph for the Old Cemetery well.

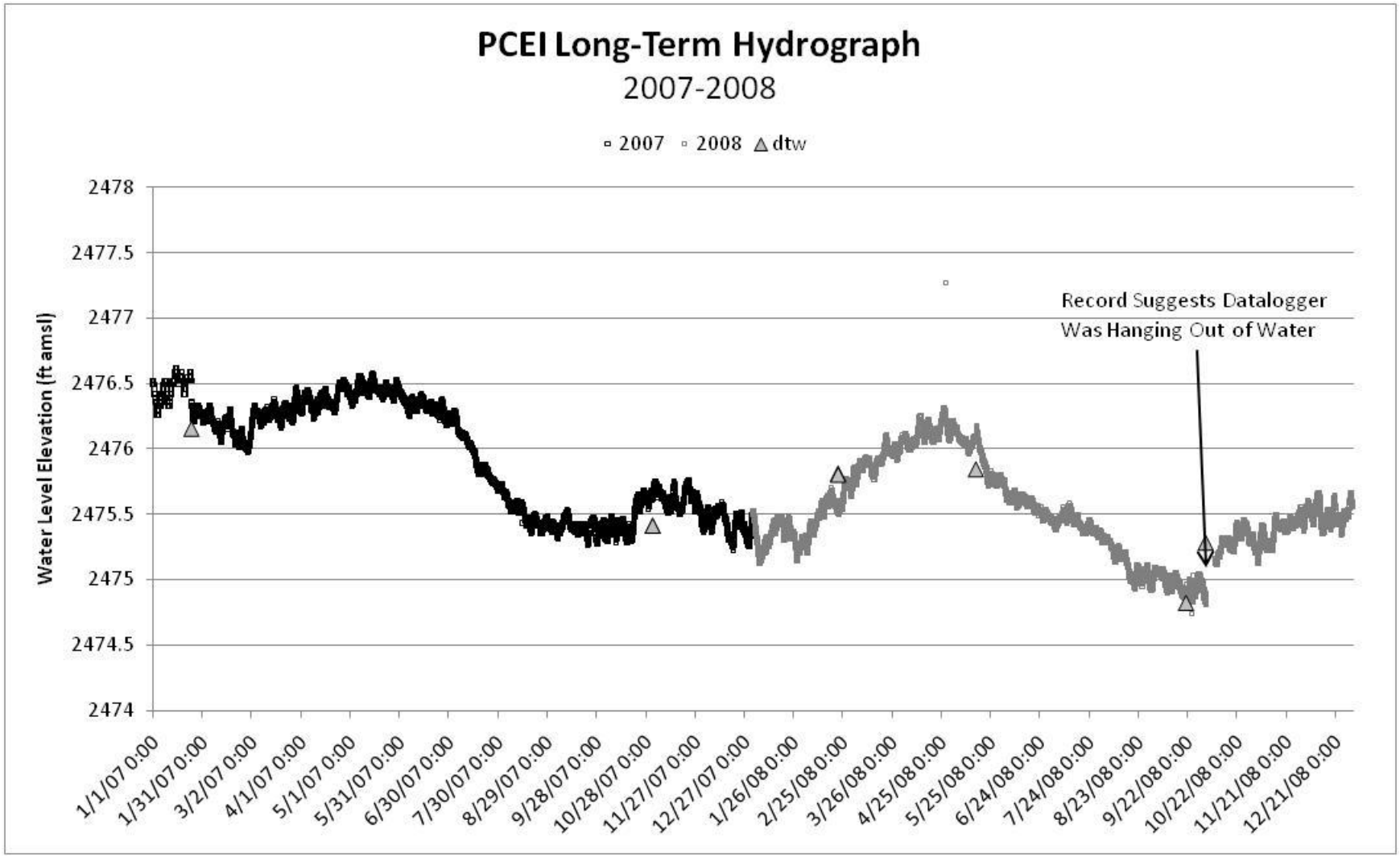


Figure B16. Long-term water level hydrograph for the PCEI well.

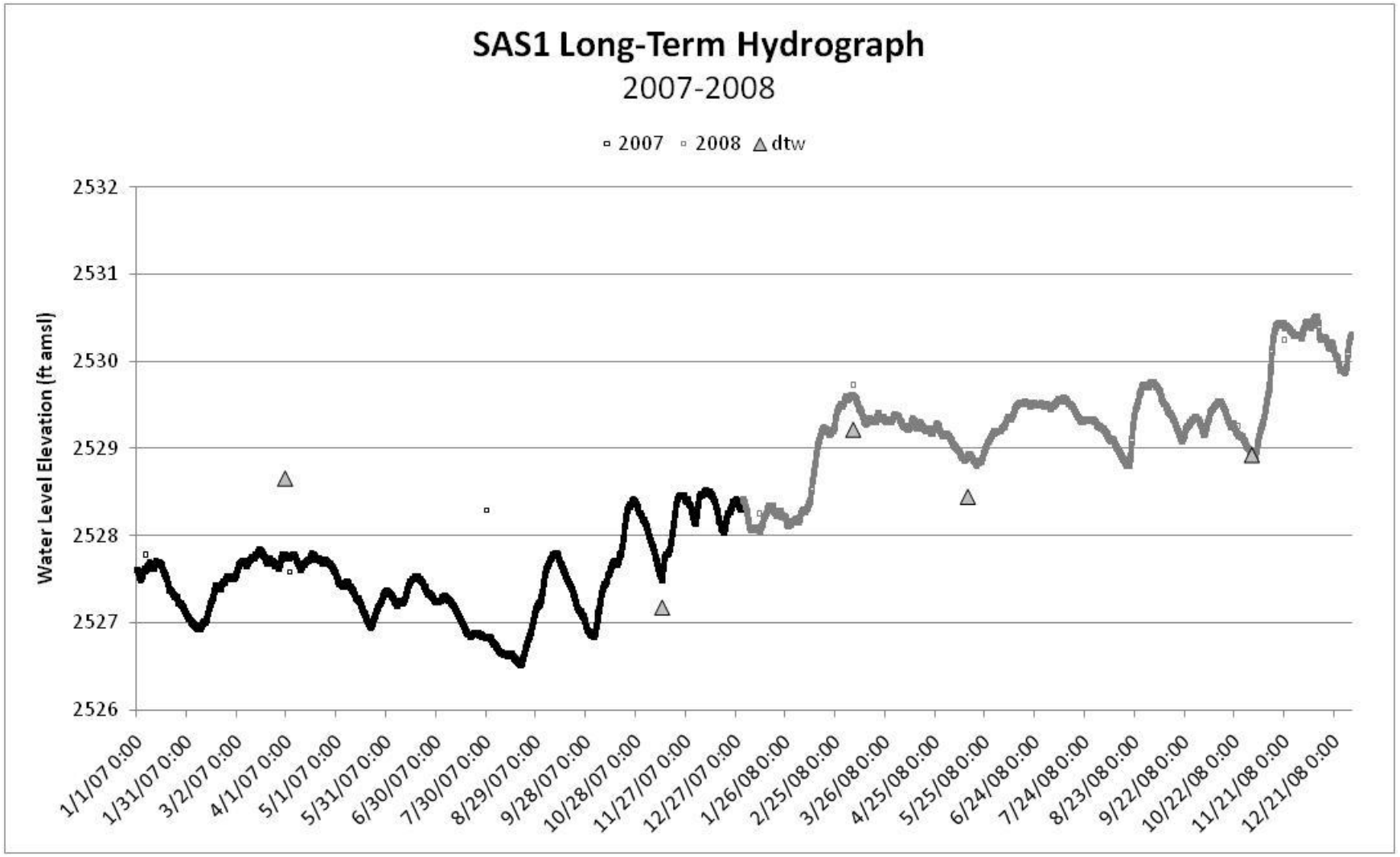


Figure B17. Long-term water level hydrograph for the SAS1 well.

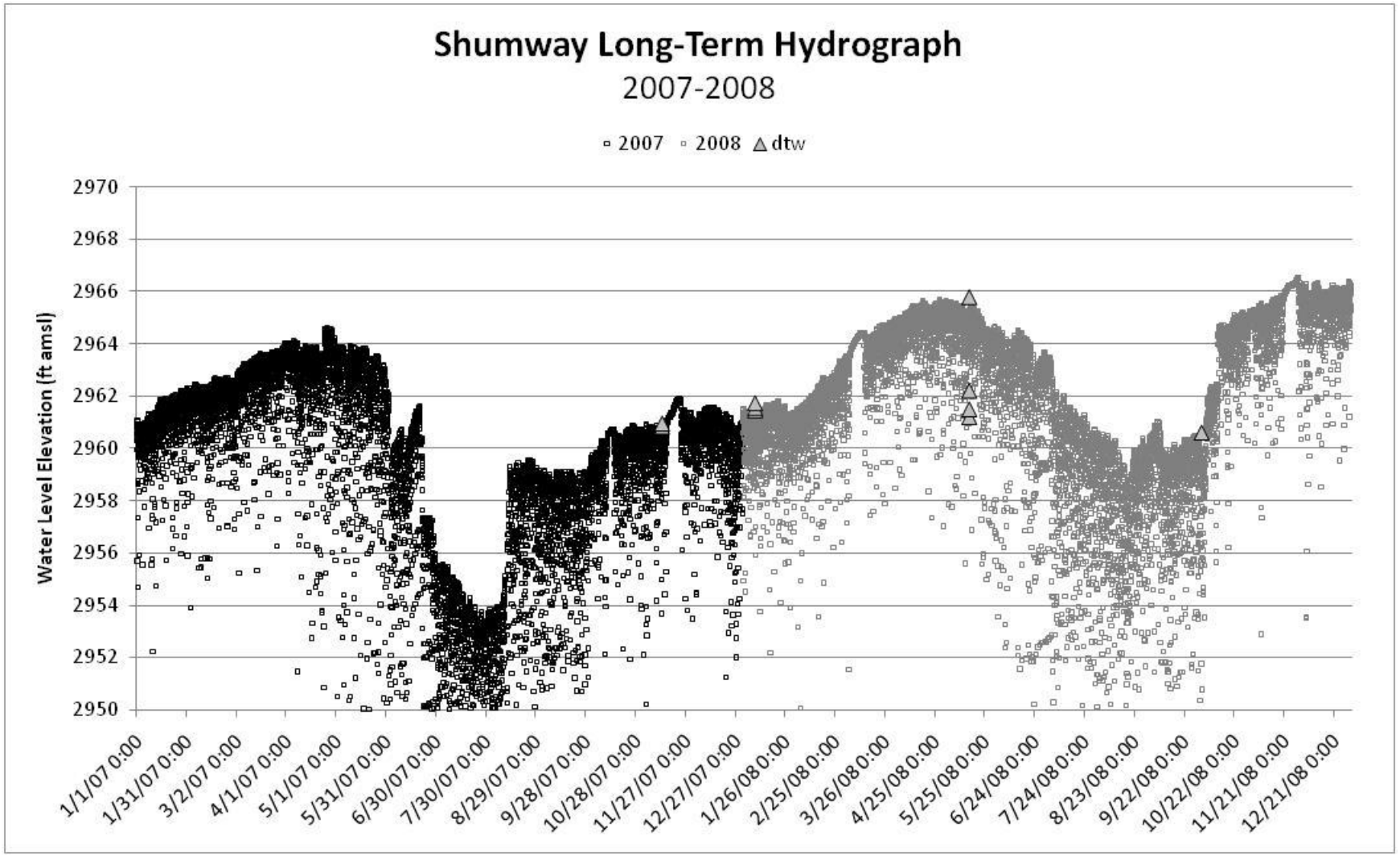


Figure B18. Long-term water level hydrograph for the Shumway well.

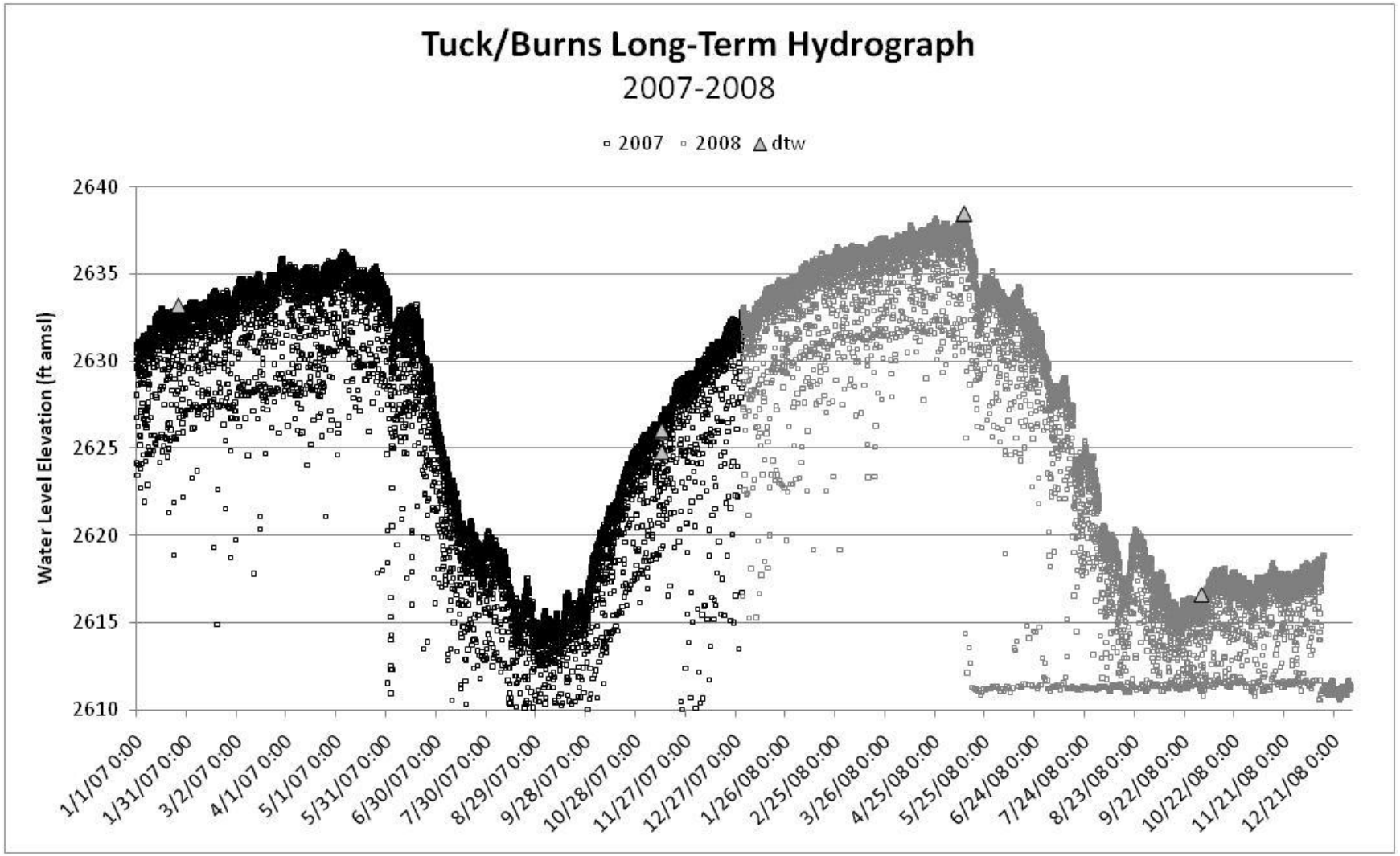


Figure B19. Long-term water level hydrograph for the Tuck/Burns well.

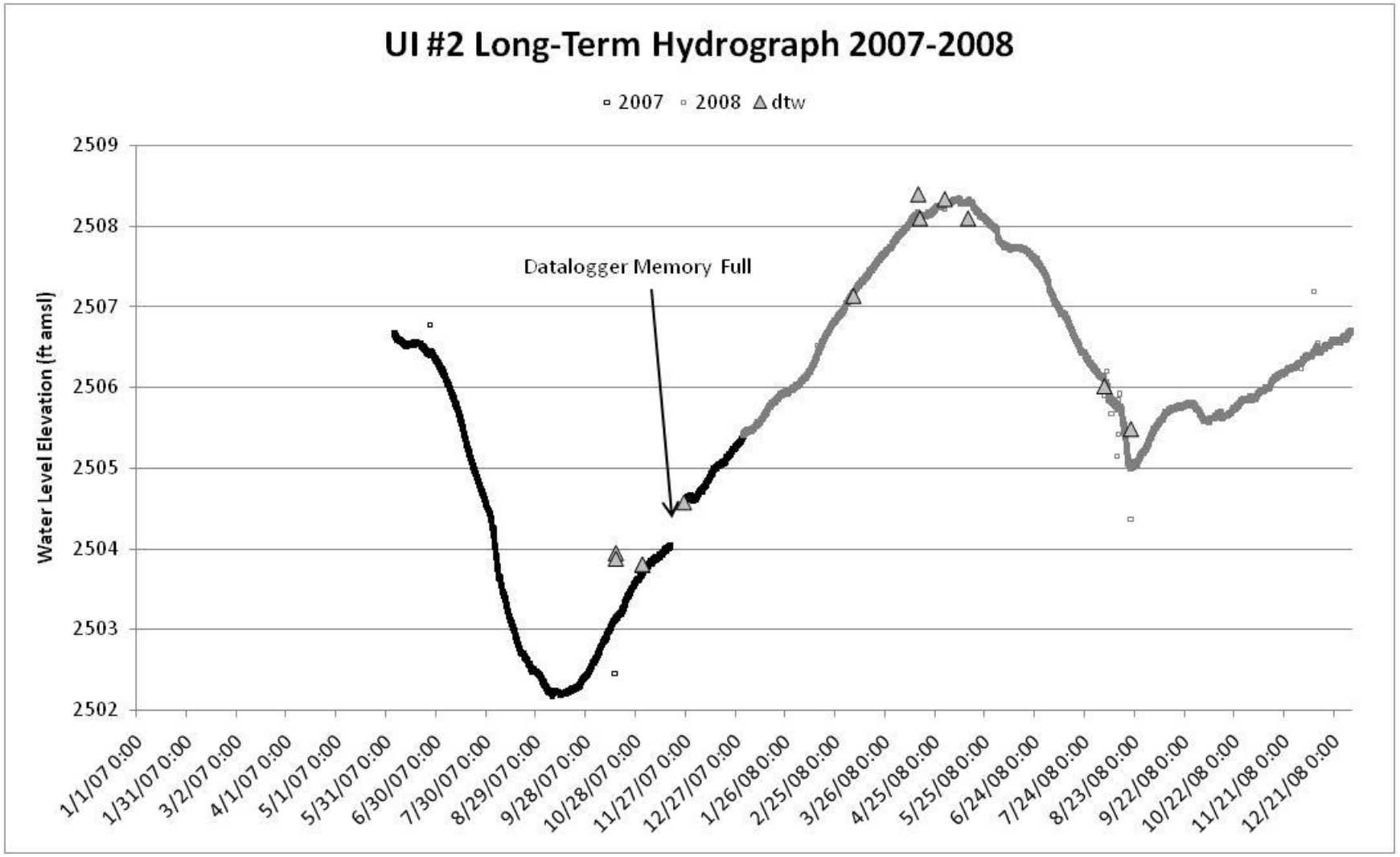


Figure B20. Long-term water level hydrograph for the UI #2 well.

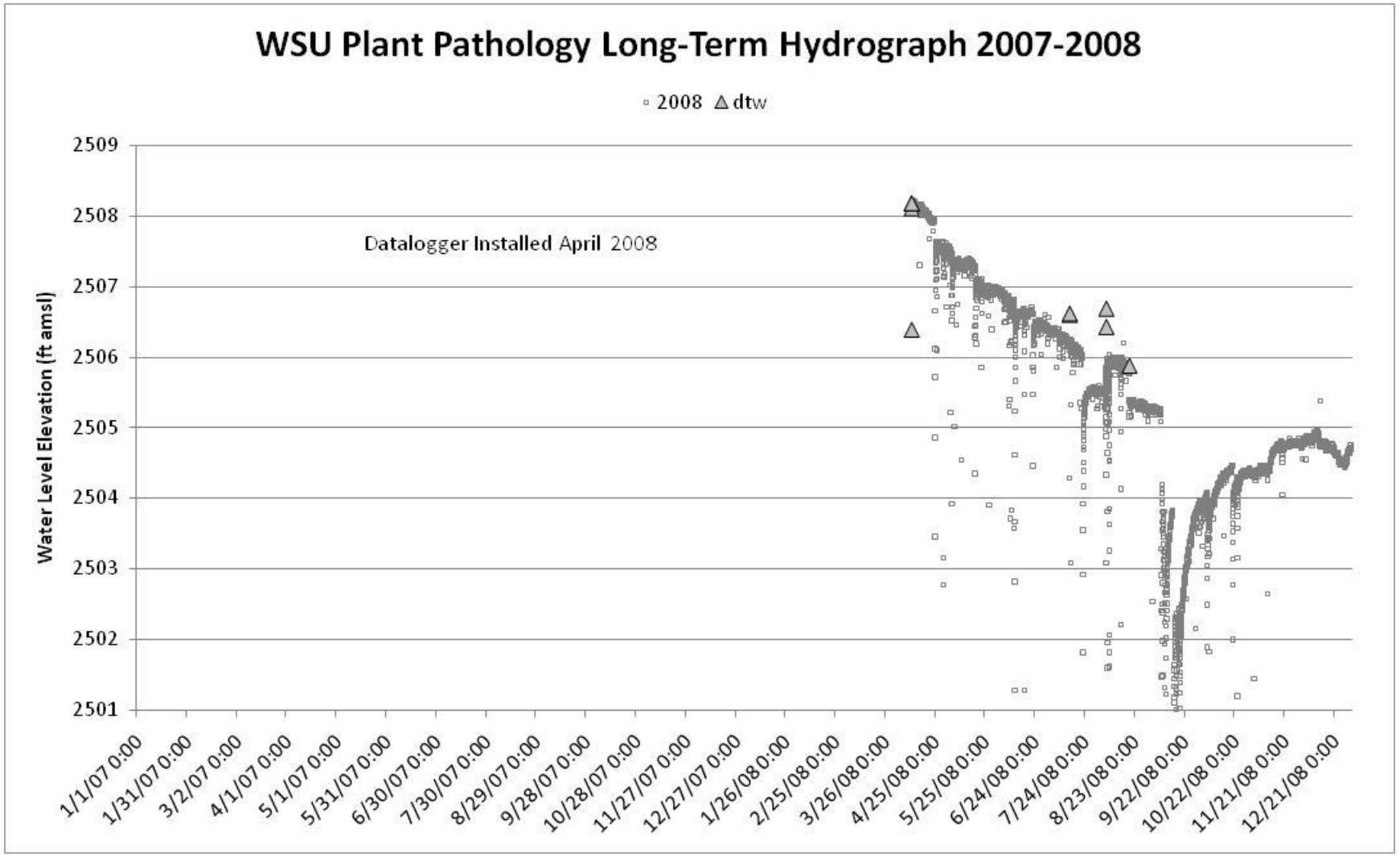


Figure B21. Long-term water level hydrograph for the WSU Plant Pathology well.

Appendix C

Removal of Barometric Pressure Effects in Water Level Records

Removal of Water Level Fluctuations Caused by Barometric Pressure Changes

BETCO© was used to remove fluctuations in water levels due to barometric pressure changes during the aquifer tests. Water levels were corrected using barometric pressure data collected at the same times as water level data. BETCO©, a computer software program developed by Nathaniel Toll of Sandia National Laboratories, and Dr. Todd Rasumssen of the University of Georgia, applies a multiple regression technique to remove barometric effects. Once barometric pressure influences were removed from the water level records, pumping effects were more easily observed. The data presented in this appendix are represented as water level elevation versus time, and barometric pressure effects have been removed from the water level data using BETCO©.

In order to remove the barometric fluctuations, water level and barometric pressure data collected at the same times were placed into BETCO©. Generally, barometric responses in water levels lag behind changes in barometric pressure (Toll and Rasmussen, 2007). This phenomenon is due to borehole storage effects, well skin effects, or the muting effects of aquifer overburden. Time lag responses between barometric pressure changes and water level responses are evaluated by BETCO© using regression deconvolution (Toll and Rasmussen, 2007). Lag times can be adjusted in the BETCO© program by trial-and-error. In order to determine the appropriate lag time to use for a given well, removal of barometric effects was evaluated using four arbitrarily chosen time lags: 5, 12, 26, and 42 hours. The “cleaned” water levels were then offset vertically and plotted on the same graph. Of the four lag-times plotted, one was chosen to most effectively remove barometric responses from the water level record. The lag time of the water level hydrograph that resulted in the most visually pleasing (i.e., smoothest) data plot was considered to remove barometric effects most effectively. Figure C1 illustrates the process through which the “cleanest” water level record was selected. For the data set shown in Figure C1, a lag of 26 hours, (black data points) was chosen as the smoothest and cleanest water level record for presentation and analysis.

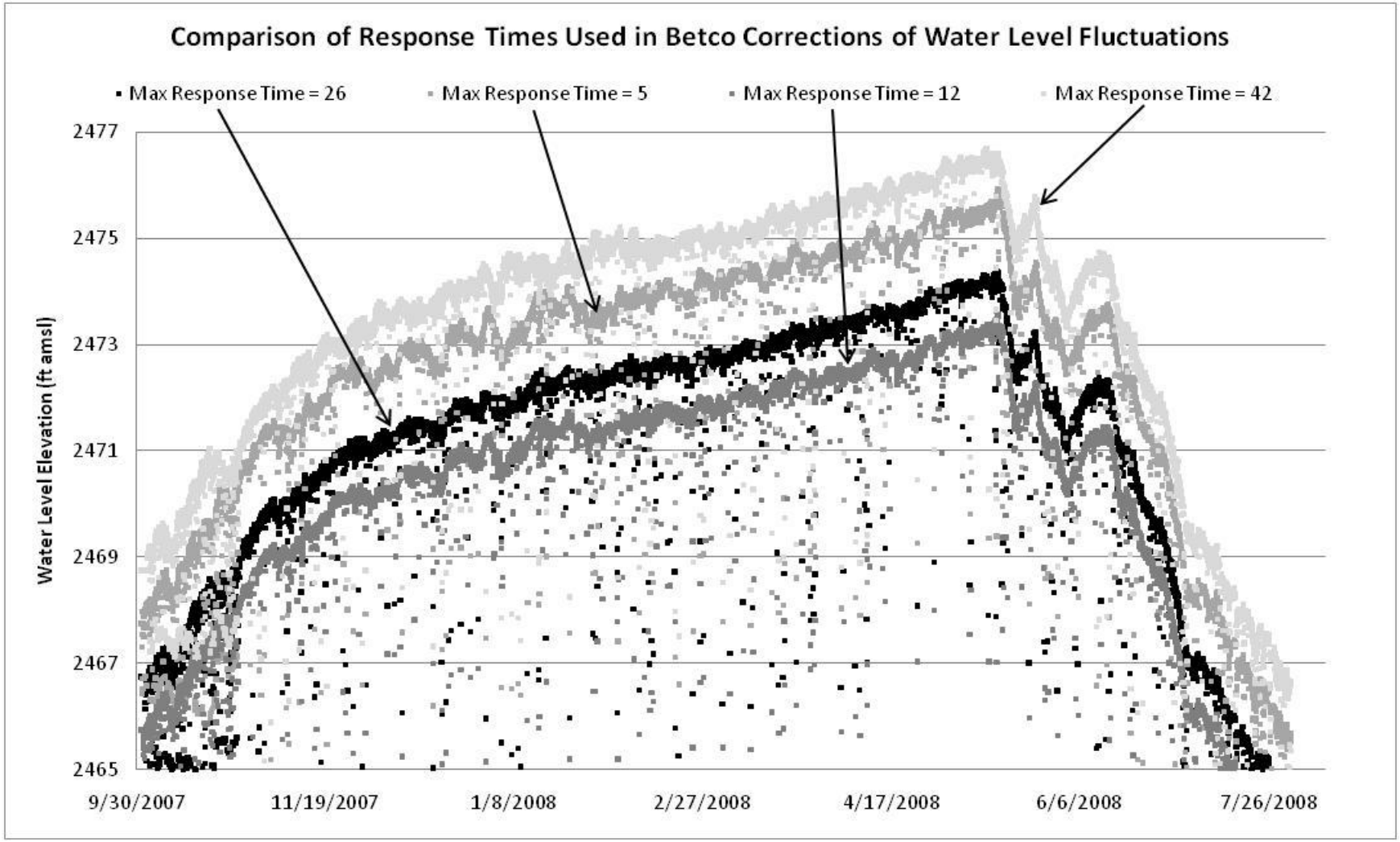


Figure C1. Example of process by which barometric pressure effects were removed from water level elevation hydrographs. The maximum response time of 26 hours (black data points) was chosen as the smoothest and cleanest water level record for presentation and analysis.

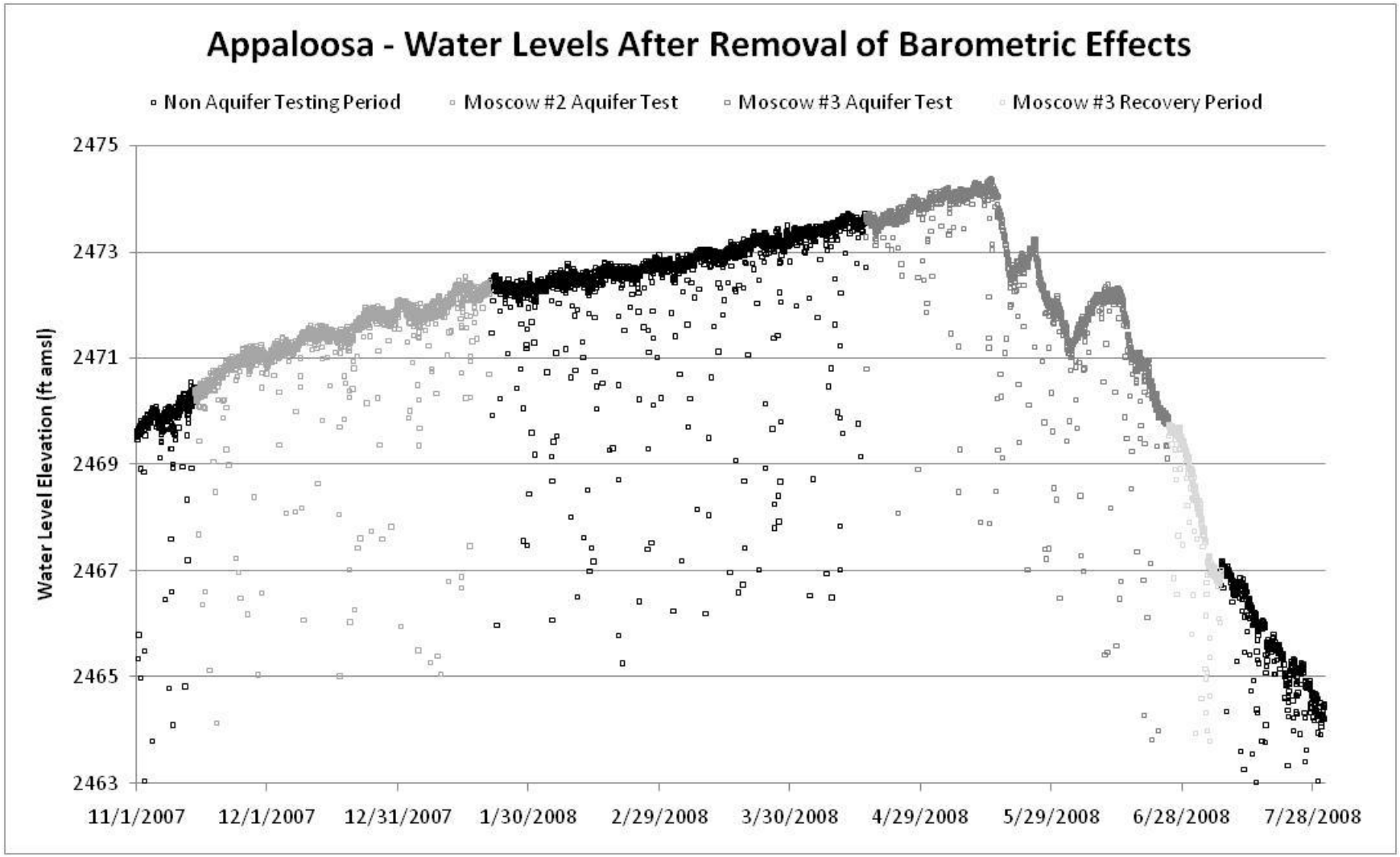


Figure C2. Appaloosa water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

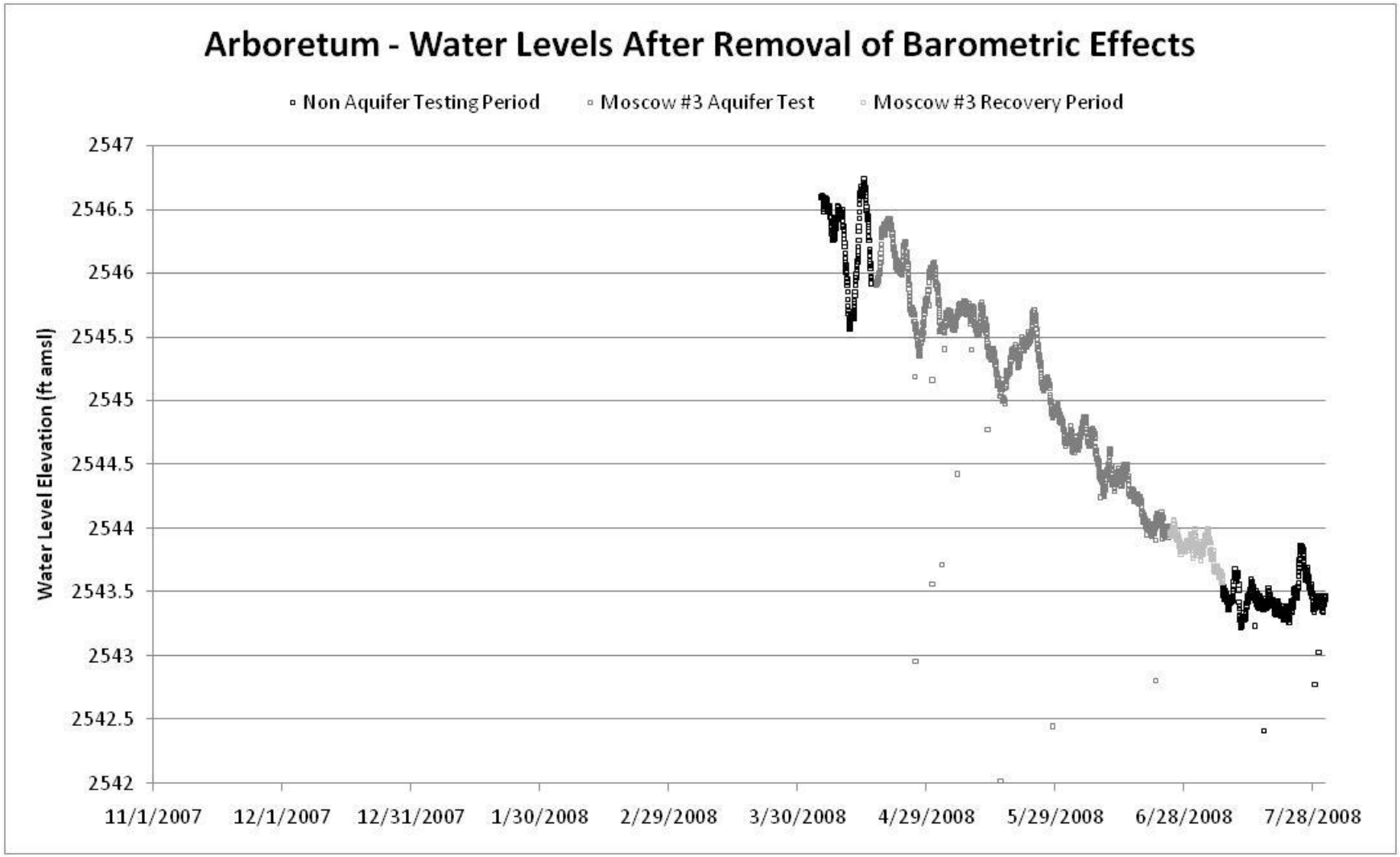


Figure C3. Arboretum water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

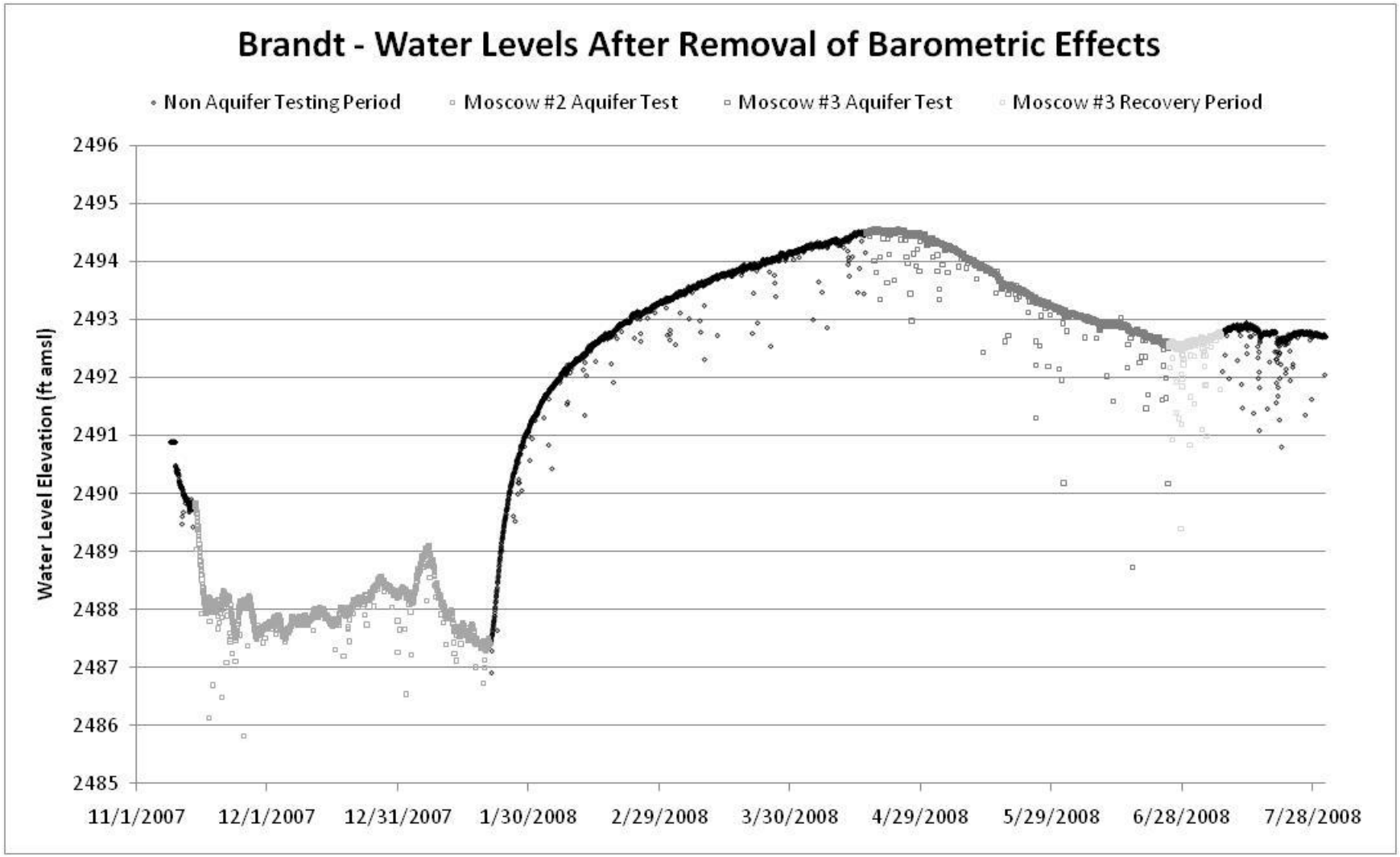


Figure C4. Brandt water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

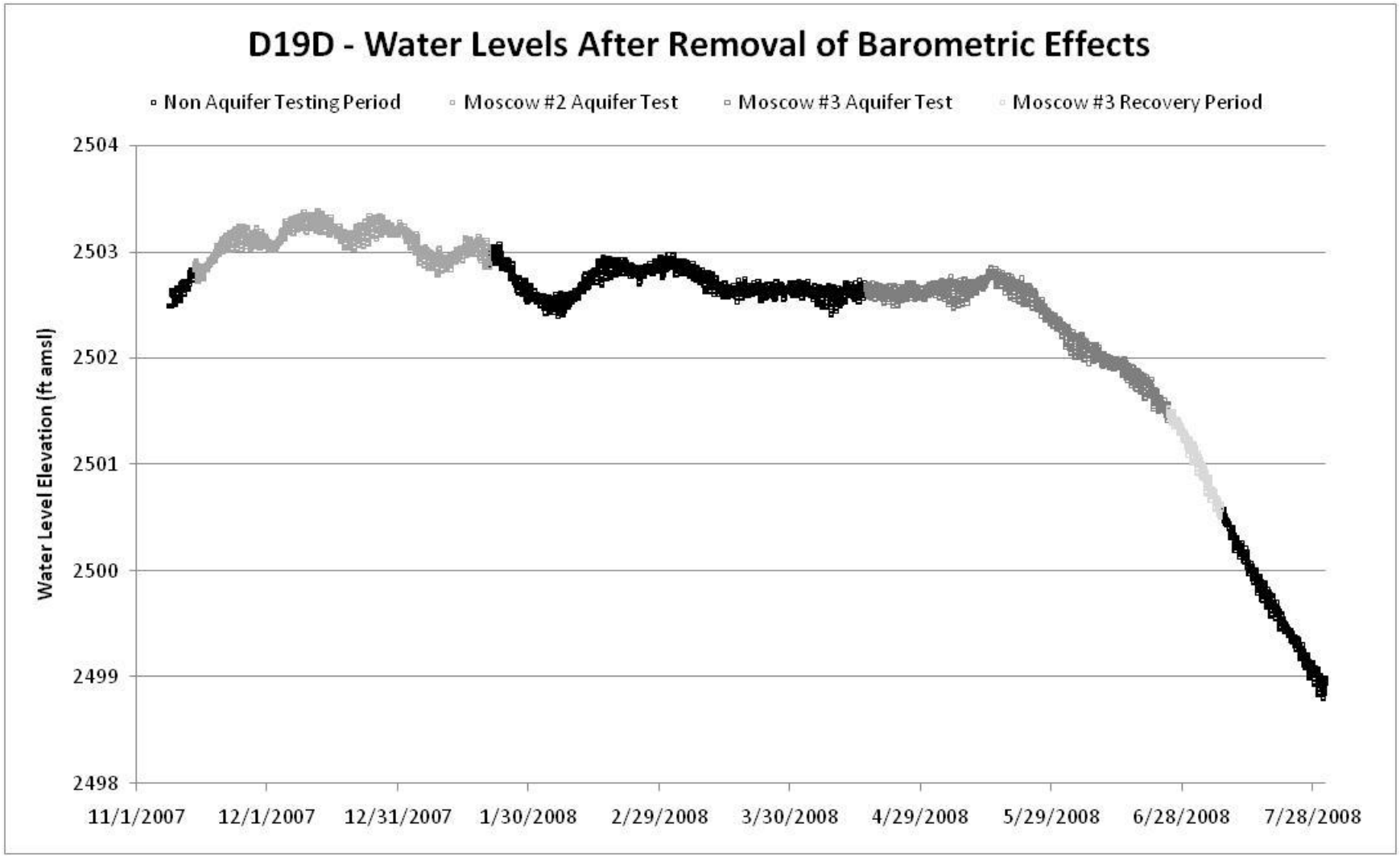


Figure C5. D19D water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

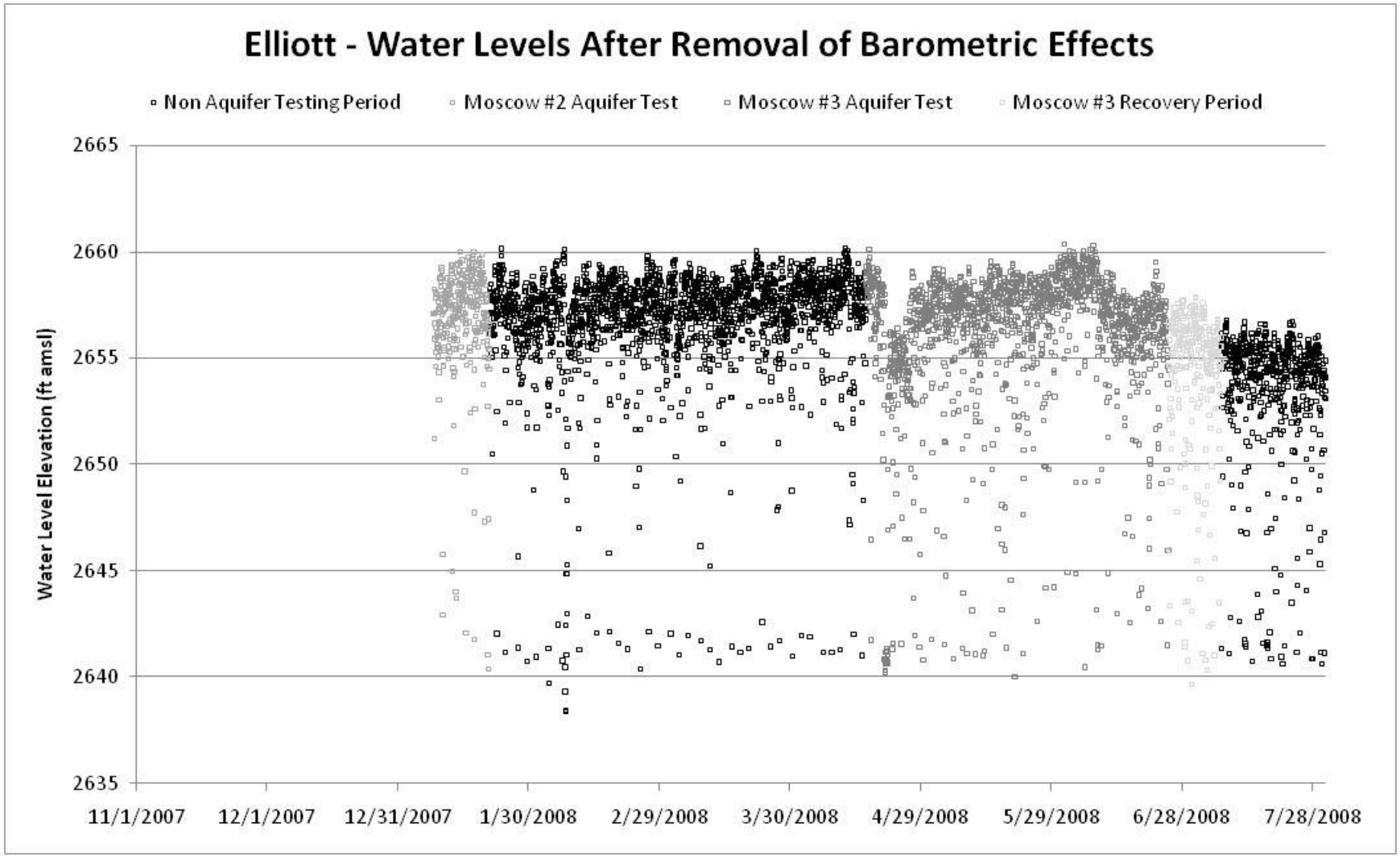


Figure C6. Elliott water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

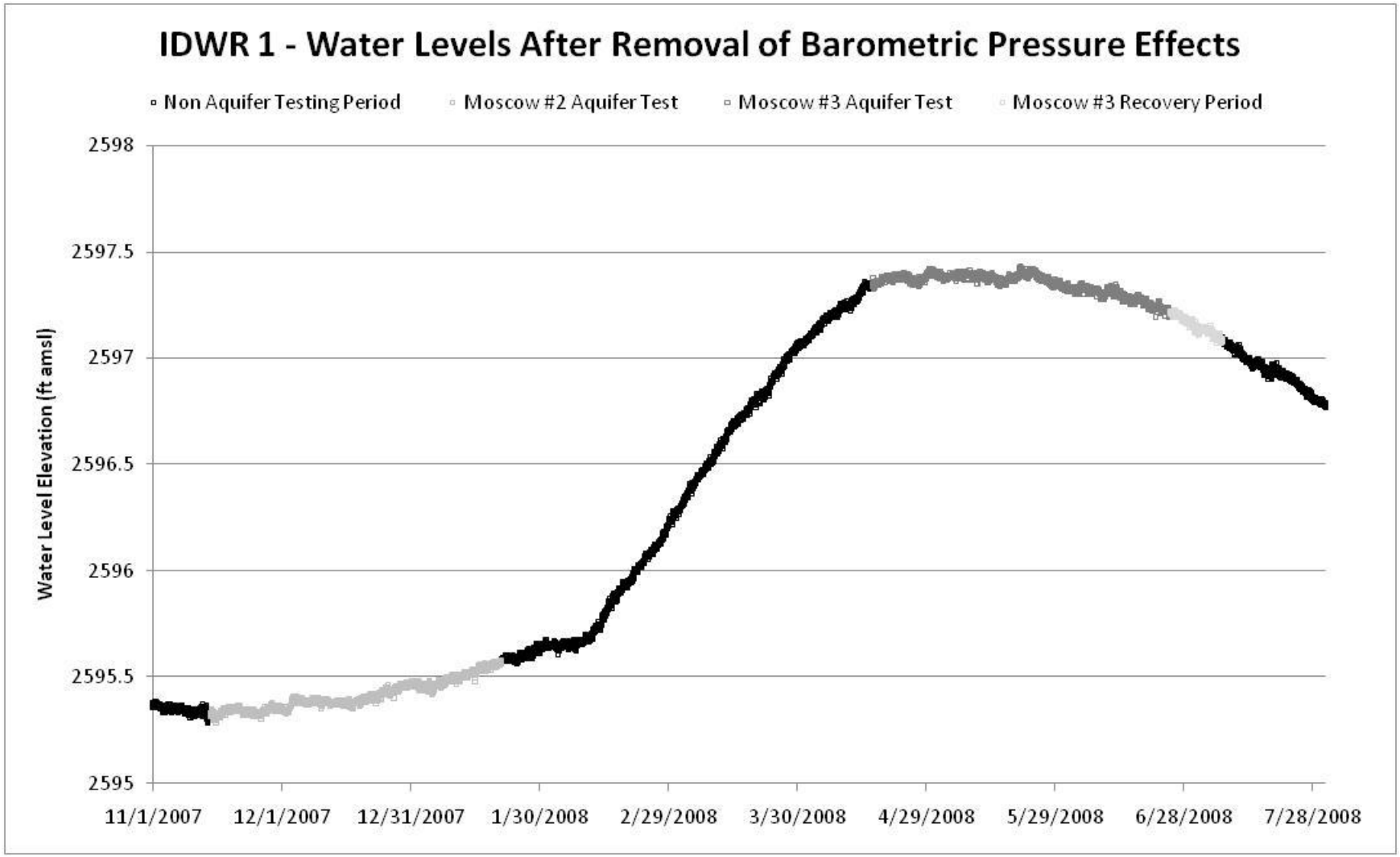


Figure C7. IDWR1 Water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

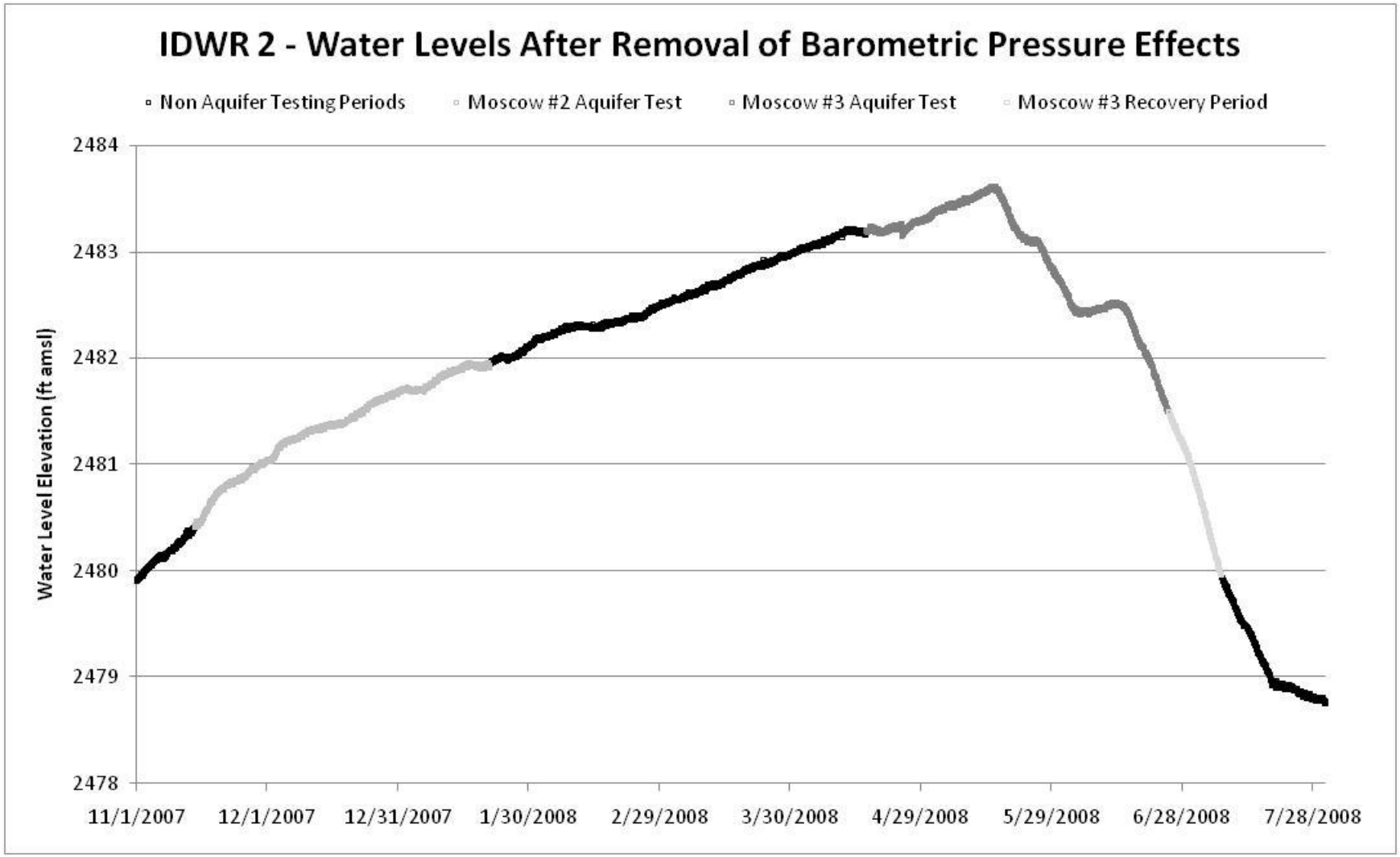


Figure C8. IDWR2 water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

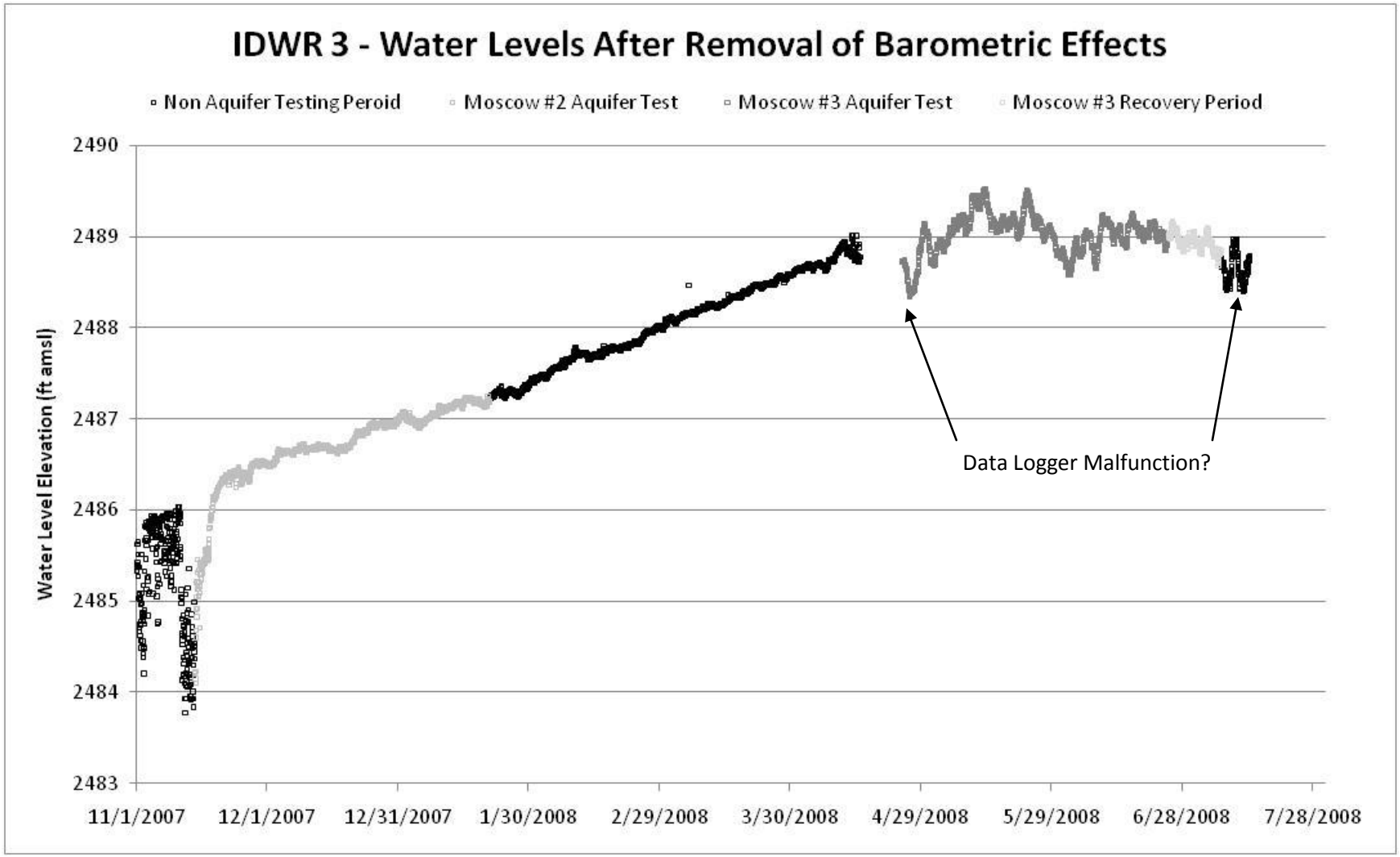


Figure C9. IDWR3 water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

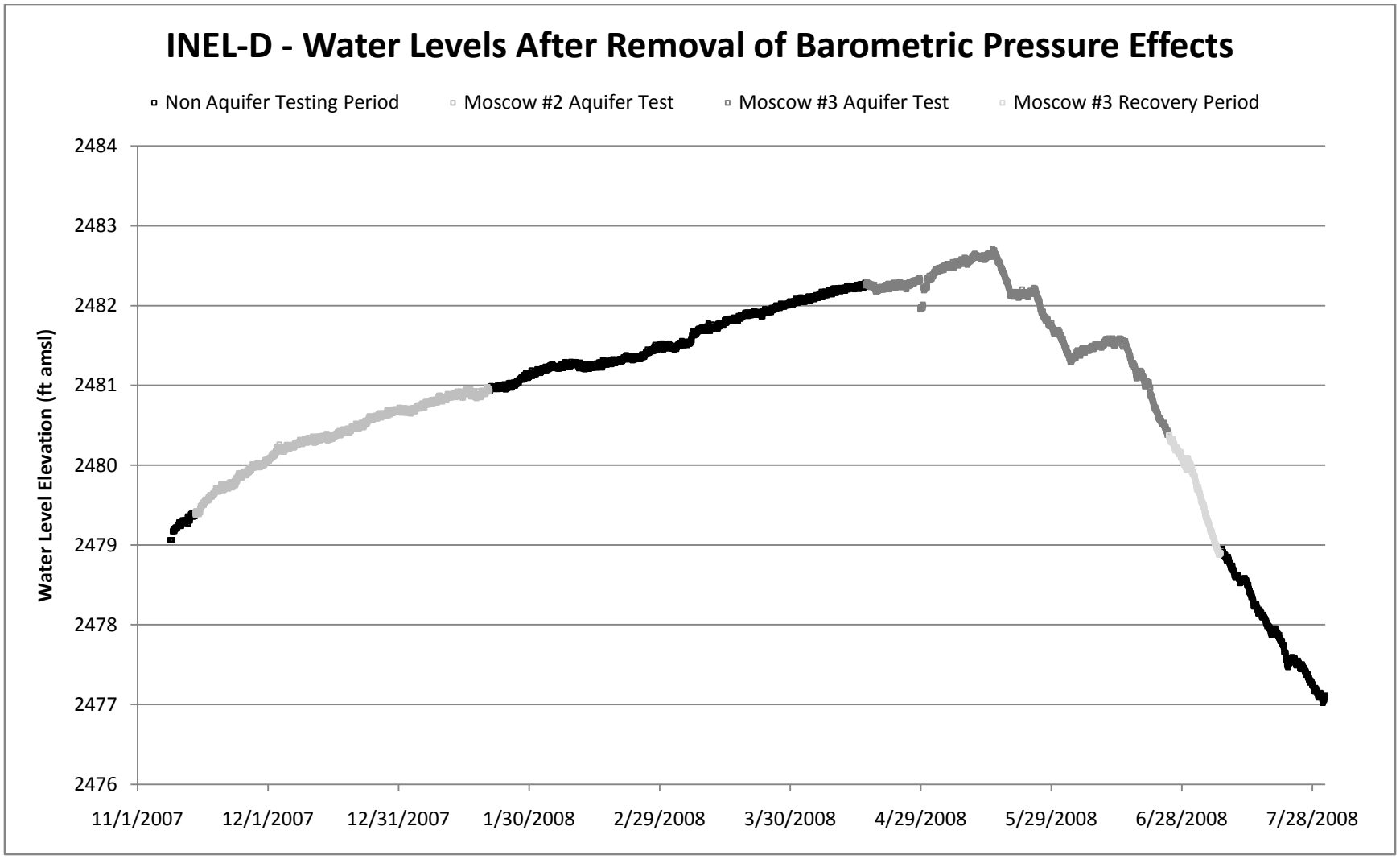


Figure C10. INEL-D water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

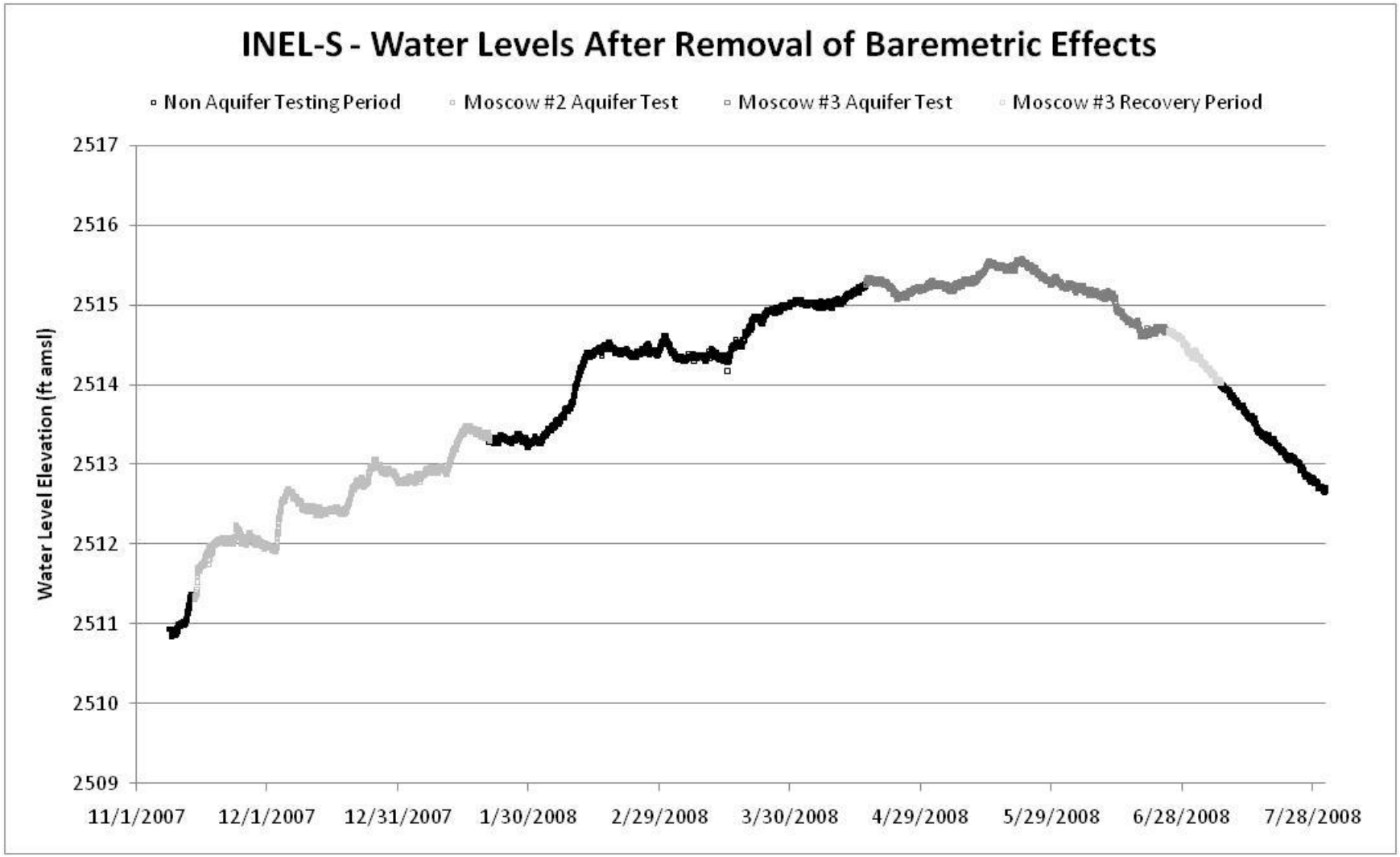


Figure C11. INEL-S water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

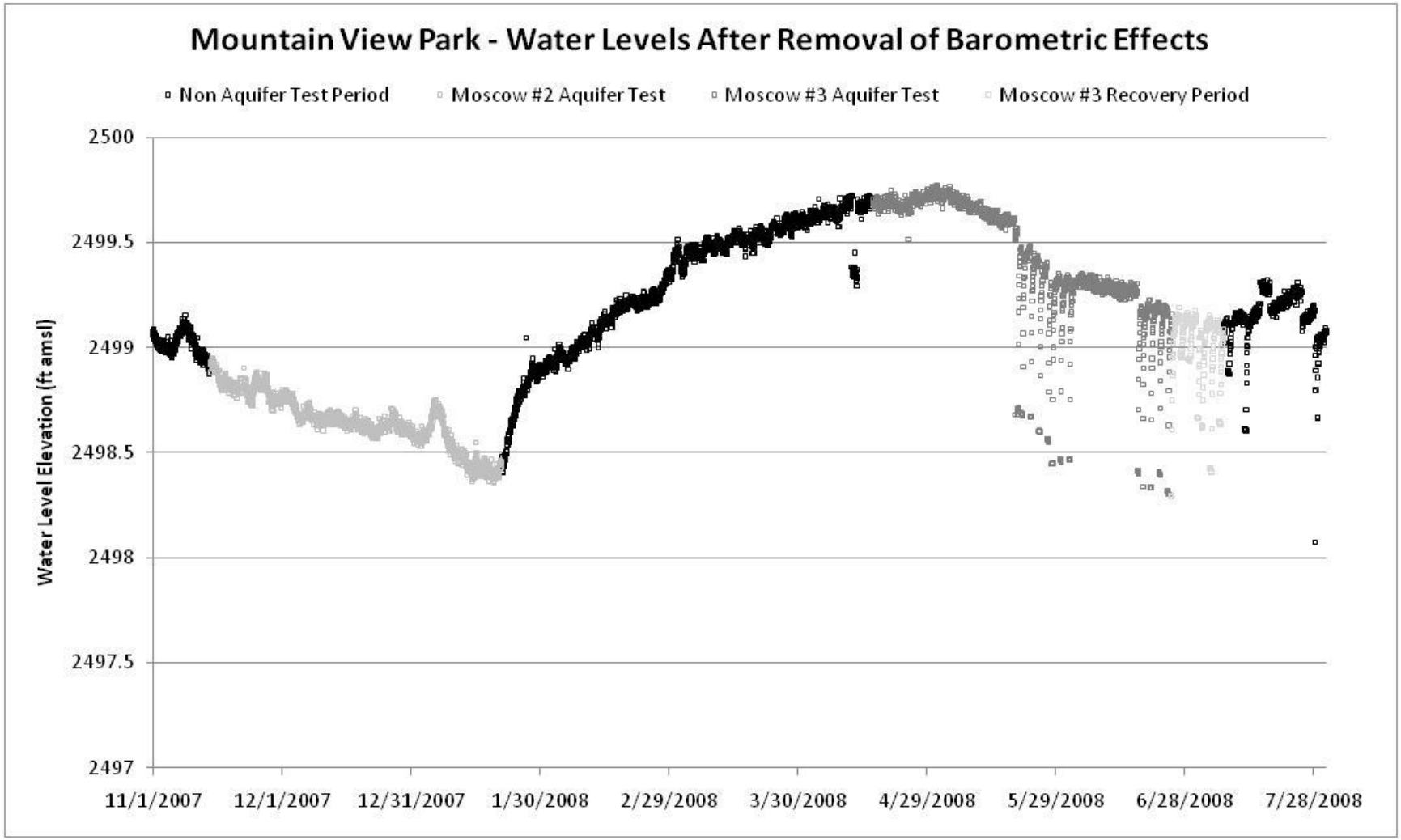


Figure C12. Mountain View Park water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

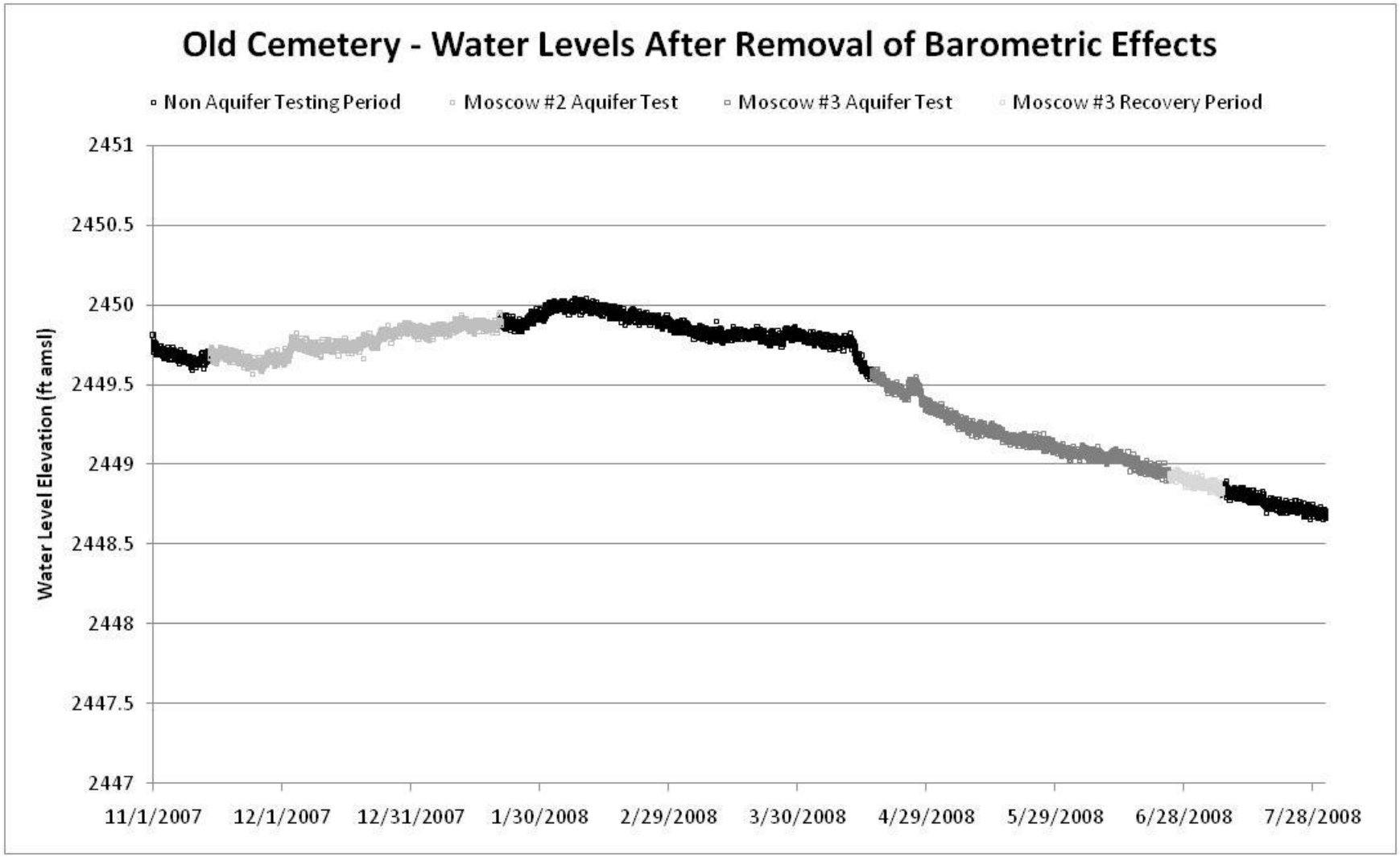


Figure C13. Old Cemetery water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

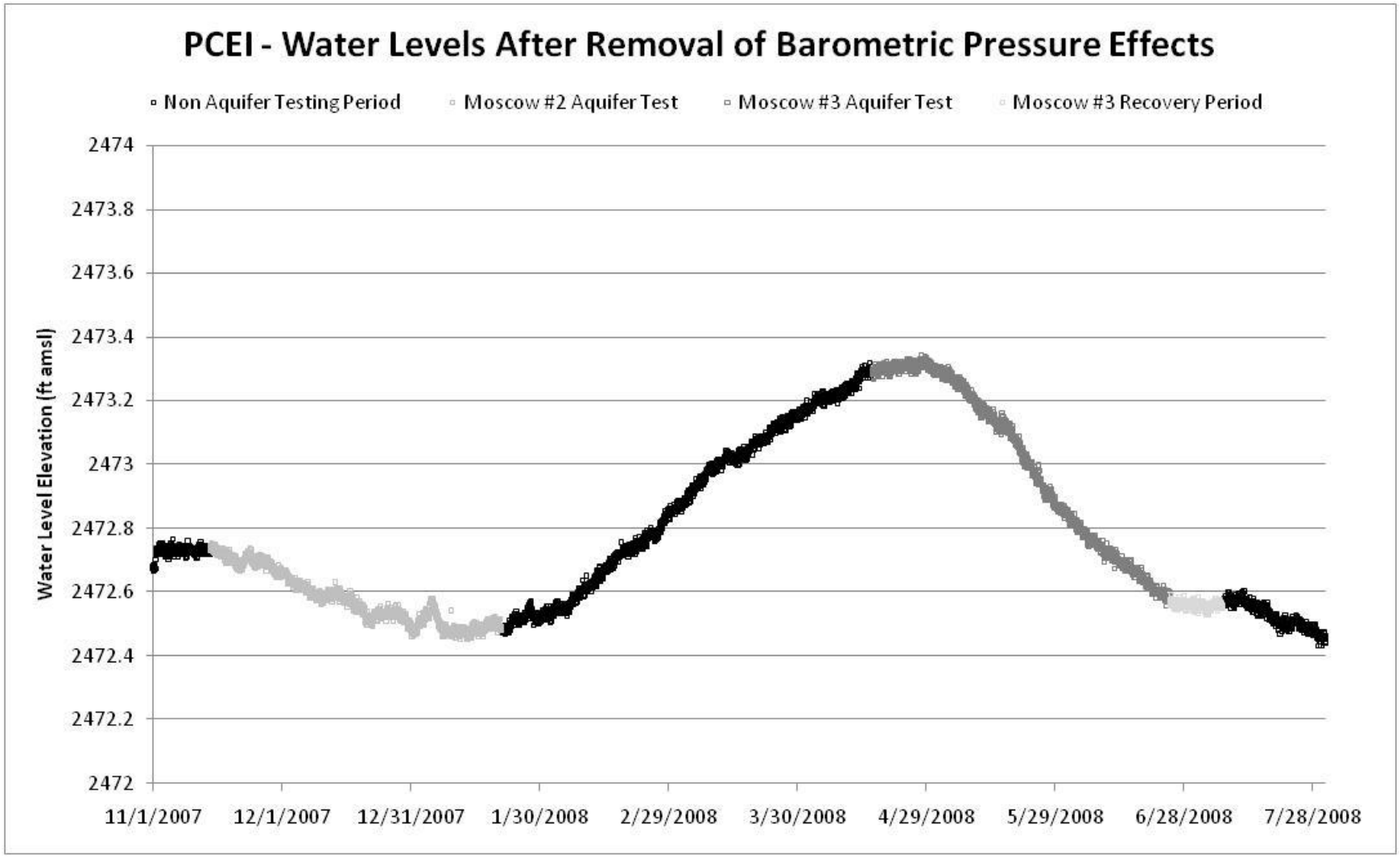


Figure C14. PCEI water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

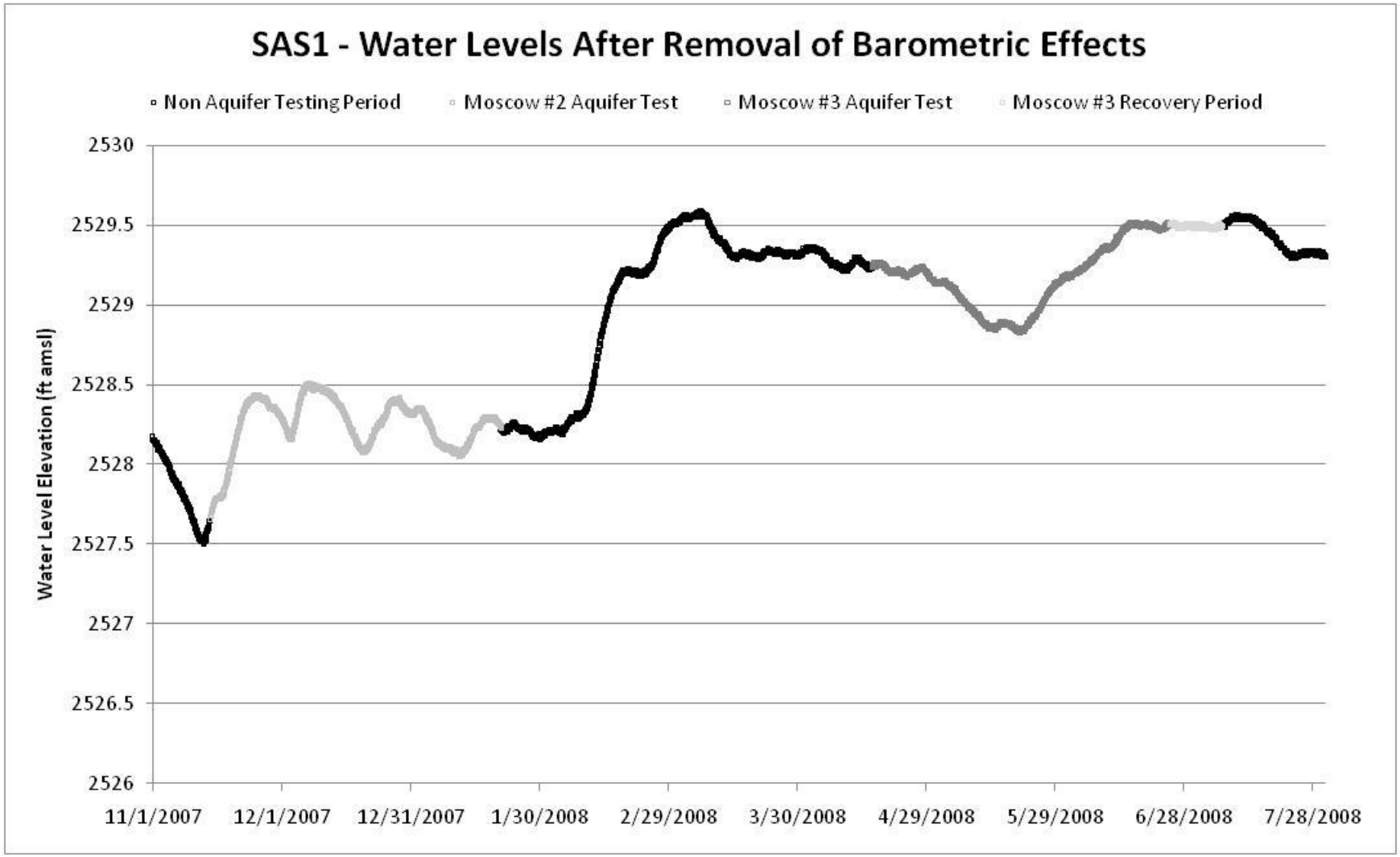


Figure C15. SAS1 water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

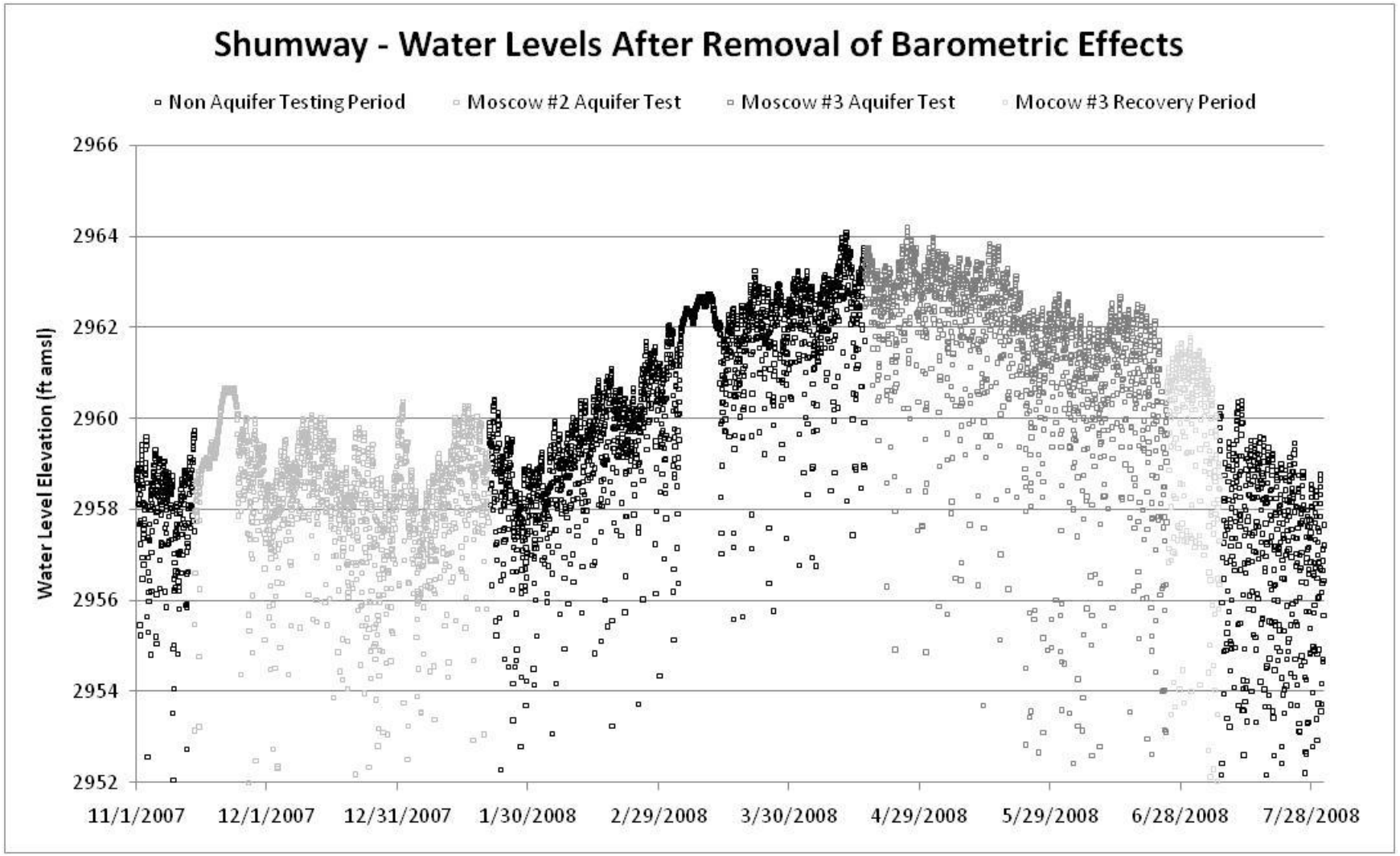


Figure C16. Shumway water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

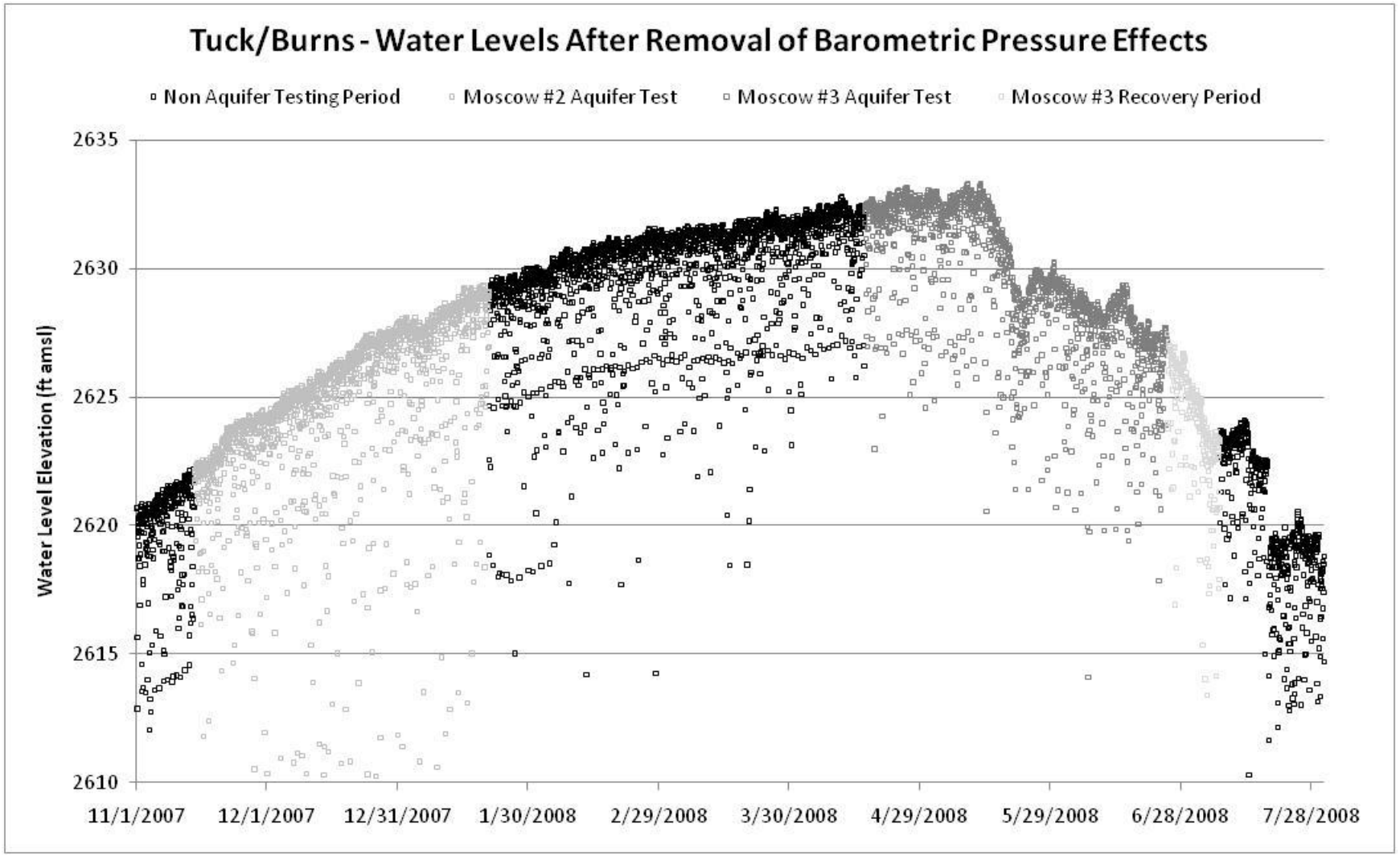


Figure C17. Tuck/Burns water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

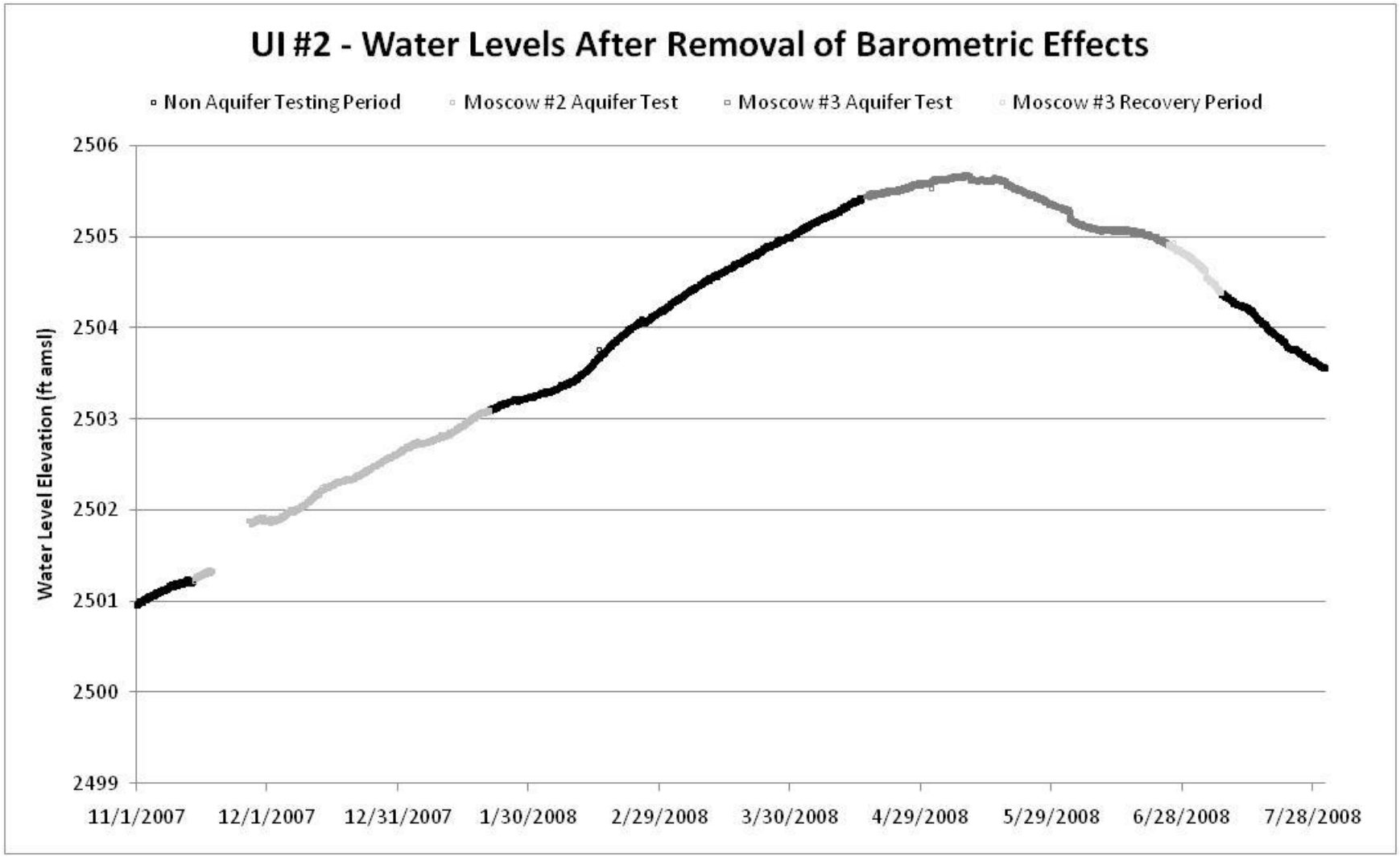


Figure C18. UI #2 water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

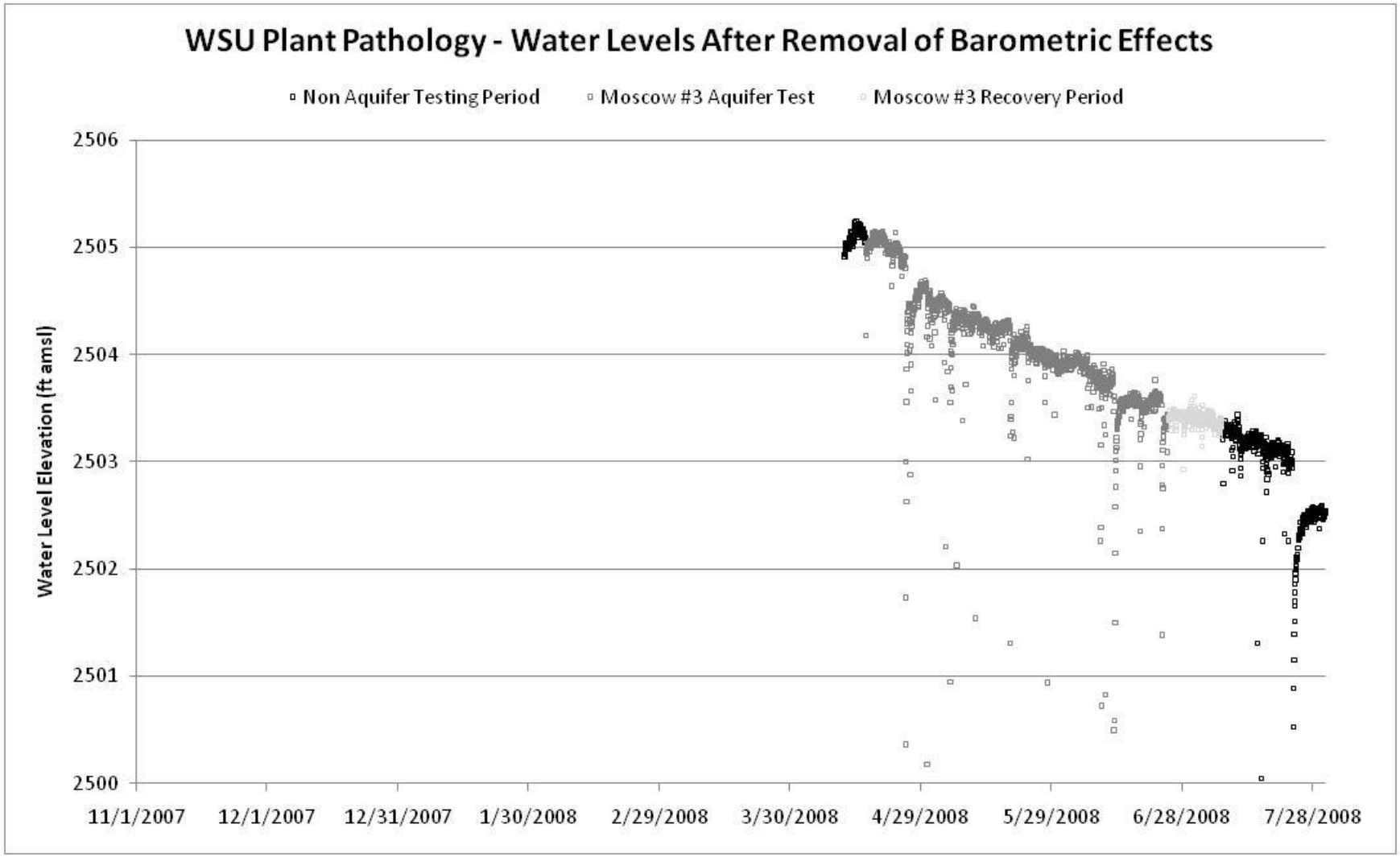


Figure C19. WSU Plant Pathology water level hydrograph for the period of the aquifer tests; barometric pressure effects were removed using BETCO©.

Appendix D

Descriptions of Analytical Aquifer Analysis Tools Used in AQTESOLV®

Description of Analytical Aquifer Analysis Tools Used in Aqtesolv®

The following discussion is taken directly from AQTESOLV® for Windows Version 4.5 User's Guide (Duffield, 2007) It encompasses theory, methods, and concepts designed to help identify the appropriate solution method for curve matching.

Theis (1935)/Hantush (1961) Solution for a Pumping Test in a Confined Aquifer

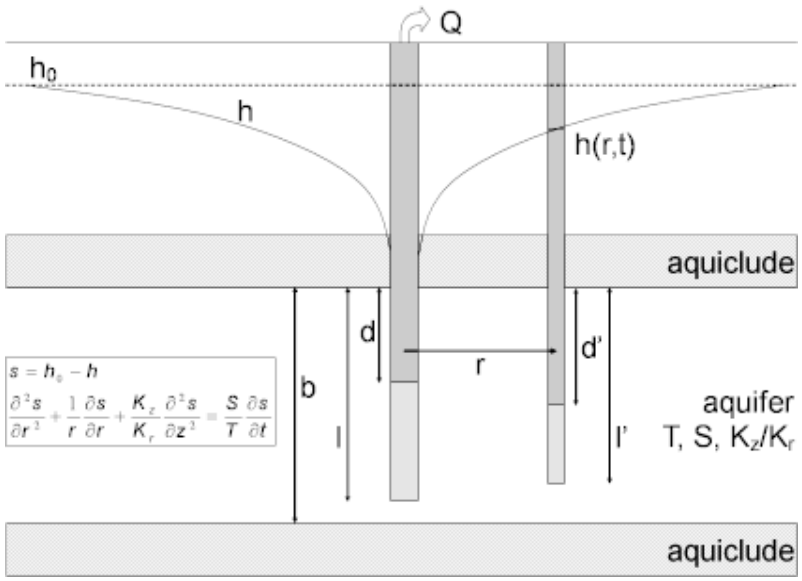
Theis (1935) derived a solution for unsteady flow to a fully penetrating well in a confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

Hantush (1961a, b) extended the Theis method to correct for partially penetrating wells. When you choose the Theis solution in AQTESOLV, you may analyze data for fully or partially penetrating wells.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Theis solution. AQTESOLV uses the principle of superposition to analyze both pumping and recovery data from constant - or variable-rate pumping tests.

You can use the Theis (1935) solution for residual drawdown to analyze a recovery test via a straight-line matching procedure. For a well performance test, you may choose the Theis (1935) solution for a step-drawdown test.

Illustration



Equations

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy$$

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

$$s_D = \frac{4\pi T}{Q}s$$

$$t_D = \frac{Tt}{r^2 S}$$

where:

- Q is pumping rate [L3/T]
- r is radial distance [L]
- s is drawdown [L]
- S is storativity [dimensionless]
- t is time [T]
- T is transmissivity [L2/T]

Hydrogeologists commonly refer to the exponential integral in the drawdown equation as the Theis well function, abbreviated as W(u). Therefore, we can write the Theis drawdown equation in compact notation as follows:

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

Hantush (1961a, b) derived equations for the effects of partial penetration in a confined aquifer. For a piezometer, the partial penetration correction is as follows:

$$s = \frac{Q}{4\pi T}\left(W(u) + \frac{2b}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{1}{n}\left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right] \cdot \cos\left(\frac{n\pi z}{b}\right) \cdot W\left(u, \sqrt{\frac{K_z}{K_r}}\frac{n\pi r}{b}\right)\right)$$

For an observation well, the following partial penetration correction applies:

$$s = \frac{Q}{4\pi T}\left(W(u) + \frac{2b^2}{\pi^2(l-d)(l'-d')} \sum_{n=1}^{\infty} \frac{1}{n^2}\left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right] \cdot \left[\sin\left(\frac{n\pi l'}{b}\right) - \sin\left(\frac{n\pi d'}{b}\right)\right] \cdot W\left(u, \sqrt{\frac{K_z}{K_r}}\frac{n\pi r}{b}\right)\right)$$

where:

- b is aquifer thickness [L]
- d is depth to top of pumping well screen [L]
- d' is depth to top of observation well screen [L]
- l is depth to bottom of pumping well screen [L]
- l' is depth to bottom of observation well screen [L]
- Kz/Kr is vertical to horizontal hydraulic conductivity anisotropy [dimensionless]
- W(u,r/B) is the Hantush-Jacob well function for leaky confined aquifers
- z is depth to piezometer opening [L]

At large distances, the effect of partial penetration becomes negligible when

$$r > 1.5\, b / \sqrt{K_z / K_r}$$

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- pumping well is fully or partially penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- partial penetration depths (optional)
- saturated thickness (for partially penetrating wells)
- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

Solution Options

- constant or variable pumping rate including recovery
- multiple pumping wells
- multiple observation wells
- partially penetrating wells
- boundaries

Estimated Parameters

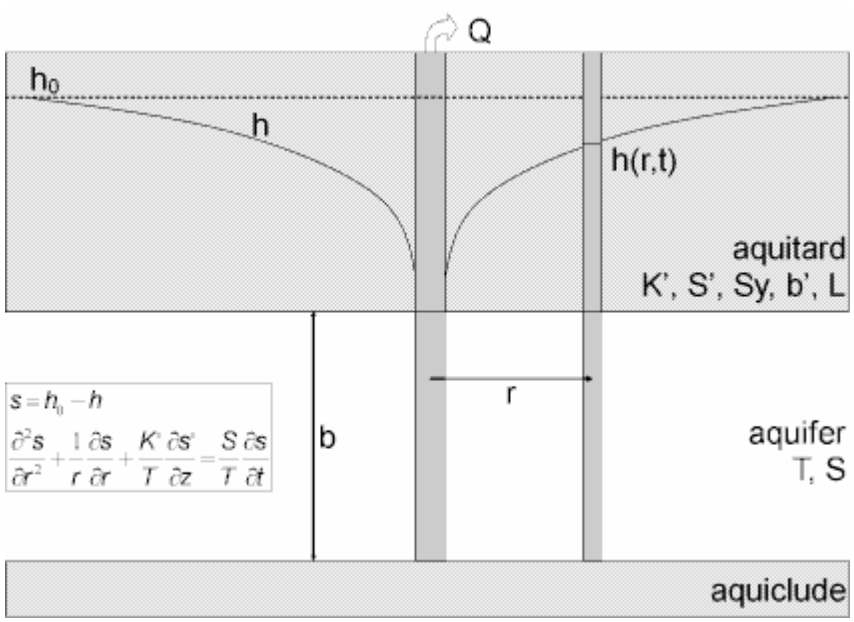
- T (transmissivity)
- S (storativity)
- Kz/Kr (hydraulic conductivity anisotropy ratio)
- b (saturated thickness)
- Partially penetrating wells are required to estimate Kz/Kr and b.

Cooley-Case (1973) Solution for a Pumping Test in a Confined Aquifer Overlain by a Water-Table Aquitard

Cooley and Case (1973) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer overlain by a water-table aquitard. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

The Cooley-Case solution can simulate variable-rate tests including recovery using the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Illustration



Equations

Cooley and Case (1973) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer overlain by a water-table aquitard. The Laplace transform solution is as follows:

$$\bar{s}_D = \frac{2K_0(x)}{p}$$

$$x = (p + \bar{q}_D)^{1/2}$$

$$\bar{q}_D = 4\sqrt{p}\beta \coth\left(\frac{4\sqrt{p}\beta}{(r/B)^2}\right) + \left[p\,\mathrm{sech}^2\left(\frac{4\sqrt{p}\beta}{(r/B)^2}\right)\right]\left[p\frac{L/b'}{(r/B)^2} + \frac{(r/B)^2}{16\beta^2}\frac{S'}{S_y} + \frac{\sqrt{p}}{4\beta}\tanh\left(\frac{4\sqrt{p}\beta}{(r/B)^2}\right)\right]^{-1}$$

$$B = \sqrt{\frac{T(b'+L)}{K'}}$$

$$\beta = \frac{r}{4}\sqrt{\frac{K'S'}{b'TS}}$$

$$t_D = \frac{Tt}{Sr^2}$$

$$s_D = \frac{4\pi T}{Q}s$$

Where:

- b' is thickness of the aquitard [L]
- K' is vertical hydraulic conductivity of the aquitard [L/T]
- K_i is modified Bessel function of second kind, order i
- L is height of capillary fringe [L]
- p is Laplace transform variable
- Q is pumping rate [L^3/T]
- r is radial distance [L]
- s is drawdown [L]
- S is storativity [dimensionless]
- S' is storativity of the aquitard [dimensionless]
- S_y is specific yield of the aquitard [dimensionless]
- t is time [T]
- T is transmissivity [L^2/T]

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is leaky confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- confining bed has infinite areal extent, uniform vertical hydraulic conductivity, storage coefficient, specific yield and thickness
- flow is vertical in the aquitard

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- constant or variable pumping rate including recovery
- multiple pumping wells
- multiple observation wells
- boundaries

Estimated Parameters

- T (transmissivity)
- S (storativity)
- r/B (leakage parameter)
- b (leakage parameter)
- S'/Sy (storage ratio in aquitard)
- L/b' (dimensionless height of capillary fringe)

The report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

Appendix E

Aquifer Test Pumping On/Off Times

Aquifer Test Pumping On/Off Times can be found in the DVD attached to the inside back cover of this thesis.

Appendix F

Aquifer Test Daily Pumping Volumes for Municipal Wells

Aquifer Test Daily Pumping Volumes for Municipal Wells can be found in the DVD attached to the inside back cover of this thesis.

Appendix G

Well completion information (well logs) for Wanapum aquifer system monitoring network wells.

```
:Last Modified - 6/24/01

SETUP:  0       -214    117.0383815108  46.7334124986   2557.57

LITH: appaloosa horse club
0       -29     soil^
-29     -42     fractured basalt
black^
-42     -55     basalt
hard^
-55     -214    basalt w/water
hard^
END-DATA:

WELL-COLUMN: appaloosa horse club Column
1       -55     8       0       surface casing
-55     -214    8       0       open
END-DATA:

END-LOG:
```

Figure G1. Appaloosa well information.

Form 238-7
6/89

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Steve Brandt

Address Moscow

Owner's Permit No. 87-90-N2

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Well diameter increase
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☑ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other _____ (specify type)

4. METHOD DRILLED

☑ Rotary ☑ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other _____

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other _____

Thickness	Diameter	From	To
.250 inches	8 inches +	1 feet	119 feet
inches	inches	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet

Was casing drive shoe used? ☑ Yes ☐ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch ☐ Gun
Size of perforation _____ inches by _____ inches

Number	From	To
perforations	feet	feet
perforations	feet	feet
perforations	feet	feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name _____
Type _____ Model No. _____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel _____
Placed from _____ feet to _____ feet
Surface seal depth 119 Material used in seal: ☐ Cement grout
☑ Bentonite ☐ Puddling clay ☐ _____
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing
☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☑ Welded ☐ Solvent Weld
☐ Cemented between strata
Describe access port _____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name _____
Lot No. _____ Block No. _____
County LaTah
SE ¼ SE ¼ Sec. 6, T. 39 N ☑ S ☐ R. 5 E ☐ W ☑

7. WATER LEVEL

Static water level 128 feet below land surface.
Flowing? ☐ Yes ☑ No G.P.M. flow _____
Artesian closed-in pressure _____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature _____ °F. Quality _____
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☑ Air ☐ Other _____

Discharge G.P.M.	Pumping Level	Hours Pumped
approx. 5		

9. LITHOLOGIC LOG

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	0	45	overburden, clay		✓
8	45	46	quartz + sand	✓	
8	46	115	clay		✓
8	115	153	basalt, firm	✓	

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NORTHERN REGION
I.D.W.R.

10.

Work started 4/11/90 finished 4/13/90

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name WITT Well Drilling Firm No. 58
Address 619 Powers Lew. Date 4/29/90
Signed by (Firm Official) Earl L. Witt
and
(Operator) Roger Witt

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure G2. Brandt well log.

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Form 2897 2 0 1995 POSTED
IDWR

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

Use Typewriter or Ball Point Pen

091413

1. DRILLING PERMIT NO. 87-90-N 2 -100
Other IDWR No.

2. OWNER:
Name Steve Brandt
Address
City Moscow State ID Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

N / W / E / S

Twp. 39 North ☑ or South ☐
Rge. 5 East ☐ or West ☑
Sec. 6 1/4 SE 1/4 SE 1/4
Gov't Lot ____ County LATAH

Address of Well Site
City
(Give at least name of road + Distance to Road or Landmark)

Lt. ____ Blk. ____ Sub. Name

4. PROPOSED USE:
☑ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other

5. TYPE OF WORK DEEPEN
☐ New Well ☑ Modify or Repair ☐ Replacement ☐ Abandonment

6. DRILL METHOD
☐ Mud Rotary ☑ Air Rotary ☐ Cable ☐ Other

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	

Was drive shoe used? ☐ Y ☐ N Shoe Depth(s)
Was drive shoe seal tested? Y☐ N☐ How?

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
					☐	☐	☐	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe Length of Tailpipe

9. PERFORATIONS/SCREENS
☐ Perforations Method
☐ Screens Screen Type

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
135 ft. below ground Artesian pressure ____ lb.
Depth flow encountered ____ ft. Describe access port or control devices:
SESE 6 39N 5W

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
approx. 15		275	30 min.

Water Temp. Bottom hole temp.
Water Quality test or comments:

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
8	154	279	basalt, firm	✓	

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Department of Water Resources
MICROFILMED
OCT 0 8 1996

Completed Depth 279' (Measurable)
Date: Started 8/10/94 Completed 8/11/94

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Witt Well Drilling Firm No. 58
Firm Official Earl L Witt Date 12/15/95
and
Supervisor or Operator Roger Witt Date 12/15/95
(Sign Once if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Figure G3. Brandt well log, continued.

Carson Well

Information as dictated by well owner Allan Carson.

0 – 55 feet below ground surface: overburden
55 – 120 feet below ground surface: basalt

The pump is located at approximately 90 feet below ground surface and the well is a gently flowing artesian well.

Figure G4. Carson well information (from Badon 2007).

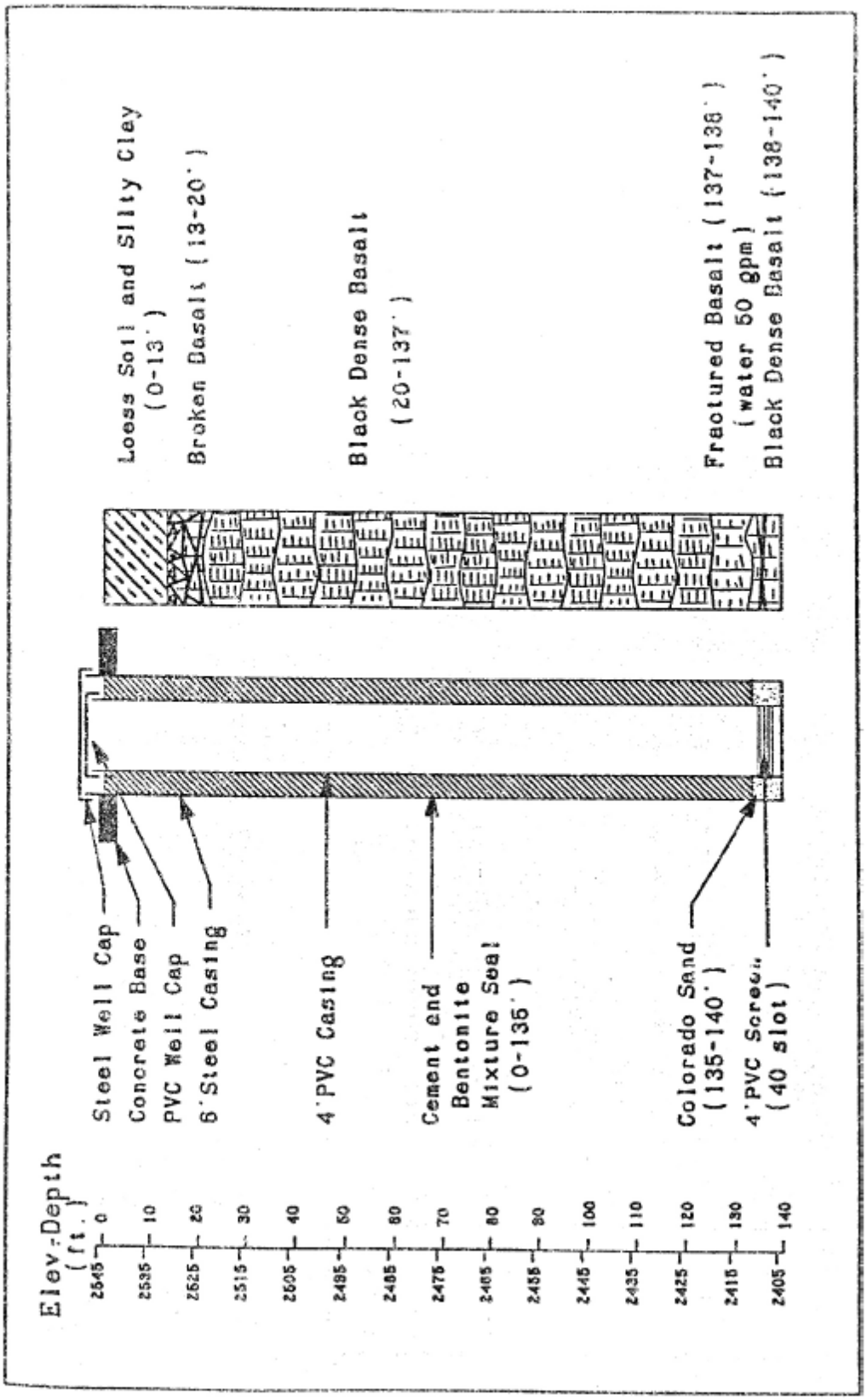

Figure G5. D19D well information.

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MAY 01 1995
NORTHERN REGION
IDWR

Form 238-7
7/94

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

Use Typewriter or Ball Point Pen

1. DRILLING PERMIT NO. 87-95-N-5-000
Other IDWR No.

2. OWNER:
Name Bill Elliott
Address 1676 Palmer
City Moscow State Id Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

N / W / E / S

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 29, NE 1/4 (10 acres) NE 1/4 (40 acres) ____ 1/4 (160 acres)
Gov't Lot ____ County Latah

Address of Well Site Pastime Rd
Moscow City Idaho
(Give at least name of road + Distance to Road or Landmark)

Lt. ____ Blk. ____ Sub. Name ____

4. PROPOSED USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ____

5. TYPE OF WORK
☒ New Well ☐ Modify or Repair ☐ Replacement ☐ Abandonment

6. DRILL METHOD
☐ Mud Rotary ☒ Air Rotary ☐ Cable ☐ Other ____

7. SEALING PROCEDURES

SEAL/FILTER PACK Material	From	To	AMOUNT Sacks or Pounds	METHOD
bentonite	0	80	200 lbs	

Was drive shoe used? ☒ Y ☐ N Shoe Depth(s) ____
Was drive shoe seal tested? Y ☐ N ☒ How? ____

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+2	239	200	Steel	☒	☐	☒	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe ____ Length of Tailpipe ____

9. PERFORATIONS/SCREENS
☐ Perforations Method ____
☐ Screens Screen Type ____

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
80 ft. below ground Artesian pressure ____ lb.
Depth flow encountered 238 ft. Describe access port or control devices: ____
NENE 29 40N 5W

11. WELL TESTS:
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
approx 20		220	30 min

Water Temp. ____ Bottom hole temp. ____
Water Quality test or comments: ____

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	80	overburden clay		✓
8	80	107	~~Quartz~~ clay		✓
8	107	112	Quartz		✓
8	112	127	clay		✓
8	127	134	Quartz		✓
8	134	237	clay		✓
8	237	238	Quartz	✓	

Completed Depth 238 (Measurable)
Date: Started 4/14/95 Completed 4/21/95

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name WITT Well Drilling Firm No. 58
Firm Official Earl L Witt Date 4/24/95
and
Supervisor or Operator Roger Witt Date 4/28/95
(Signature if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Figure G6. Elliott well log.

This well was constructed at the East Drilling Site to a total depth of 73 feet using an air rotary drilling rig. Twelve-inch diameter steel casing was driven to a depth of 73 feet and then removed as the permanent casing was installed. The well has 4-inch diameter PVC casing to a depth of 70 feet with 0.010-inch, factory slotted casing in the depth interval of 60 to 70 feet. A sand pack was installed around the casing in the depth interval of 57 to 70 feet with a bentonite seal from land surface to a depth of 57 feet. Eight-inch diameter surface casing was installed to a depth of about 10 feet and equipped with a locking cap. The reported yield by the driller was 5 to 8 gpm (gallons per minute). The reported depth to water was 35 feet below ground surface. The geologic log prepared by the well driller is provided below.

0 to 3 feet fill, coarse rock

3 to 13 feet dark brown soil

13 to 19 feet tan/brown soil, clay-like

19 to 23 feet yellow and tan clay-like with sands

23 to 34 feet broken basalt, medium

34 to 45 feet blue/tan clay

45 to 55 feet white and tan clay with sand

55 to 70 feet sand with clay and water

70 to 73 feet yellow/tan clay

Figure G7. Notes for IDWR 1 - Sediments of Bovill Well (Directly from Ralston, 2007).

This well was constructed at the West Drilling Site to a total depth of 282 feet using an air rotary rig. Eight-inch diameter temporary steel casing was driven to a depth of 63 feet and then removed as the permanent casing was installed. The well has 4-inch diameter PVC casing to a depth of 280 feet with 0.010-inch, factory slotted casing in the depth interval of 270 to 280 feet. A sand pack was installed around the casing in the depth interval of 265 to 280 feet with a bentonite seal from land surface to a depth of 265 feet. Eight-inch diameter surface casing was installed to a depth of about 10 feet and equipped with a locking cap. The reported yield by the driller was 50 gpm. The reported depth to water was 170 feet below ground surface. The geologic log prepared by the well driller is provided below.

0 to 3 feet gravel fill

3 to 18 feet brown clayish soil

18 to 43 feet yellow clayish soil

43 to 58 feet soft brown basalt with rounds

58 to 110 feet hard basalt

110 to 116 feet basalt with water, 5 gpm

116 to 245 feet hard basalt

245 to 248 feet basalt with rounds

248 to 277 feet hard basalt

277 to 282 feet sand and clay, water

Figure G8. Notes for IDWR 2 - Wanapum Basalt Well (Directly from Ralston, 2007).

This well was constructed at the West Drilling Site to a total depth of 355 feet using an air rotary rig. Twelve-inch diameter temporary steel casing was installed and driven to a depth of 60 feet. A 12-inch diameter open hole was drilled through the basalt and then 8-inch diameter temporary steel casing was advanced to a depth of 345 feet. Both sections of temporary casing were removed as the permanent casing was installed. The well has 4-inch diameter PVC casing to a depth of 350 feet with 0.010-inch, factory slotted casing in the depth interval of 345 to 355 feet. A sand pack was installed around the casing in the depth interval of 340 to 355 feet. The product "Hole Plug" was installed from land surface to a depth of 340 feet. Eight-inch diameter surface casing was installed to a depth of about 10 feet and equipped with a locking cap. The reported yield by the driller was 50+ gpm. The reported depth to water was 140 feet below ground surface. The geologic log prepared by the well driller is provided below.

0 to 2 feet fill rock

2 to 10 feet brown top soil

10 to 19 feet loamy-tan clay

19 to 23 feet yellowish-tan clay with sand

23 to 43 feet broken basalt

43 to 50 feet whitish tan clay

50 to 58 feet honey basalt

58 to 61 feet light grey soft basalt

61 to 110 feet hard basalt

110 to 116 feet basalt with water, 5 gpm

116 to 245 feet hard basalt

245 to 249 feet broken basalt with rounds

249 to 280 feet hard basalt

280 to 301 feet sand, lots of water

301 to 304 feet hard grey clay

304 to 345 feet sand with clay seams and wood

345 to 348 feet hard clay with basalt

348 to 355 feet sand with water

Figure G9. Notes for IDWR 3 - Vantage Member Well (Directly from Ralston, 2007).

DRILL CUTTINGS LOG

INEL PACKER TEST WELL

MOSCOW, IDAHO

DEPTH (FT)	**DESCRIPTION** (logged 4/1/92 by JDK)
0 - 7	No cuttings, soil and silt
7 - 14	No cuttings, orange-brown and gray clay
14 - 16	Coarse, poorly-sorted granitic and basalt sand with some granitic pebbles
16 - 20	Coarse sand and broken vesicular basalt fragments up to 2 inches; sand may be contamination from above
20 - 55	Dark gray to black basalt, some localized cavity filling, pale amber to pale greenish alteration (?) (or possibly palagonite); green clay filling along fractures @ 52'
55 - 65	Medium gray basalt with considerable alteration; scattered light tan weathered basalt and possibly baked sediments; approximately 5 gpm water
65 - 70	Dark gray basalt with black glassy patches; pale greenish cavity filling
70 - 75	Dark gray basalt with light tan coatings along fractures (possibly siderite or opalized material)
75 - 80	Dark gray basalt with orange and rust oxidation coatings along fractures and cavities
80 - 90	Black, dense basalt with sparse cavity filling; some pale greenish to amber phenocryst (probably pyroxenes)
90 - 100	Black, glassy basalt with angular olive-brown cavity filling
100 - 105	Medium gray to dark gray basalt; one large plag lath noted about 0.2" long; considerable alteration
105 - 125	Dark gray to black, dense basalt, less alteration

Figure G10. INEL well information.

125 - 145	Medium gray to dark gray basalt, minor opal or siderite along fractures, moderate alteration around cavities with some oxidation
145 - 155	Medium gray basalt, more alteration, oxidation along some fractures; irregular thin black glassy crystals(?) throughout
155 - 170	Dark gray basalt, more dense, less alteration
170 - 180	Medium gray basalt, slightly more alteration
180 - 200	Medium gray basalt, altered; abundant irregular black specks; thin greenish-gray coating on some surfaces
200 - 202	Dark gray, dense basalt, scattered vesicles with filling
202 - 205 T.D.	Gray, well-sorted arkose consisting of subangular to subrounded clear quartz, white feldspar, black basalt and minor muscovite

The entire basalt sequence is diktytaxitic with variable amounts of alteration(?) or coatings around the diktytaxitic openings giving the cuttings a mottled appearance under the hand lens. The term "alteration" does not imply hydrothermal or deuteric alteration, but is used ~~and~~ descriptively for the soft pale greenish and amber material around the diktytaxitic cavities. Dense portions of the basalt have a felted texture. Judging from the stratigraphic position of the basalt, it is likely a flow of the Priest Rapids Member of the Wanapum Basalt sequence. Although possible sediment fragments were seen at 55 - 65', no flow top material or other indication of a flow top or flow-to-flow contact was apparent. Identification of the sediment fragments is therefore questionable.

Figure G11. INEL well information continued.

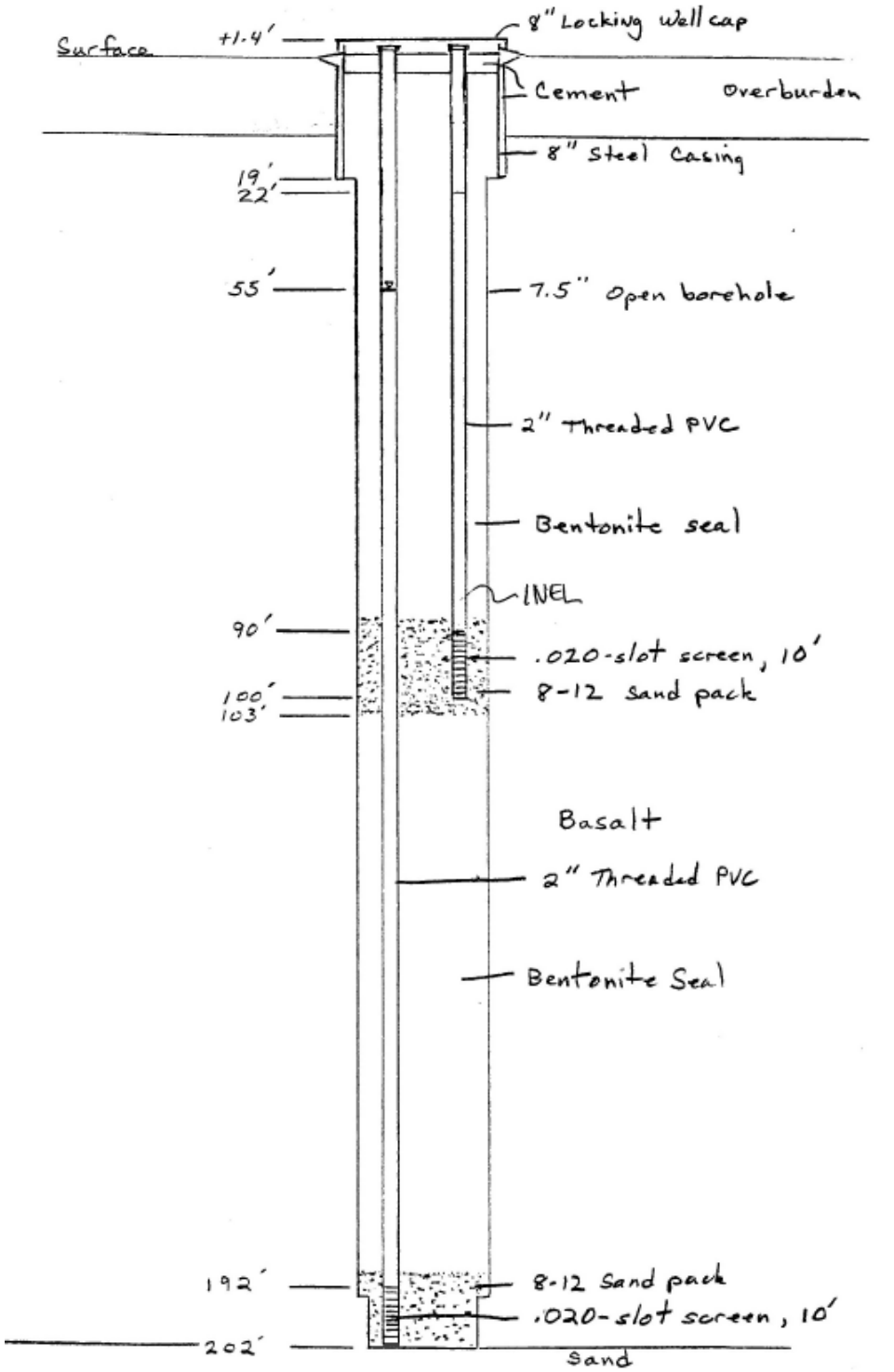
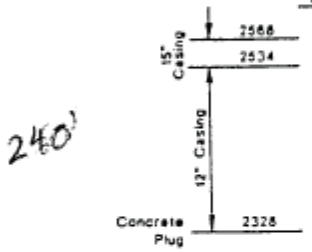


Figure G12. INEL well information continued.

CITY OF MOSCOW

WELL NO. 2

A ST. AND JACKSON ST.



ELEVATION	MATERIAL
2568	
2532	Soil
2496	Basalt
2491	Gravel
2409	Basalt, vesiculsar at top
2344	Basalt, very dense at base
2328	Blue-Gray Clay or Shale
2314	Blue-Gray Clay or Shale
2295	Gray Granite Sand
2289	Blue Gray Sandy Shale
2263	Gray Sand, 3/8" Pebbles at 280ft.
2256	Cemented Sand
2254	Blue-Green Micaceous Shale
2243	Black-Brown Soil
2213	Brown Clay-Soil at top, many small Pebbles at base
2173	Blue-Gray Micaceous Shale
2124	Brown Sandy Shale
2106	Sand Cemented by Pyrite and Silica
2068	Light Brown Shale
2043	Blue-Gray Non-Micaceous Shale and Sand
2015	Chocolate-Brown Shale
2008	Quartzite

Figure G13. Moscow #2 well information.

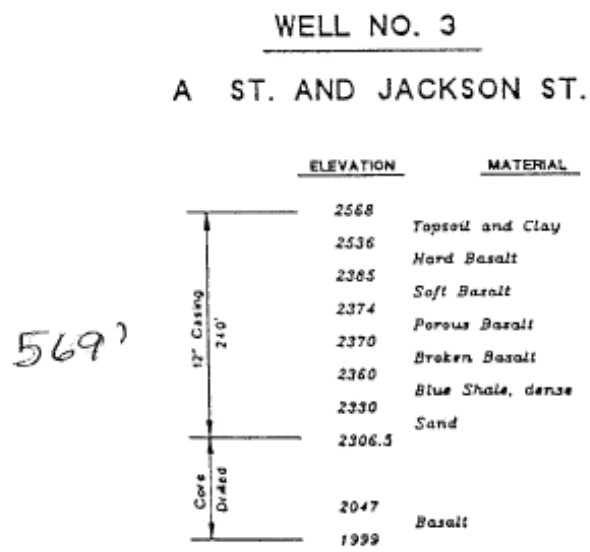


Figure G14. Moscow #3 well information.

To

RECEIVED OCT 18 1983

Well Log City Of Moscow
IRRIG. WELL @ N.E. MOSCOW PARK

Uhlenkott Well Drilling
Fenn, Idaho 83531
Phone (208) 962-3209
Pumps - Sales - Service

REGARDING: **DATE:** Oct. 16, 1983

0 - 7 Overburden (Dirt)
7 - 19 Brown Clay
19 - 26 Sand
26 - 45 Clay and Sand Mix
45 - 75 Decomposed Granite and some clay
75 - 135 Med. soft grey type Besalt
135 - 145 Grey Sand with some water
145 - 243 Med hard grey Besalt
243 - 248 Brown seams in grey Besalt
248 - 287 Grey Besalt (hard)
287 -294 Seams in Grey Besalt were brown to Tan with some Water
294 - 311 Grey Hard Besalt
311 - 329 Softer Med. Grey Besalt (Granite type rock) More water 20 - 25 GPM
329 - 344 Brown Sand Water Bearing (600 - 1000 GPM)

By William Uhlenkott
William Uhlenkott

Figure G15. Mountain View Park well information.

CITY OF MOSCOW

SUNSET MEMORIAL
GARDENS WELL
(CEMETERY WELL)

MOUNTAINVIEW ROAD AT MERCER ST.

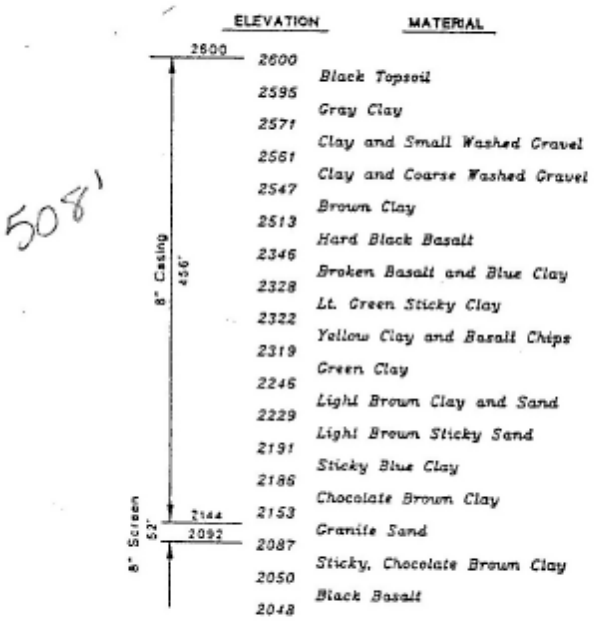


Figure G16. Old Cemetery well information.

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Form 11/97 OCT 30 2001

IDWR/North

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Office Use Only
Inspected by _____
Twp ____ Rge ____ Sec ____
____ 1/4 ____ 1/4 ____ 1/4
Lat: Long:

1. WELL TAG NO. D 0017523
DRILLING PERMIT NO.
Other IDWR No. 270704

2. OWNER:
Name Kenneth L Mable
Address P.O. Box 191
City Lander Wy State Zip 82520

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp. 39 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 5 SW 1/4 SE 1/4 ____ 1/4
Gov't Lot ____ County Latah
Lat: Long:
Address of Well Site 1040 Rodeo
City Moscow
Dawn
(Give at least name of road + distance to road or crossroad)

Lt. ____ Blk. ____ Sub. Name ____

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ____

5. TYPE OF WORK check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other ____

6. DRILL METHOD
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other ____

7. SEALING PROCEDURES

SEAL/FILTER PACK Material	From	To	AMOUNT Sacks or Pounds	METHOD
Bentonite	0	58	145 sks	Dry Pour

Was drive shoe used? ☒ ☐ N Shoe Depth(s) 58'
Was drive shoe seal tested? ☒ Y ☐ N How? AIR

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+2	58	125	Steel	☒	☐	☐	☐
6"	-5	165		PVC	☐	☒	☐	☐
					☐	☐	☐	☐

Length of Headpipe ____ Length of Tailpipe ____

9. PERFORATIONS/SCREENS
~~Perforations~~ Method Slot Saw
Screens Screen Type ____

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
145	165	1/8	40	6"	PVC	☐	☒
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
55' ft. below ground Artesian pressure ____ lb.
Depth flow encountered 130 ft. Describe access port or control devices: Re Mable Well Cap

39N 5W 5

11. WELL TESTS:
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal/min	Drawdown	Pumping Level	Time
100+		160	1hr

Water Temp. 50° Bottom hole temp. ____
Water Quality test or comments: clear
Depth first Water Encounter 130

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	2	Soil		☐
10"	2	55	Clay		☒
8	55'	70	Granite		☒
8	70	75	Sandy Clay		☐
8	75	90	Basalt		☒
8	90	110	Lava		☒
8	110	165	Basalt	☒	

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[illegible]

Completed Depth 165 (Measurable)
Date: Started 8-22 Completed 8-24

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Company Name Pacific Well Drilling Firm No. 103
Firm Official [signature] Date 8-26
and
Driller or Operator ____ Date ____
(Signature if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Figure G17. PCEI well log.

Form 238-7
9/82

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Ken Piel

Address Moscow

Owner's Permit No. 87-88-N-10

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☑ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other _____ (specify type)

4. METHOD DRILLED

☑ Rotary ☑ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other _____

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other _____

Thickness	Diameter	From	To
.164 inches	8 inches +	1 feet	20 feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet
____ inches	____ inches	____ feet	____ feet

Was casing drive shoe used? ☐ Yes ☑ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number	From	To
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet
____ perforations	____ feet	____ feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name _____
Type _____ Model No. _____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel _____
Placed from ____ feet to ____ feet
Surface seal depth 20 Material used in seal: ☐ Cement grout ☑ Bentonite ☐ Puddling clay ☐ _____
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☑ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port _____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N / W / E / S

Subdivision Name Nearing 2nd Edition

Lot No. 16 Block No. _____

County LaTah

____ ¼ ____ ¼ Sec. 17, T. 40 N. R. 5 W.

7. WATER LEVEL

Static water level 20 feet below land surface.
Flowing? ☐ Yes ☑ No G.P.M. flow _____
Artesian closed-in pressure _____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality _____
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☑ Air ☐ Other _____

Discharge G.P.M.	Pumping Level	Hours Pumped
approx. 4		

9. LITHOLOGIC LOG

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
12	0	6	soil overburden		✓
12	6	17	granite, soft		✓
12	17	20	granite, firm		✓
8	20	70	granite, firm		✓
8	70	73	granite, fract. 1½	✓	
8	73	90	" firm 1	✓	
8	90	91	" fract. 2	✓	
8	91	109	firm		✓

10. Work started 6/13/88 finished 6/14/88

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Earl Witt Well Drilling No. 58
Address 619 Rewers Lewiston Date 7/5/88
Signed by (Firm Official) Earl L. Witt
and
(Operator) Roger Witt

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Figure G18. Shumway well log.

Form 238-7
7/94

RECEIVED
MAY 15 1995
NORTHERN REGION
IDWR

1-12-96 dt

DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

Use Typewrite or Ball Point Pen

1. DRILLING PERMIT No. 87 95-N-18 -600
Other IDWR No.

2. OWNER:
Name Richard Tuck
Address 1055 W. Purcell Rd
City Mount Id State Id Zip 83543

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

N / W / E / S

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 33 NE 1/4 NE 1/4 ___ 1/4
Gov't Lot ___ County Lewis

Address of Well Site Same
(Give at least name of road + Distance to Road or Landmark) City

Lt. ___ Blk. ___ Sub. Name ___

4. PROPOSED USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other

5. TYPE OF WORK
☒ New Well ☐ Modify or Repair ☐ Replacement ☐ Abandonment

6. DRILL METHOD
☐ Mud Rotary ☐ Air Rotary ☒ Cable ☐ Other

7. SEALING PROCEDURES

SEAL/FILTER PACK Material	From	To	AMOUNT Sacks or Pounds	METHOD
Bent	0	80	400 lbs	Slurry

Was drive shoe used? ☒ Y ☐ N Shoe Depth(s) 192'
Was drive shoe seal tested? Y☐ N☐ How?

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
[illegible]	[illegible]	[illegible]	[illegible]	Steel	☐	☐	☒	☐
8"	+2	170	264	Steel	☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe ___ Length of Tailpipe ___

9. PERFORATIONS/SCREENS
☐ Perforations Method
☐ Screens Screen Type

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
80 ft. below ground Artesian pressure ___ lb.
Depth flow encountered ___ ft. Describe access port or

11. WELL TESTS:
☒ Pump ☐ Bailer ☐ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
35+	0	80'	4 hr

Water Temp. ___ Bottom hole temp. ___
Water Quality test or comments:

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Y
10	0	20	Top Soil & Clay	X
8	20	35	Sand & Clay	X
11	35	105	Shale	X
11	105	125	Rock & Clay	X
11	125	132	Dark Clay Combo	X
11	132	155	Basalt Hard	
11	155	160	Basalt Porous	X

Completed Depth 160' (Measural
Date: Started April 1-'95 Completed April 1

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied w
the time the rig was removed.

Firm Name Will Well Drilling Firm No. 5
Firm Official Earl Elliott Date Apr. 10
and

Figure G19. Tuck/Burns well log.

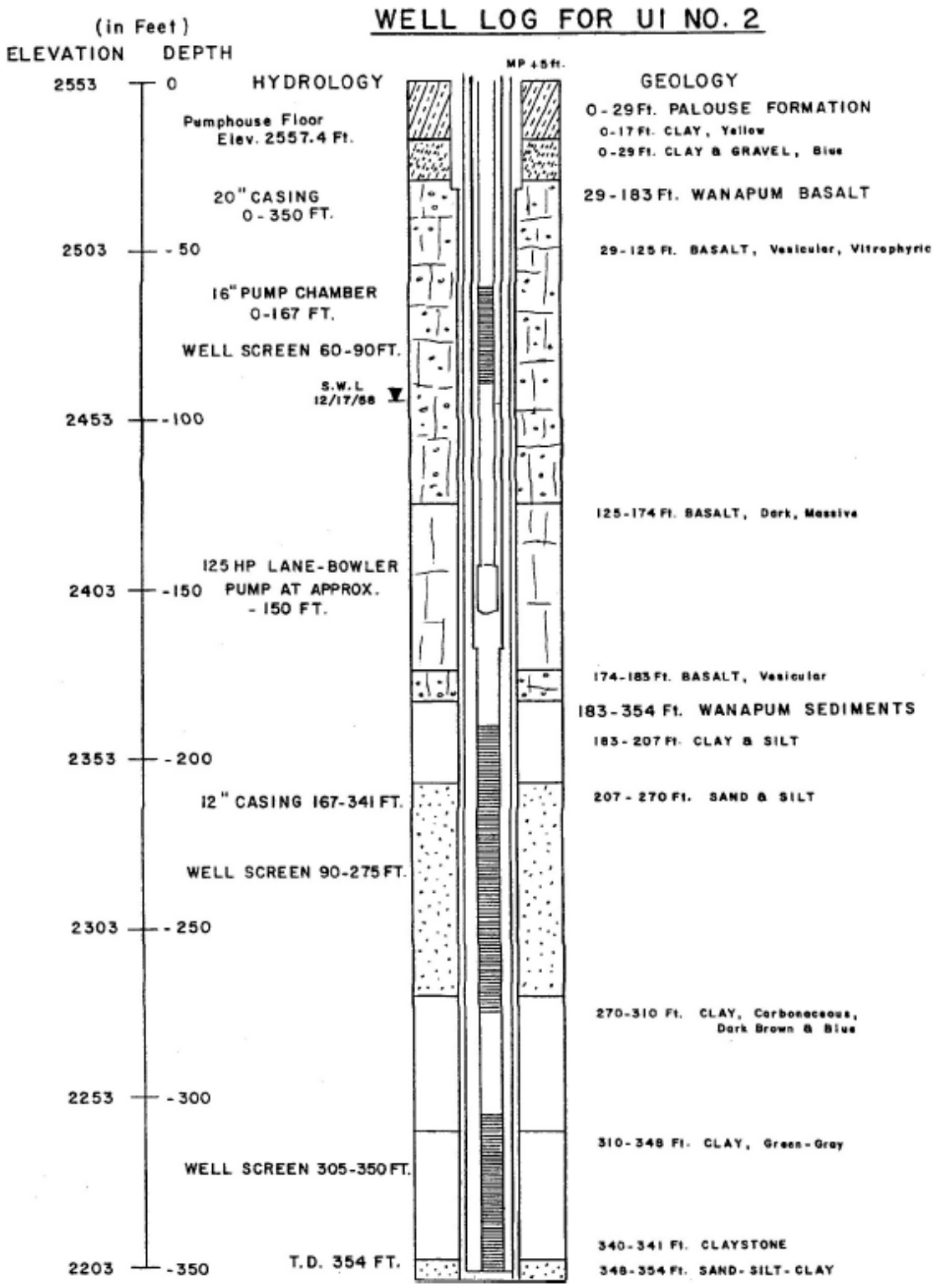

Figure G20. UI #2 well information.