Analysis of the Hydrogeological Conditions and the Effects of Development on the Hydraulic Head at Redmond Ridge East

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Executive Summary

Redmond Ridge East (RRE) is a large-scale master plan community in East King County, WA. In this report, I evaluate the spatial variability of the Quaternary Advance Outwash (Qva) at RRE and the time-series data for 16 water wells with the intent to better understand groundwater below the RRE area. I investigate changes between pre- and post-development conditions through the determination of temporal changes in annual water level, annual water level fluctuations, hydraulic head response to precipitation, and ambient drainage of the aquifer. I also perform a basic analysis of the annual aquifer recharge and a determination for the storage through the implementation of the water table fluctuation (WTF) method. Associated Earth Sciences (AESI) was tasked with monitoring the geological and environmental impacts during the development of RRE and collected the data I use in this report. AESI involvement in monitoring began in 1998 and extends to the present.

Sixteen wells were identified in the RRE area with adequate temporal data to conduct the analysis. A comparison of the well logs and aquifer testing data allowed local variations in the Qva to be mapped. The WTF was used to determine a range of reasonable specific yield values for locations where the Qva was unconfined. Yearly average of the seasonal water level high and lows, and the fluctuations were quantified. Temporal relationships were established through linear regression. The average water level was found to be increasing in some locations, and the corresponding fluctuations were found to decrease. However, no clear change between pre- and post-development was observed. The response of hydraulic head to precipitation was investigated through an analysis of hydrographs for ten wells. Periods of consistent response and the corresponding precipitation during each period were delineated. A linear relationship between precipitation and water level change was determined. The threshold precipitation under which there is a positive response in the hydraulic head was established. No observable changes were apparent between pre- and post-development conditions. The ambient drainage for the Qva was calculated using recessional periods on the hydrograph.

The transmissivity of Qva varies with thickness of the overlying lodgment till and thickness of the Qva, itself. Water level fluctuations observed in the Qva are consistent with regional observations. Localized areas in the Qva display the large 10 foot fluctuations and these anomalies are likely due to a combination of the local variability in the storativity as well as the concentration and channeling of water due to geographical variations in the Qva and the overlying topography. All trends seen in the RRE area remained relatively constant through time. There was no evidence showing an effect of development on the hydraulic head at RRE. This implies that the style and distribution of infiltration has not changed as a result of development, and that any measures in place are properly mitigating the effects of development on the RRE region.

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1.0 Introduction

The Seattle metropolitan area is one of the fastest growing areas in the United States and is expected to reach 4 million people by 2017 (Inghram and Naito, 2016). With population growth comes the urban development needed to sustain it. One area that has recently undergone extensive development is the Novelty Hill region of Redmond Ridge (Figure 1). Prior to planned development of an area, analysis and monitoring of the area are performed in order to assess the environmental impact of development. AESI prepared the Environmental Impact Statement (EIS) for development of the Redmond Ridge East (RRE) area, and will hereafter be referred to as "RRE EIS". A development on the scale of RRE can have a dramatic effect on the local environment. Removal of vegetation and creation of impermeable surfaces can greatly alter the regional characteristics of the hydraulic head, including an increase in runoff and a decrease in infiltration (Bent, 2001; Harbor, 1994). These changes are mitigated through the implementation of retention ponds and infiltration structures (King County, 2016).

In preparing their EIS, AESI placed a large emphasis on quantifying the hydrogeological characteristics of the area and groundwater monitoring, specifically through the implementation of monitoring wells. The main unit of focus was the Vashon Advance Outwash (Qva) aquifer.

AESI possesses decades of groundwater-level measurements and data spanning from before construction to the present. These data present a unique opportunity, undertaken in this report, to analyze groundwater conditions extending from before to after development. Given the magnitude of construction in the area, I expected to see a change in groundwater behavior due to the redistribution and concentration of precipitation at infiltration facilities. This signal might be quantified and in doing so both the effectiveness and the response of the mitigation efforts can be assessed. I hypothesized that there would be an increase in response near these infiltration facilities, and a decrease distal to these facilities, following construction.

1.1 Purpose and Scope

The purpose of this project is to investigate groundwater conditions in the RRE development area, and to assess whether any changes in the groundwater response can be associated with development.

Temporal data are organized into pre-development, post-development, and all time groups. This analysis provides insight into the effects of development and helps in the quantification of the overall aquifer characteristics of RRE. The emphasis for this paper is to quantify the spatial variabilities within the Qva in RRE, and to quantify the temporal changes in the hydraulic head. The spatial characteristics I will address include the thickness of the Qva and Qvt, the hydraulic conductivity, and the storativity in the Qva aquifer. The temporal relationships I will address include changes in the annual water level, changes in annual water level fluctuations, the hydraulic heads response to precipitation, and ambient drainage in the Qva aquifer. The report includes a site map, a surface contour map, a cross-section representative of the groundwater flow and aquifer variability in the region, pump and slug test analyses, summaries of the data used in the different analyses, and descriptions of the aforementioned relationships.

2.0 Background

2.1 Project Location

The RRE area is located on the Bear Creek Plateau in the Puget Lowlands, approximately 2 miles east of Redmond, WA, in east King County (Figure 1). It is located within sections 2 and 3 of T25N R6E and section 34 of T26N R6E (RRE EIS). In 1998 the Redmond Ridge area began extensive residential development including three master plan communities (Redmond Ridge, Redmond Ridge East and Trilogy), the Trilogy Golf Course, and a strip mall. RRE is bound to the west by the Bear Creek valley and to the east by the Snoqualmie River valley. A drainage divide bisects the project area. The southwestern portion of the area drains the Bear Creek drainage basin and the northeastern portion drains into the Snoqualmie Drainage basin (Figure 2) (RRE EIS).

2.2 Geologic and Topographic Setting

The Puget Lowland is a physiographic province that lies between the Cascade and Olympic mountain ranges and was influenced by multiple periods of glaciation, the most recent being the Fraser Glaciation (Lasmanis, 1991). The uppermost geological units in the study area were deposited during the last advance and retreat of the Puget Lobe of the Cordilleran Ice Sheet. The Vashon Stade of the Fraser glaciation represents the maximum advance of the Cordilleran Ice Sheet approximately 14,900 years before present (ybp) (Porter and Swanson, 1998). Retreat of the Vashon Ice Sheet was complete by approximately 13,600 ybp (Porter and Swanson, 1998).

The geologic units observed in exploration borings from RRE are the Pepper Creek Diamict (Qpd), Olympia Non-glacial Deposits (Qo), Vashon Advance Outwash (Qva), and Vashon Till (Qvt). The Qpd is a glaciolacustrine deposit that pre-dates the Qo and is tentatively correlated with the Possession Drift (RRE EIS). All borings in the study area extending deeper than the Qva include Qpd. The Qo was observed in several wells and represents a break between glaciations. The Qva and Qvt are the deposits of interest with regards to groundwater at RRE. The thickness of the Qva at RRE ranges from 160 feet to non-existent, with thickness determined using core logs and well drilling. The Qva is overlain by a layer of Qvt that ranges in thickness from less than 5 feet to 73 feet, although thickness in the study area generally ranges between 10 and 25 feet (RRE EIS).

The aquifer unit used in this study is the Qva, an expansive upper aquifer unit and the principal aquifer that underlies the Novelty Hill area (RRE EIS). Within the study area, the Qva is a moist to saturated, dense, sand unit with variable amounts of gravel and fines (RRE EIS). Qva deposits were consolidated into a dense condition as a result of the overburden load from the Vashon Glacier. Hydraulic conductivity and storativity for the Qva around the region vary by several orders of magnitude and greatly affect the aquifer's response to precipitation, recharge, and flow properties (Vaccaro et al., 1998).

AESI interprets the Qva is to pinch out along boundaries within the project area (Figure 2). Groundwater flow is confined to areas between these boundaries. Using elevation heads collected from monitoring wells, AESI has established groundwater flow divides for the area that further constrain groundwater flow (RRE EIS).

The Redmond Ridge area is located on a topographic high, and elevations range from approximately 660 feet above mean sea level (fmsl) in the southeast corner to 440 fmsl along the top of the Snoqualmie River valley wall. The topography of RRE is characterized by gently rolling hills, which restrict channel drainage to the swales between the hills (RRE EIS). Prior to development, the area was densely vegetated with coniferous trees and had negligible pasture land or impervious surfaces.

2.3 Previous Studies

AESI conducted extensive field exploration activities in both the preparation and development stages of the RRE area. These studies included: reconnaissance and mapping of geologic and hydrologic conditions for the site; excavation and sampling of 103 exploration pits; drilling of 56 monitoring wells and exploration borings; stream reconnaissance; infiltration testing; aquifer testing; groundwater level monitoring; groundwater quality sampling; and implementation of a groundwater infiltration pond (RRE EIS). AESI has continued recording water levels in their monitoring wells, and data exists from 1996 to the present. Continual monitoring efforts include both monthly hand readings for active wells and continuous time series water level data from transducers and data loggers. Using the exploration borings, AESI has produced several cross-sections that provide insight to the local dimensions and local variability within the Qva aquifer. Pump and slug testing provide insight into local aquifer properties such as hydraulic conductivity, transmissivity, storativity and specific yield. Cross sections and select aquifer testing values are reported in AESI's EIS documents for RRE. The remaining aquifer testing values are stored in AESI project archives.

2.4 Observation Well Data

Of the 56 monitoring wells at RRE, I chose 9 wells along a transect of the area for this study (Figure 3) (here after the "Transect Wells"). These wells are: G-2, OBW-16, OBW-18, OBW-19, OBW-20, OBW-22, OBW-24, OBW-29, and OBW-35. These wells run along an inferred groundwater flow line and have the most complete continuous water level data spanning the longest time (Table 1).

Pre- and post-development conditions were established on the basis of field reports and aerial photography. The distinguishing factor quantifying "developed" conditions was the removal of tree cover either directly on or adjacent to areas where observations wells exist. Changes for developed conditions include marked increases in paved roads, houses, and fields. Development of the area began in 2007, but the majority of construction did not occur until 2009. Thus, September 2009 is arbitrarily used to delineate the transition since this is also a bounding month of the water year. In order to compare the hydrologic setting before and after development, it was imperative that the majority of the wells chosen contained data with multiple water years before and after September 2009.

I chose an additional 6 wells in order to better understand the overall groundwater conditions of the RRE site. These wells are OBW-1R, OBW-4R, OBW-11, OBW-12, OBW-32 and 32R, and OBW-34 (Supplemental Wells) (Figure 3). Data from these wells help increase the robustness of the overall analysis. Similar to the transect wells, these wells have long spans of monitoring data (Table 2). The development transition for wells OBW-12, OBW-32 and 32R, and OBW-34 was also September 2009, However, the region near OBW-11 experienced earlier development (September 2004). OBW-1R and OBW-4R are in undeveloped areas that are still densely forested.

2.5 Data Sources

Well boring logs, water level data, and pump test data came from a review of project archives at AESI, Results were primarily stored in the form of Microsoft Excel spreadsheets. Precipitation records are available through the King County Hydrology Resources web page: (http://green2.kingcounty.gov/hydrology/gaugemap.aspx). These gauges and the time interval of records are 18u (1/1/1995 to 1/7/1999), 18v (1/8/1999 to 11/18/2004), the Redmond Ridge UPD Weather Station (RRUPD) (11/19/2004 to 10/17/2005), the Trilogy Golf Course Met Station (Trilogy Met) (10/18/2005 to 2/26/2010), and 18v2 (2/27/2010 to the present). LiDAR images for the area are from the Puget Sound LiDAR Consortium (http://pugetsoundlidar.ess.washington.edu/lidardata/restricted/projects/2014cedarriver.html). The LiDAR data was recorded at 6 foot resolution taken as part of the Cedar River Delivery 2 flight.

3.0 General Hydrogeological Conditions

3.1 GIS

All GIS analysis used ArcGIS with a 15-foot elevation contour layer and a hillshade of the project area based on the LiDAR data. The well locations were imported into Transect and Supplemental Well layers. Well logs and pump tests (in tables created by AESI), were added to the Transect and Supplemental Well layers. The Absence of Qva layer, Elevation Head Lines layer, and Potential Groundwater Flow Divide layers were digitization of an AESI map (RRE EIS). All information used in this project is further described in Appendix 1.

Location maps included a Washington State base map, King County base map, major King County cities and roads, and a hillshade. The Transect Wells layer delineated the topographic profile for the cross-section. All additional figures used a base map of the project area hillshade, and Absence of Qva layer. I added the digitized AESI data to the base map to create a figure showing hydraulic head flow and the Bear Creek and Snoqualmie river Valley Drainages. I added the Transect and Supplemental well layers to the base map to create a well location map. I created additional figures showing the spatial distributions of average water level fluctuations and drainage values were created through the alteration of labeling for the well location map. I created a contour map using the base map and the 15 foot contour layer.

3.2 Cross Section

3.2.1 Methods

I constructed a topographic profile, running through the transect wells, in ArcMap and used it as the surface of the cross section (Figure 3). I drew the transect wells along the topographic profile in their respected locations. These wells and their geological boundaries are presented in Appendix 2 (Well Table). I drew contacts and interpreted boundaries between wells. This cross section corresponds to a similar cross section F-F' which was produced for the RRE EIS prior to the 2007 development.

In addition to the geological contacts, I drew average high and low water levels onto the cross section. This was done for the purpose of showing locations in the aquifer that displayed confined, unconfined, or seasonally confined conditions. These water levels were taken from monthly hand measurements collected from 2002 through the present.

3.2.2 Results

The cross section (Appendix 2) shows the spatial variability in thickness of the Qva. The Qvt in the transect wells ranges in thickness from 10 to 54.5 feet with an average thickness 17 feet. The Qva for the transect wells ranges in thickness from 11 to 127 feet with an average thickness of 47.7 feet. Small lenses of Qo are seen throughout the RRE area with Qo increasing in prominence northwards. In all wells whose depths extended through the Qva, the bottom most observed layer is Qpd. These thicknesses are representative of the range of values for the RRE area.

The Qva in the RRE area transitions between unconfined (UC), seasonally confined (SC), and confined (C). The cross section illustrates locations where the status of the aquifer changes both spatially and annually. The Qva is predominantly unconfined, but during yearly water level highs the aquifer often becomes confined, particularly in locations where the hydraulic head is near the Qvt/Qva boundary and annual fluctuations are large. Areas where the Qvt is significantly thicker than the Qva tend to be confined. Areas where the Qva is much thicker than the Qvt, or where fluctuations are small, tend to be unconfined.

3.3 Water Level fluctuations

3. 3.1 Methods

I determined the average annual water level fluctuations using monthly hand data collected by AESI. Annual minimum and maximum water level values were collected for wells G-2, OBW-16, OBW-18, OBW-19, OBW-20, OBW-22, OBW-24, OBW-35, OBW-12, OBW-11, OBW-1R, OBW-4R, OBW-32 and 32R, and OBW-34. I determined the annual water level fluctuation for each well by taking the difference between the minimum and maximum yearly water levels.

3.3.2 Results

Annual water level fluctuations range widely at the RRE site. Fluctuations ranged from 1.67 to 9.8 feet, with an average of 6.25 feet (Figure 6). The largest fluctuations occur towards the center of the map near wells OBW-24 and G-2, and decrease in magnitude distally from those wells.

3.4 Pump and Slug Tests

3.4.1 Methods

AESI performed four constant rate aquifer pump tests on the wells OBW-25, OBW-33, OBW-36, and OBW-37. Results were analyzed both using graphical curve fitting and Aqtesolv software (AESI archives) using either confined wells (Theis, 1935), leaky confined wells (Hantush, 1961a and b), or unconfined wells (Neuman 1972 and 1974). The pump test on OBW-37 was reanalyzed here in order to gain experience in using the application and to confirm the previously published (AESI archive) results. Different wells were analyzed due to availability of data and discrepancies between these two data sets are likely due to a difference in time and location for the pump tests.

Slug tests for wells OBW-16, OBW-19, and OBW-28 were also reanalyzed using Aqtesolv (based on the Kansas Geological Survey Model (Hyder et al., 1994)). These slug tests provide a comparison for the aquifer property values obtained through pump testing, and show how the aquifer properties change along the length of the cross section.

3.4.2 Results

The results of the pump and slug tests conducted at the RRE area are presented in the tables in Appendix 3. Results for a 3 day pump test for OBW-25 (RRE EIS) indicate that hydraulic conductivity for the Qva in the RRE area range from 3.22 feet per day to 55.2 feet per day, which is consistent with average values for the Qva around the Puget Lowland (Turney et al., 1995). Results for a 3 day pump test performed on OBW-37 on 5/21/2007 provide a point of comparison for the OBW-25 pump test. The OBW-37 pump test shows a range of hydraulic conductivity values from 18 feet per day to 210 feet per day which is a noticeably higher range. Hydraulic conductivities delineated by slug tests range from 1.8 to 47 which corroborates the results observed in the OBW-25 pump test.

The aquifer tests provided reasonable values for the hydraulic conductivity for the area. The associated storativity values were reasonable for confined portions of the aquifer. However the storativity values were unreasonable for locations in the Qva where the aquifer is unconfined. Storativity values for the latter should be approximately the specific yield (Sy). The storativity values predicted using pump and slug testing methods are unreasonably small. Because of this I implemented other methods to determine Sy.

3.5 Recharge and Specific Yield

3.5.1 Methods

The WTF method for estimating recharge (Healy and Cook, 2002; adapted by Crosbie et al., 2004) was applied to the RRE data in an effort to better understand recharge and Sy at locations where the Qva aquifer is unconfined. The basic assumption is that any water level rise follows from immediate precipitation infiltration. Given a known water level rise (ΔH) and specific yield (Sy), recharge (R) is (Crosbie et al., 2004):

$$R = \Delta H \ x \ Sy \tag{1}$$

Yearly maximum and minimum water levels were determined for each well in order to quantify ΔH. Annual recharge is estimated using a regression equation for till-covered areas in King County, Washington calibrated at a nearby location (Vaccaro et al., 1998), with the precipitation data (P) for RRE:

$$R = 0.542 \ x \ P - 6.06 \tag{2}$$

With R and ΔH determined, equation (1) provides an estimate for Sy at each well.

The WTF method assumes that all water level changes are caused only by precipitation and that all water arriving at the water table goes immediately into storage (Healy and Cook, 2002). The WTF method also assumes that entrapped air (Lisse effect) and barometric fluctuations are negligible (Crosbie et al., 2004). The recharge equation presented by Vaccaro et al., 1998, was created using data for Big Soos Creek (BSC) in King County, WA, and a Deep Percolation Model (DPM) study of King County (Bauer et al., 1987). BSC is approximately 20 miles southwest of RRE. This equation is limited by possible differences in the Qva between BSC and RRE and the accuracy of the DPM.

3.5.2 Results

Total annual precipitation for the water years between October 1997 and October 2014 ranged between 36.0 and 59.9 inches with a yearly average of 45.8 inches. By applying equation (2), annual recharge was estimated to range between 13.5 inches and 25.9 inches, with an average recharge of 18.8 inches (See Appendix 8). This equated to an average recharge efficiency of 40.7 percent.

Given the annual average recharge and the annual average maximum water level fluctuation for each well, the specific yields for the unconfined wells in the RRE area were calculated using equation (1). Values ranged between 0.14 (plausible) to 3.9 (unphysical) (See Appendix 8). Sy is highly dependent on the magnitude of the maximum fluctuations. The unconfined wells with the largest water level fluctuations gave Sy estimates between 0.14 and 0.24. These agree with specific yields reported for the Qva in other locations around the Puget Lowland (Vaccaro et al., 1998).

3.6 Discussion

3.6.1 Hydrogeological Conditions

Surface conditions and how they have changed through time will impact the hydrogeological conditions. The RRE area initially had a sparse distribution of rural homes with localized clearings. The aquifer experienced negligible draws for household consumption. Development required significant deforestation and construction of impermeable surfaces and storm water runoff and infiltration systems. This should change aquifer recharge in several ways. The decrease in interception by vegetation can increase infiltration in open permeable fields. The construction of impermeable surface can prevent rain from reentering the groundwater system and might increase the amount of evapotranspiration; however, storm water and artificial infiltration systems should also serve to increase recharge. In particular, a large infiltration pond was installed at RRE in 2013. These infiltration facilities also act to redistribute where water infiltrates by concentrating water at a specific location.

The geologic cross section shown in Appendix 2 aids interpretation of spatial variabilities in thickness, precipitation infiltration, groundwater flow, and water level fluctuations. This transect is constructed along an interpreted groundwater flow line. Thus, the flux of water at each point is the sum of up-gradient infiltration sources. Variations in the thickness of the Qvt and Qva are interpolated between well logs. Thickness of the Qvt ranges by over 40 feet and influences the time it takes for precipitation to infiltrate to the hydraulic head due to low vertical hydraulic conductivity. Locations where the Qvt is thicker will take longer for precipitation to recharge the aquifer.

The cross section also provides insight into subsurface dimensions and distributions of hydraulic properties of the Qva aquifer. The annotated cross section, in conjunction with the digitized AESI Qva boundary map (Figure 2) and the tables in Appendix 3, document the range of aquifer properties based on pump and slug tests. The pump tests were undertaken near the infiltration pond where the aquifer in either confined or seasonally confined. The location of the pump test is likely the cause of the small storativity values. Measured values of hydraulic conductivity and storativity fall within the regional averages for confined portions of the Qva as determined by Turney et al., 1995. The lowest value of 3.2 ft/day falls below the 25th percentile and the maximum value of 210 ft/day falls slightly above the 75th percentile for Qva. It appears that hydraulic conductivities might increases down-gradient towards the discharge point at Unnamed Creek.

As shown in Figure 4 there is a large range of water level fluctuations. Fluctuations for the RRE area range from approximately 1.5 to 10 feet. The RRE area can be classified as coarse grained deposits directly underlying till (Vaccaro et al., 1998), and fluctuations generally range from 1 to 5 feet for similar deposits around the Puget Lowlands (Walters and Kimmel, 1968; Drost, 1982; Carr and Associates, 1983). The RRE wells experienced larger than average fluctuations. These large fluctuations predate any local development; therefore development does not explain such observations.

I propose several possible explanations for the large fluctuations. The largest fluctuations seem to be concentrated near the center of the area (Figure 4). One explanation is that the surface topography and subsurface conditions are channeling water towards these wells and amplifying the fluctuations. The shallowly rolling hills could act to channel surface flow towards local depressions, and constraints on the Qva due to pinching out could potentially channel flow towards the wells experiencing the large fluctuations.

Figure 5 addresses this first possibility. Surface contours indicate that the topography could channel the water towards the wells clustered in the center of the map. There are also two pockets where the Qva is not present that could potentially take infiltrating rain and channel it down gradient. The largest water level fluctuations occur in wells directly downgradient of locations where flow is potentially channelized (light blue lines Figure 5). OBW-24, G-2, OBW-22, OBW-32 and OBW-34 experience the largest fluctuations and are located on the convergent path of those channelized flow lines. The location of these wells in relation to the topography and aquifer configuration supports the idea that geographic constraints on the aquifer is a potential explanation.

Another potential explanation for the large fluctuations is variability in the aquifer storage, specifically the specific yield. The hydrogeological characteristics of the aquifer play a role in how the aquifer will respond to infiltrating precipitation. Local variations in storativity will dictate whether the aquifer displays a larger or small signal. A smaller storativity value will force a larger fluctuation, and given the results of both the pump tests and WTF method this is a reasonable conclusion. The larger than normal fluctuations could simply be the result of these local variations.

Given the spatial distribution of the wells and the responses, it is likely that both factors play a role in the magnitude of these fluctuations. The largest fluctuations occur in locations where a channeling effect is likely to occur. This analysis is limited by the extent of the project. In order to further pursue the idea that geographic conditions can affect the magnitude of fluctuations, additional wells showing in the region would have to be analyzed.

3.6.2 Recharge and Specific Yield

The storativity values obtained through traditional pump test methods were unreasonable for locations in the Qva where the aquifer is unconfined. This is likely due to the pump test being conducted in an area where the Qva is predominantly confined or seasonally confined. Therefore it was important to provide an alternate method to obtain these values. It was of particular importance to help understand how the water level fluctuations varied across the region. The WTF method provided an adequate means of doing this. A range of Sy values of 0.14 to 0.24 is realistic for unconfined Qva the area given the large fluctuations seen at these wells. These values help in both the interpretation of the water fluctuations, and in quantifying the spatial variability of Sy around the RRE area.

Although this method provides reasonable results, there are some limitations. These values were determined using annual averages, and relationships determined for the Puget Sound as a whole and not specifically for RRE. The WTF method is best applied over shorter single storm events. A more accurate estimate could be generated using a recharge equation, which could account for single storm events and a more refined variation of the WTF method. The effect of precipitation on the water table is a much more complex process than illustrated above. The recharge still needs to be sufficient enough to account for the fluctuations that were observed. By implementing the methods above a rough but reasonable estimate of Sy was determined, which supports the fluctuations that were observed.

4.0 Temporal Groundwater Changes and Response to Development

4.1 Temporal Changes to the Water Level and Fluctuations

4.1.1 Methods

Temporal changes to the annual hydraulic head and water level fluctuations based on monthly hand logging are considered in this section. The average annual water level was determined from the average of the minimum and maximum yearly water levels. An average of the minimum and maximum is taken to account for annual variability in precipitation. The average annual water level fluctuation was determined from the difference between the minimum and maximum yearly hydraulic head levels. The average annual hydraulic head are in Appendix 4 and the annual water level fluctuations are in Appendix 5.

4.1.2 Results

Figure 6 shows the average water level for three representative wells. Well OW-29 (panel a) shows a gradual increase in water level by two feet over 10 years with no change in slope around development of RRE. This behavior is characteristic of the majority of the wells in the RRE area. In panel b, well OBW 1R shows no trend in water level and year to year fluctuations of several feet. In panel c well OBW 16 shows near constant water level up to the time of development with a 5 foot increase in the two years following development. This is the only location which displayed a response that can be attributed directly to development.

In general there were no definable changes between pre- and post-development time periods. There was either too much scatter in the data to quantify a change, or the well maintained the same patterns between the two periods. A defined change was only observed in well OBW-16. In the two years following development the hydraulic head rose at an elevated rate; however, this change was short-lived, and the rate returned to what was seen under pre-development conditions (Figure 5 panel c).

As Described in section 3.3.2, there is a large range of annual water level fluctuations. There was significant scatter in the data, and I was unable to correct for differences in annual precipitation. Due to the significant yearly variation I was unable to derive a quantitative relationships for how fluctuations changed over time. In some wells sufficient data existed to establish general trends visually. In general, the magnitude of the fluctuations either decreased slightly (Figure 7 panel a) or remained relatively constant (Figure 7b). The majority of wells tended to experience an overall decrease in the magnitude of their water level fluctuations.

There is no observable change between pre- and post-development periods. Whatever trends were established spanned through both periods. Any changes that might have occurred are masked by the large yearly variations within the data.

4.2 Hydraulic Head Response to Precipitation

4.2.1 Methods

I determined the hydraulic head fluctuation response to precipitation using hourly water level data in conjunction with cumulative precipitation data. Water level data were collected using Solinist Waterlevel transducers and Telog dataloggers by AESI. The raw data for the Solinist tradnducers were compensated for barometric pressure and the Telog dataloggers were vented and did not require compensation (personal correspondance with Homer Welborn). The wells that were analyzed were G-2, OBW-19, OBW-20, OBW-29, OBW-12, OBW-11, OBW-1R, OBW-4R, OBW-32 and 32R, and OBW-34. The Solinist transcievers were used to collect the data for G-2, OBW-19, OBW-20, OBW-29, OBW-32, OBW-32R, and OBW-34. The Telog dataloggers were used to collect data for G-2, OBW-12, OBW-11, OBW-1R, and OBW-4R (personal correspondance with Homer Welborn).

I calculated an average weekly water level for each observation well. I used weekly averages to both smooth the noise in the data and to justify the assumption that infiltration was immediate. Other assumptions I made are that all wells were in phase, there are no outside water influences causing a response in the hydraulic head, and that any water withdrawals from pumping were negligible. I delineated periods of similar slope on the hydrograph. I calculated the water level change per week from the difference in water level between the start and end of the period divided by the period length. I calculated a running daily cumulative precipitation for each water year, and using this I determined the accumulated precipiation for each period of similar slope. This value represented precipitation per week.

I plotted precipitation per week against the water level change per week to eatablish a relationship between the two. The hydraulic head response data was divided into three groups: data spanning the entire collection period, pre-development data, and post-development data. I used data for individual wells when I analyzed individual wells and compared pre- and post-development changes for individual wells. I used the combined data sets of only wells with both pre- and post-development data when I compared pre- and post-development changes for the region. When analyzing the region as a whole the entire combined data set was used. I created linear regression lines of the form $y = mx + b$ for each well for each time period. These regressions were calculated using the least squares method. I determined a 95% confidence interval for each regression line created.

Using these regressions I calculated a precipitation rate under which the hydraulic head transitioned from declining to increasing. This value is dubbed the threshold precipitation, and corresponds to point where the linear regression line crosses the x-axis.

I also determined the rate of hydraulic head decline under conditions of no precipitation for each well. This value was calculated by identifying periods in the water year where the precipitation rate was at or near 0 and was both preceded and followed by negligible precipitation. This value corresponds to the ambient drainage rate (D) for the Qva, or the amount the hydraulic head falls given no recharge (Crosby et al., 2004).

4.2.2 Results

I performed an analysis for each individual well. The magnitude of the water level fluctuations is not uniform across the entire project area. A distinction for each individual well must be established in order to address differences between wells experiencing either large or small fluctuations. The magnitude of the fluctuation directly affects the slope of the regression line. For wells experiencing a large fluctuation, the slope of the line will be steeper and a given precipitation will elicit a larger response. Conversely, a well that experiences smaller fluctuations will show smaller responses to precipitation, and the slope of the trend line will be shallower.

Table 4 summarizes the results for each individual well. Slopes for the regression lines ranged in value between 0.66 and 9.5 and were generally comparable to the magnitude of the annual fluctuations seen for each well. Confidence interval at the 95% level for uncertainties of slopes ranged from 10% to 23%. Threshold precipitations range from 0.73 to 0.89 inches/week, with an average threshold value of 0.82 inches/week. Figures showing the distribution of precipitation rate to water level change rate for each individual well are located in Appendix 6.

A comparison of pre- and post-development data for each individual well shows slight variations between the regressions for the two time periods. The variations between the time periods are smaller than the uncertainty of the regression therefore are null. Figure 8 shows a comparison of regression lines generated for wells OBW-20 (panel a) and OBW-29 (panel b).

In order to show changes between pre- and post-development the combined data for wells OBW-19, OBW-20, OBW-11, OBW-12 and OBW-29 has to be used. These are the wells with both pre- and post-development data. Unlike the analysis for individual wells there was a large enough variation in the signal to show a difference between the two periods. For the RRE area the response to precipitation decreased by 1.1 inches (Table 4). The threshold precipitation did not change by a significant amount.

Figure 9 shows the spatial distribution of the average ambient drainage for the Qva at RRE. There is a correlation between the magnitude of the fluctuations seen at each well and the ambient hydraulic head drainage (D), which can be seen through a comparison of Figures 4 and 9. The D value can be determined either by direct measurements on hydrographs (observed D) or by the y-intercept of the modeled regression lines (modeled D). The modeled D values fell within a standard deviation of the averaged observed D values for each well. Modeled D values ranged from 0.56 to 7.1 inches/week, and the corresponding observed D values ranged from 0.42 to 6.9 inches/week (Figure 9). The Qva aquifer in the RRE area has an average modeled D of 3.0 observed D of 4.2 feet per day.

There was minimal change in D between pre- and post-development time periods. For both the modeled and observed D values there was a slight increase; however, changes were smaller than the uncertainty of the range of values.

4.3 Discussion

4.3.1 Temporal Changes to the Hydraulic Head, Fluctuations, and Response to Precipitation

The main focus of this section is to quantify temporal changes and assess and effects from development. The average water level changed consistently over the entire monitoring period. Overall, the hydraulic head elevation is increasing. Both the maximum and the minimum annual hydraulic heads have increased, but the seasonal low has increased at a greater rate. This manifests as an overall increase in the average water level for the entire RRE region. This average water level rise has no apparent cause. The water level has risen regardless of location, time, or degree of development. This observation is likely the result of either a larger scale climatic change or a climatic signal that has a smaller frequency than the monitoring period. Annual variability in precipitation affects the year-to-year water level, but an overall increase in yearly precipitation has not been observed (See Appendix 8).

There were also slight changes in the water level fluctuations. Overall the water level fluctuations tended to decreases, and these trends were observable over the entire monitoring period. The observation that the trends spanned the entire monitoring period indicated that development is not a cause for these trends. It is reasonable to make a general statement that the magnitude of the fluctuations are decreasing, but due to large variations in the annual data, any quantitative statement is moot.

There is no significant difference in the signal in response to development for either average water level or fluctuations. With the exception of OBW-16 all other wells maintained any trends they were showing through the entire monitoring period. At OBW-16 there was a spike in water level immediately following the start of development, but this signal returned to what was under pre-development conditions. As hypothesized, I expected to see a change in the signal of the hydraulic head in response to development. In particular, I expected to see the largest changes in areas where infiltration facilities concentrated water. As seen in the cross section (Appendix 2) an infiltration pond is located on top of well OBW-22, which is where I expected to see the largest change in response; however, there was no change. This implies that, regardless of development, the style and distribution of infiltration has not changed.

The regressions relating hydraulic head response to precipitation showed no distinct changes after development. There are some slight changes in hydraulic head response, but Results Table 2 of Appendix 6 shows that these changes are negligible. Any change that did occur was within the uncertainty of the analysis. I also expected to see a distinct change in response after development due to a change in infiltration styles. The infiltration ponds change the style of infiltration by essentially providing a window through the till. I expected the response to increase due to this change. In particular, I expected the most dramatic changes in wells in or near infiltration ponds as the rate of infiltration would ideally increase with the removal of till. At the very least, I expected an increase in outliers above the regression lines due to more dramatic responses to precipitation. A quick scan of the figures in Appendix 6 shows this to not be the case.

The only way to accommodate a change is by combining the pre- and post-development data for all the wells. Table 4 shows the resulting regressions for this analysis. Although the response to precipitation does change, the change is on the upper end of the uncertainty for the analysis. This relationship is a reach and should be taken with caution. Combining the wells adds the additional complication of incorporating both large and small fluctuations. Having multiple levels of response mutes the signal at any individual well, and increases the variability of the data. This manifests itself in a decreased correlation between the points and the regression line. The change in signal is likely the result of an increased spread in the data rather than an actual response to development.

4.3.2 Implications for Development

Although I was able to perform a regional assessment for the Qva at RRE there was no strong evidence to suggest that development had any effect on the hydraulic head. Any changes that were observed were either within the uncertainty of the analysis for both periods, or returned to pre-development trends after a brief change. The findings of this paper disprove my hypothesis that there would be a noticeable change in the hydraulic head signal as the result of development. The wells directly influenced through the construction of retention and infiltration facilities showed little change.

The main implication of these findings is that the style and distribution of the infiltration has not significantly changed as the result of development. If the overall infiltration had decreased, a corresponding decrease in the water level would have been expected. If the distribution of infiltration had changed, we would have expected to see changes in specific wells based on their proximity to the infiltration facilities. No definitive statements can be made to validate any such changes. Therefore it can be reasonably stated infiltration at RRE has remained unchanged following development. This implies that the facilities in place are properly mitigating any changes that would have occurred due to development.

The questions that arise are if there is a threshold level of development that needs to occur before a signal can be observed or if a certain type of development (residential vs commercial) shows a greater response? Although there was substantial development in the RRE region, the study area still remains largely rural. No quantitative evaluation in land cover was made in this study. There might be a certain level of development that is required to generate a noticeable change in the hydraulic head signal. A more urban development of a similar nature might have shown different results. RRE is also primarily a residential community and construction was primarily composed of houses. The houses in the RRE area primarily had large lawns which would allow for infiltration to occur more uniformly across the development. Whereas commercial developments have substantially more impervious surfaces and precipitation and runoff would have been more channeled. A difference in the signal might have been made present had the development been more commercial.

4.3.3 Additional Analyses

The hydraulic head response to precipitation warrants some additional attention to its predictive abilities. It provides a means of quantifying how the hydraulic head will act given a defined period and amount of precipitation. The equations outlined in Table 3 provide a way to help interpret short term responses of the hydraulic head. Previous work has predominantly focused on quantifying hydraulic head response on an annual basis, and this provides information over a weekly basis. The regression of each individual well provides a prediction method for how that specific well will respond to a simple period of precipitation. These regressions also establish a threshold precipitation rate for the region.

The average threshold precipitation rate is 0.82 inches/week, and the standard deviation of the values is small.

The ambient drainage, D, is also an important variable to quantify the hydraulic head recession. Ideally, this rate would be used to determine the rate at which the hydraulic head would fall at any time where there is no precipitation. The modeled D based on the y-intercepts is directly comparable to the measured D. The D values presented in this paper serve more as a baseline study and point of comparison. The D comes into play in performing more complicated variations of the WTF method for recharge. To provide the most accurate recharge rates using the WTF method the drainage must be taken into account. This is particularly true when looking at recharge over smaller time intervals, or over single storm events.

5.0 Summary

The spatial variabilities in the Qva for the RRE area are visually represented through LiDAR images, the annotated cross section, and a topographic contour map. A basic recharge analysis was performed using annual precipitation data. An average annual precipitation of 45.8 inches was calculated, which corresponds to 18.8 inches of yearly recharge. This was used in conjunction with the WTF method to better constrain the specific yield. Specific yields for unconfined portions of the Qva ranged between 0.14 and 0.24, which are consistent for the area and help with the interpretation of the large fluctuations seen in the Qva. It was also determined that geographic constraints on the topography and the Qva potentially play a role is the larger than normal fluctuations seen in certain wells for the RRE area.

Observations were made for the annual hydraulic head level and changes in annual water level fluctuations, and relationships were established for the hydraulic heads response to precipitation. The Qva aquifers' ambient drainage, the Qva aquifers annual recharge, and the Qva aquifers' specific yield were also quantified. In general the overall average water level increased over the entire monitoring period and any effect from development was negligible. Corresponding water level fluctuations generally decreased, and there was no observable effect from development. Similarly no changes in the response to precipitation were seen after development. The only observable changes between pre- and post-development conditions were seen using the combined wells for the RRE region. The response decreased by 1.1 inches per inch of precipitation; however there is a large uncertainty for these regressions, and they should be used with reservation. Based on the findings of the temporal analysis comparing pre- and post-development data my hypotheses that development of RRE would affect the signal was disproved. It can thusly be stated that the effects of development on recharge of the Qva aquifer have been mitigated through the processes in place.

6.0 Recommendations for Future Work

The main area for future work within this project would be to make the analysis more robust through the analysis of additional wells. Increasing the density of wells and adding more cross sections would help to better illustrate the spatial variabilities within the Qva. Adding more wells would also increase the strength of the temporal analysis by potentially providing stronger correlations. Additional wells might pick up signals that were not observed in the wells used for this project. It would also be advantageous to perform a similar analysis for a separate sight that has undergone similar development and monitoring. Doing so could determine whether the RRE site is unique in seeing no response to development.

I would also recommend a study comparing results found in the RRE area with other developments in the Puget Lowland. Due to a lack of response, I feel that there might be a threshold level of development needed to see a definitive signal. I would suggest recommend a comparison of results for more urban areas which have seen a larger level of development.

Another area for potential future work would be to alter the methods for the hydraulic head response to precipitation analysis. One alteration would be to filter the data for delays or a lag in response of the hydraulic head to precipitation. A delay in response could be attributed to factors such as intensity of precipitation, ground cover, thickness of overlying till, depth to the hydraulic head, etc. The model made the assumption that delay was negligible. This was a large assumption and is possibly a reason for a lot of the spread in the data. In fact there were wells with data that had to go unused due to an obvious lag in response of the hydraulic head. The data could also be broken up into either rising for falling groups. This might help with the identification of trends related specifically to one or the other.

A final recommendation for future work would be to analyze regional monitoring wells in the Qva for hydraulic head responses to precipitation. By expanding the analysis to a regional basis it would be possible to characterize the Qva as a whole in the Puget Lowlands. This would increase the applicability of this analysis to outside of the small RRE development area.

7.0 Figures

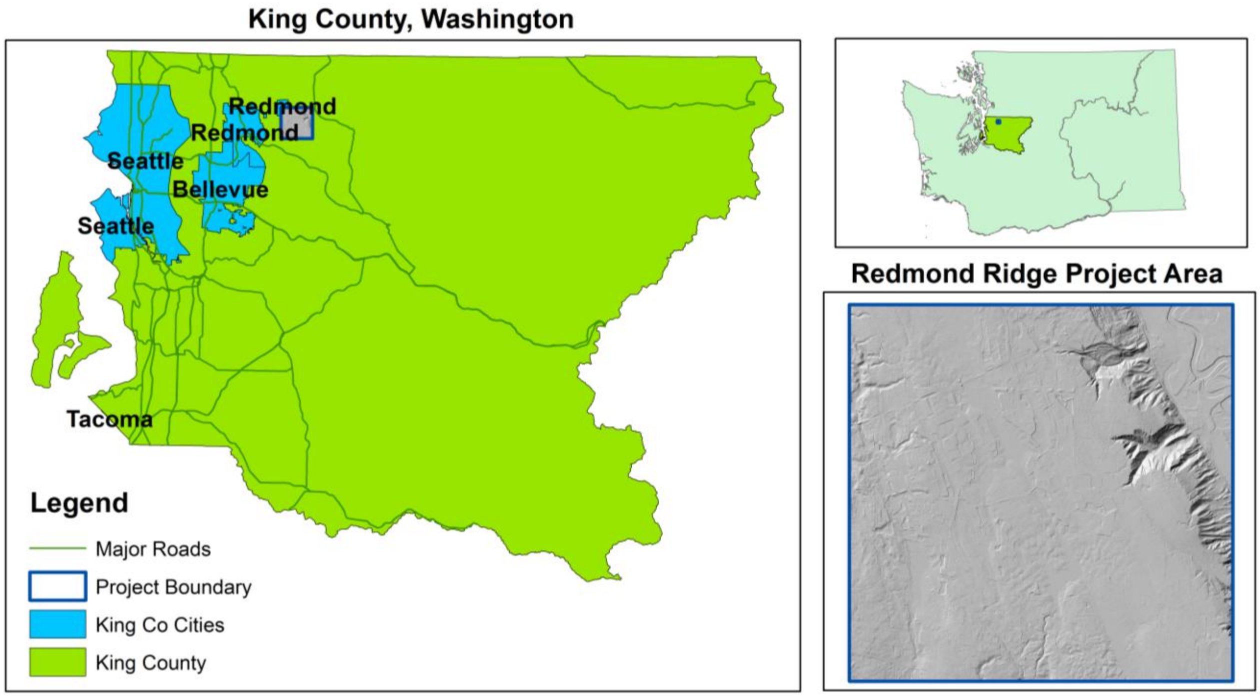


Figure 1 – Location map of Redmond Ridge Project Area, WA

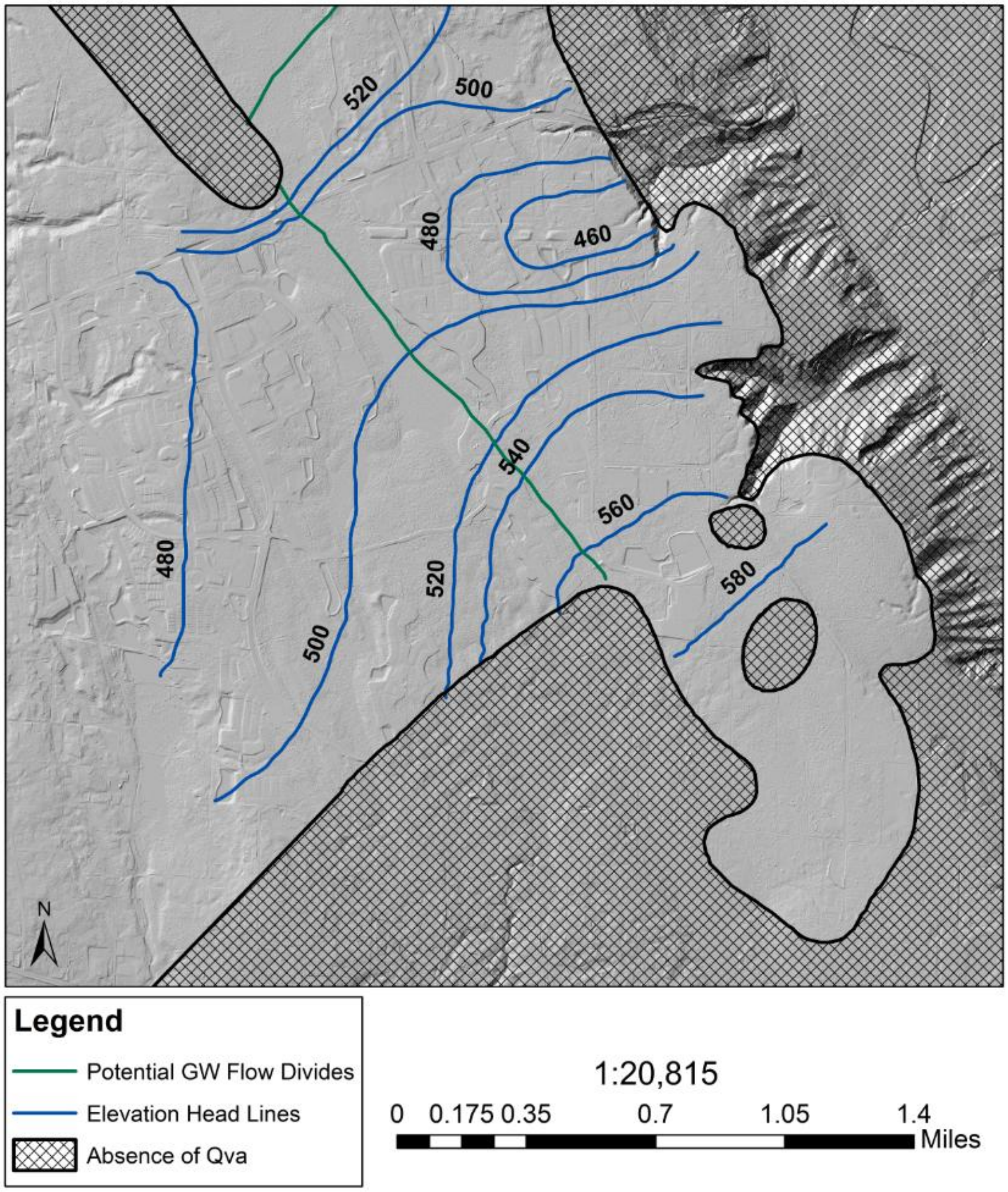


Figure 2 – LiDAR image of the RRE study area showing the boundary of the Qva and where Qva is not present (black hatched), potential groundwater flow divides (green), and interpreted elevation heads of the Qva aquifer (blue)

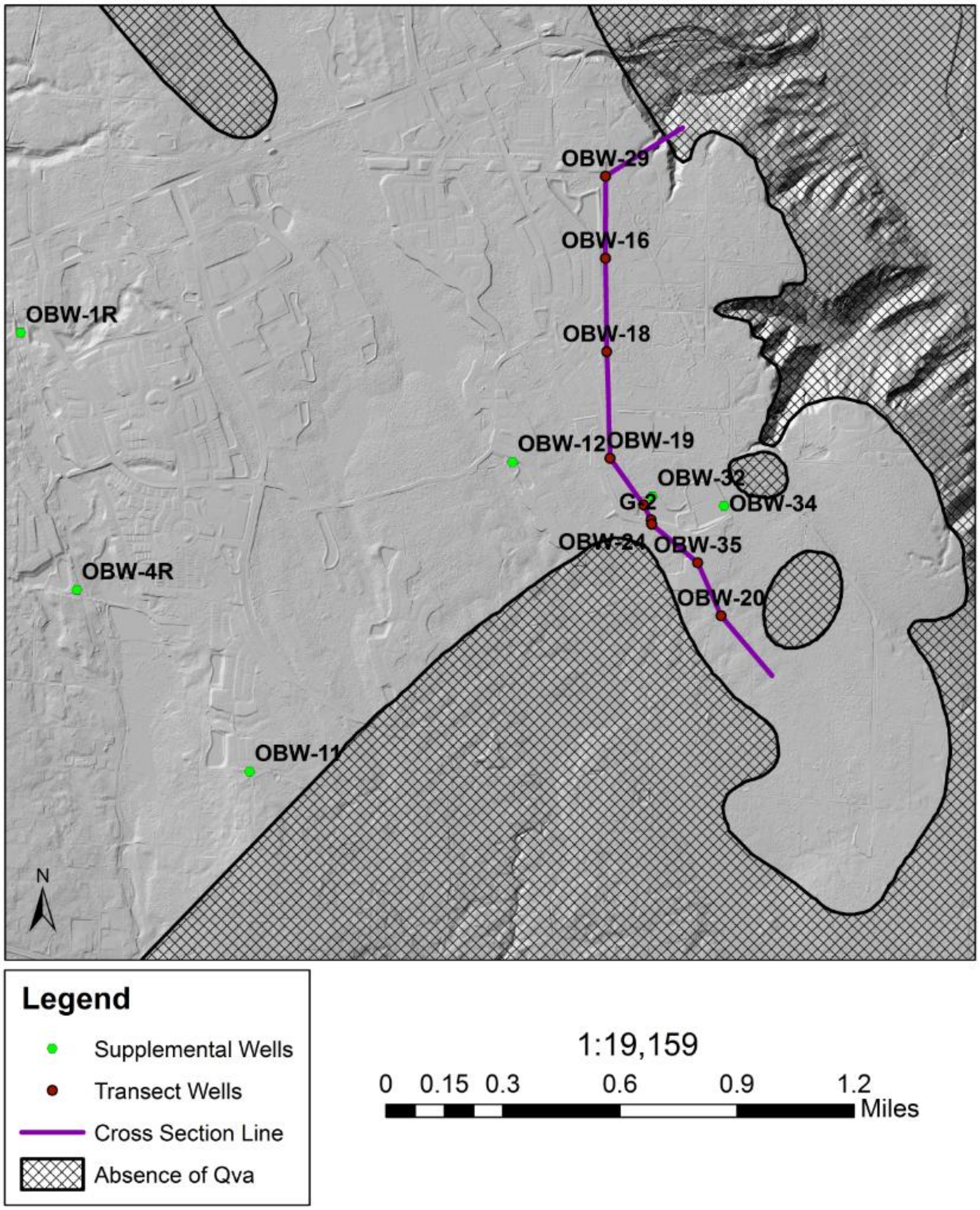


Figure 3 – LiDAR image showing the location of the monitoring wells used in this study as well as the cross-section transect line

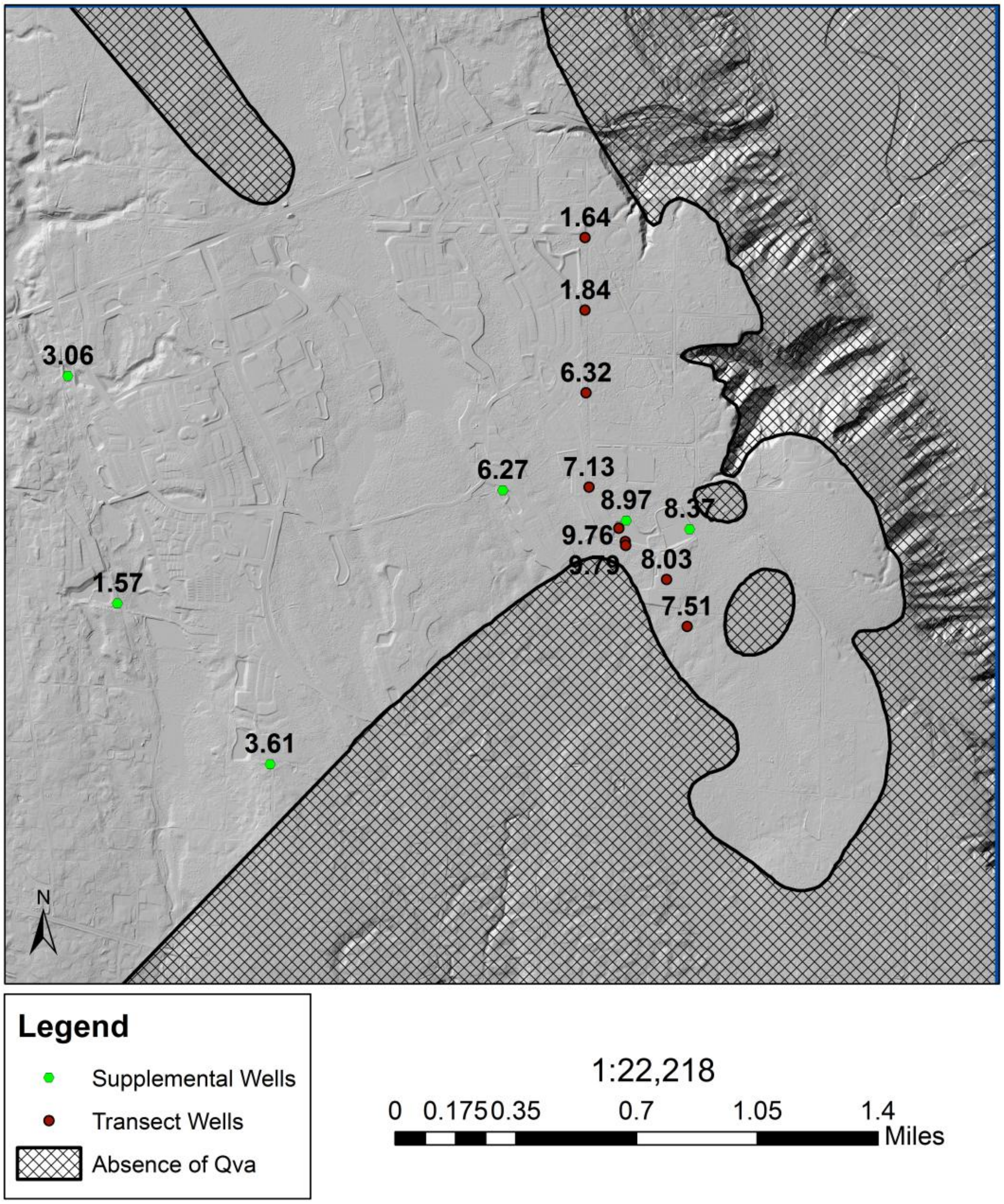


Figure 4 – Average annual hydraulic head fluctuations for wells in the RRE area

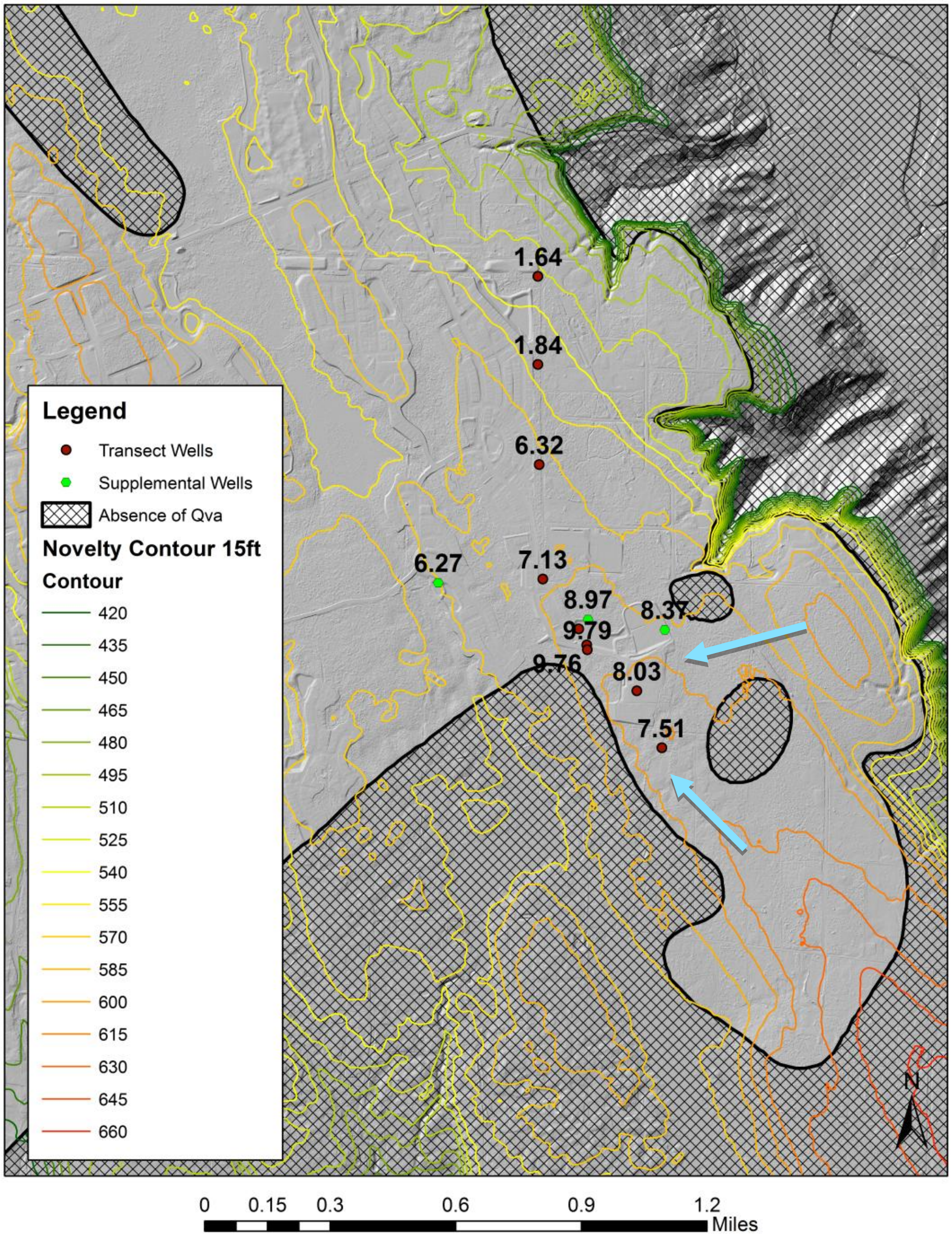
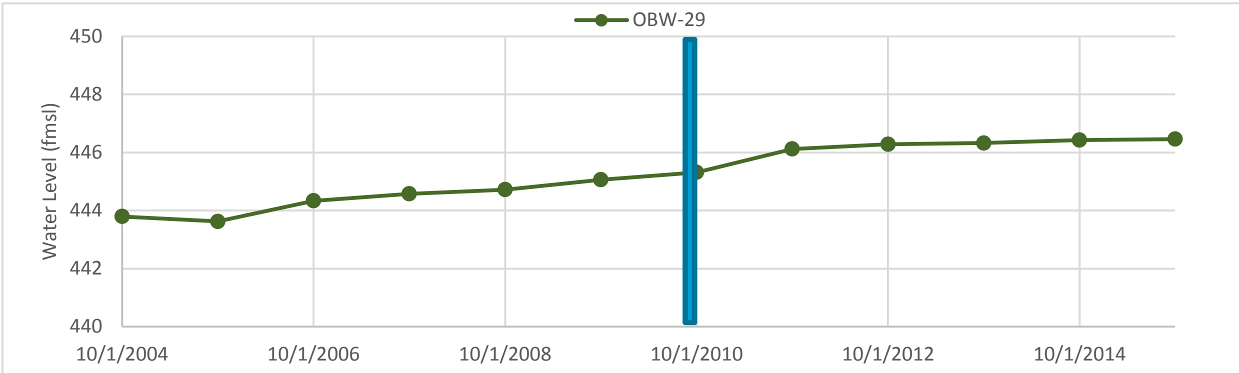
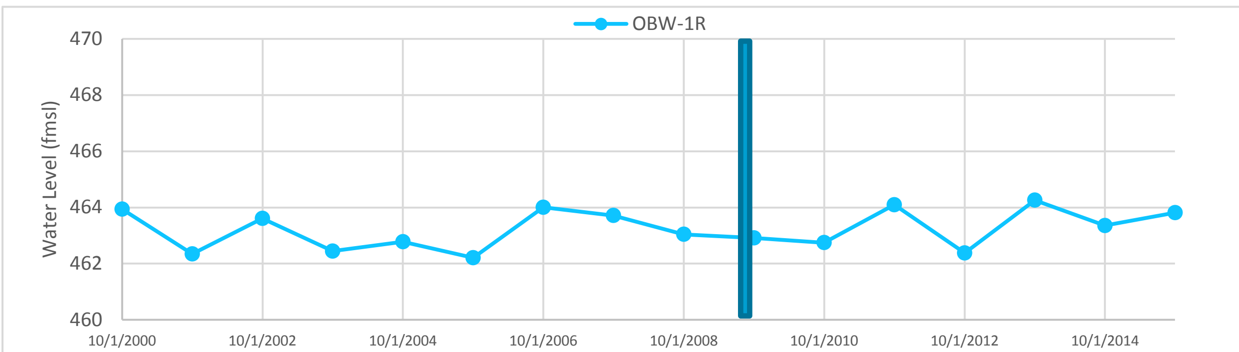


Figure 5 – Map of the RRE area showing 15 foot contours of the surface topography. Areas of high elevation are displayed in warmer colors and areas of lower elevation are displayed in cooler colors. Arrows indicate ---- see text section 3.6.1

(a)



(b)



(c)

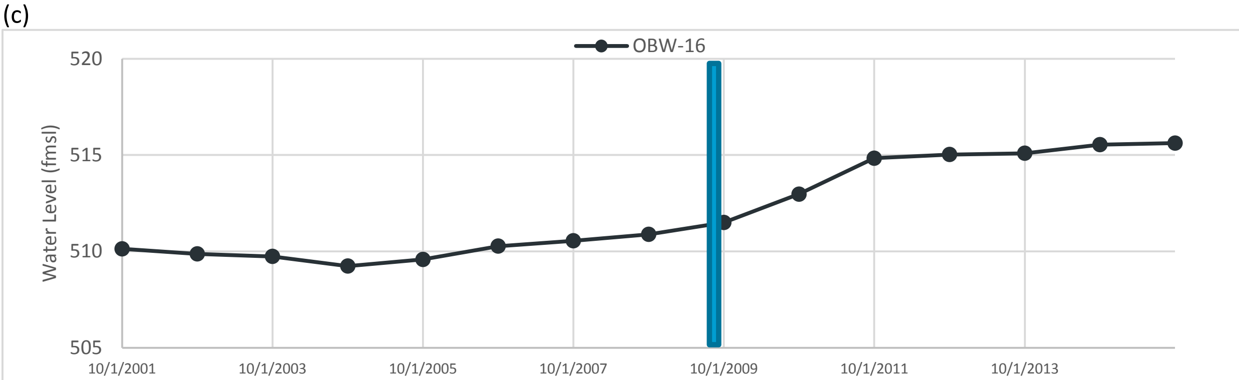
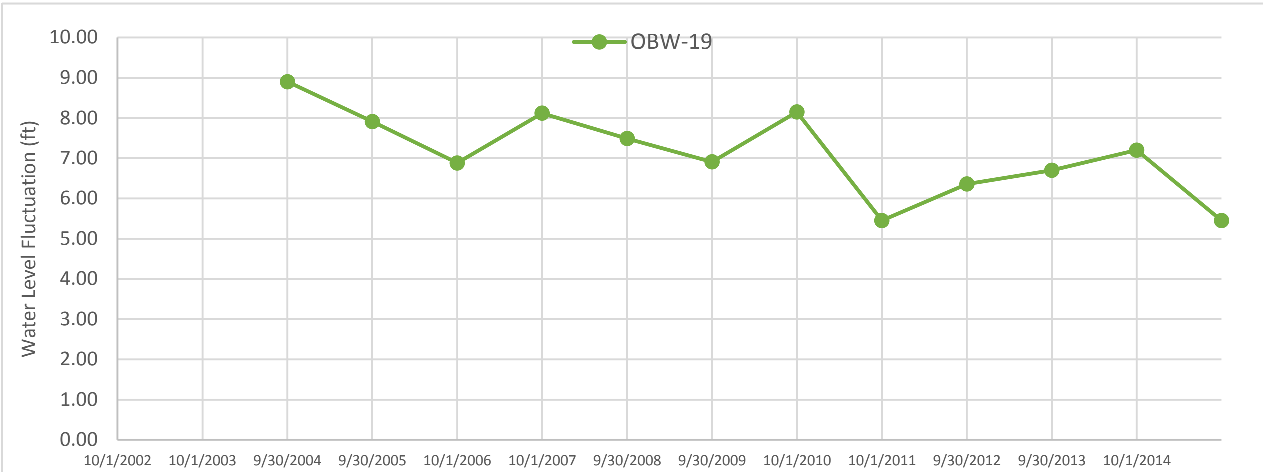


Figure 6 – The average hydraulic head level for each water year illustrating wells where the hydraulic head is rising on average (a) OBW-29, remaining constant (b) OBW-1R, and rising at a maximum (c) OBW-16. The blue line represents the break between pre- and post-development conditions.

(a)



(b)

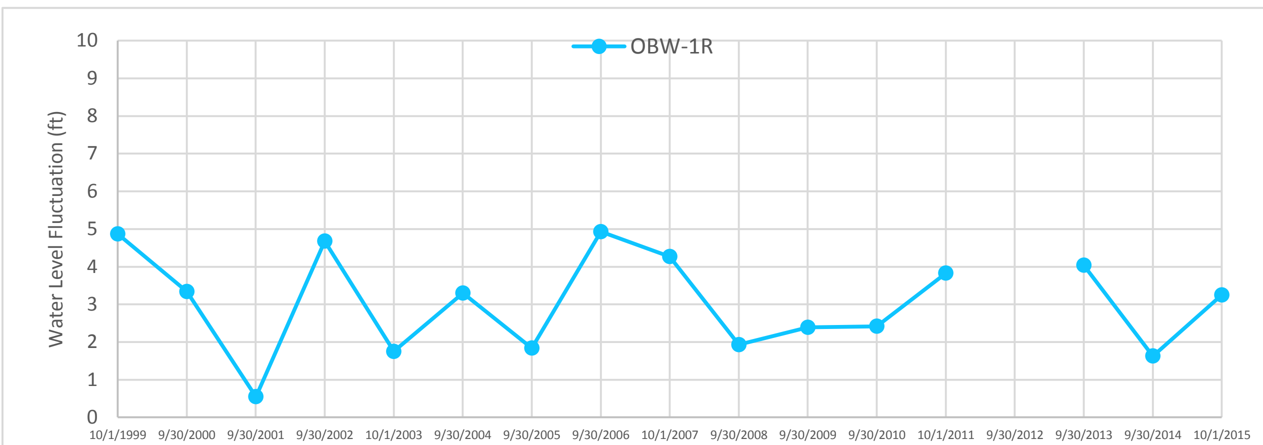
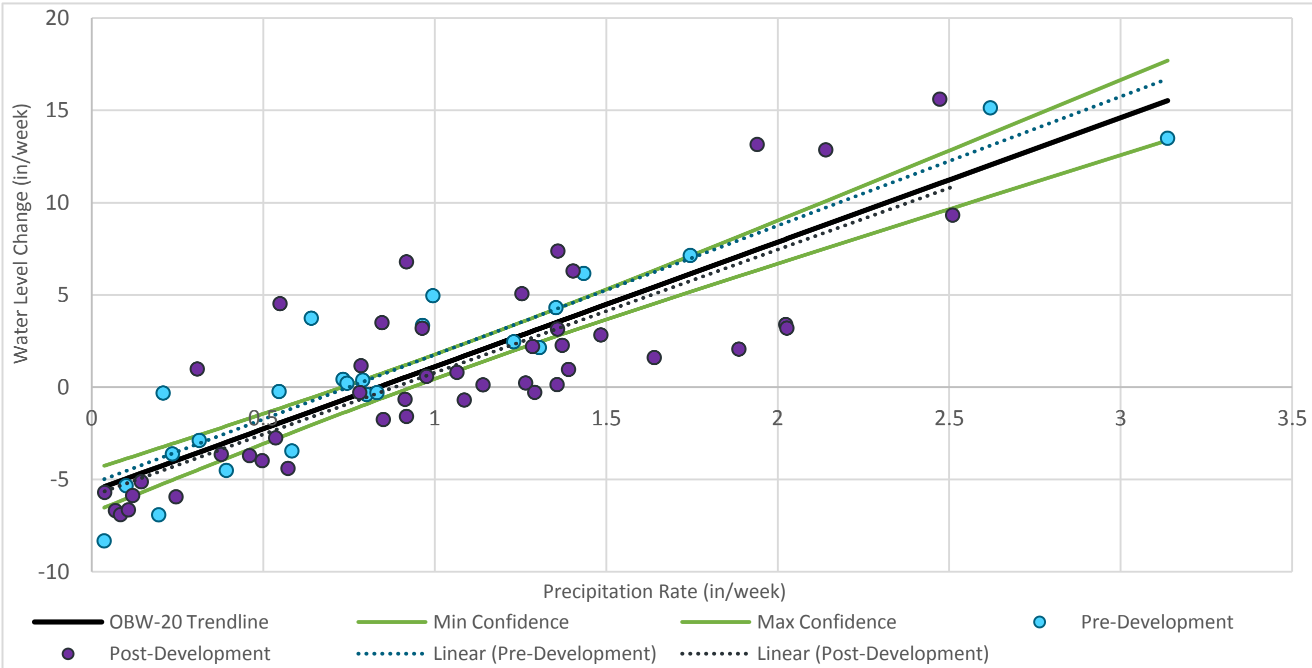


Figure 7 – The average hydraulic head fluctuation for each water year illustrating wells there the magnitude of the fluctuations are decreasing (a) OBW-19 or remaining constant (b) OBW-1R

(a)



(b)

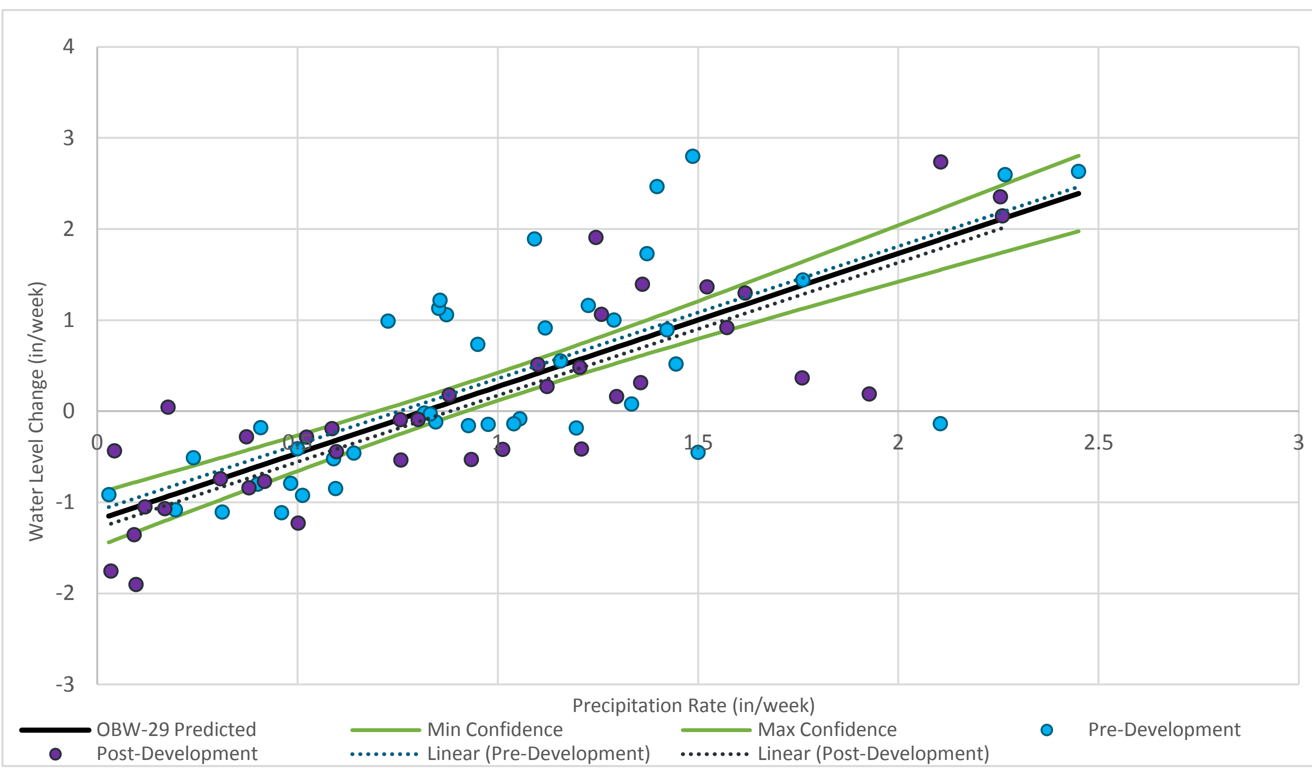


Figure 8 – The relationship between average weekly precipitation and the corresponding water level change for both pre and post-development conditions for wells (a) OBW-20 and (b) OBW-29

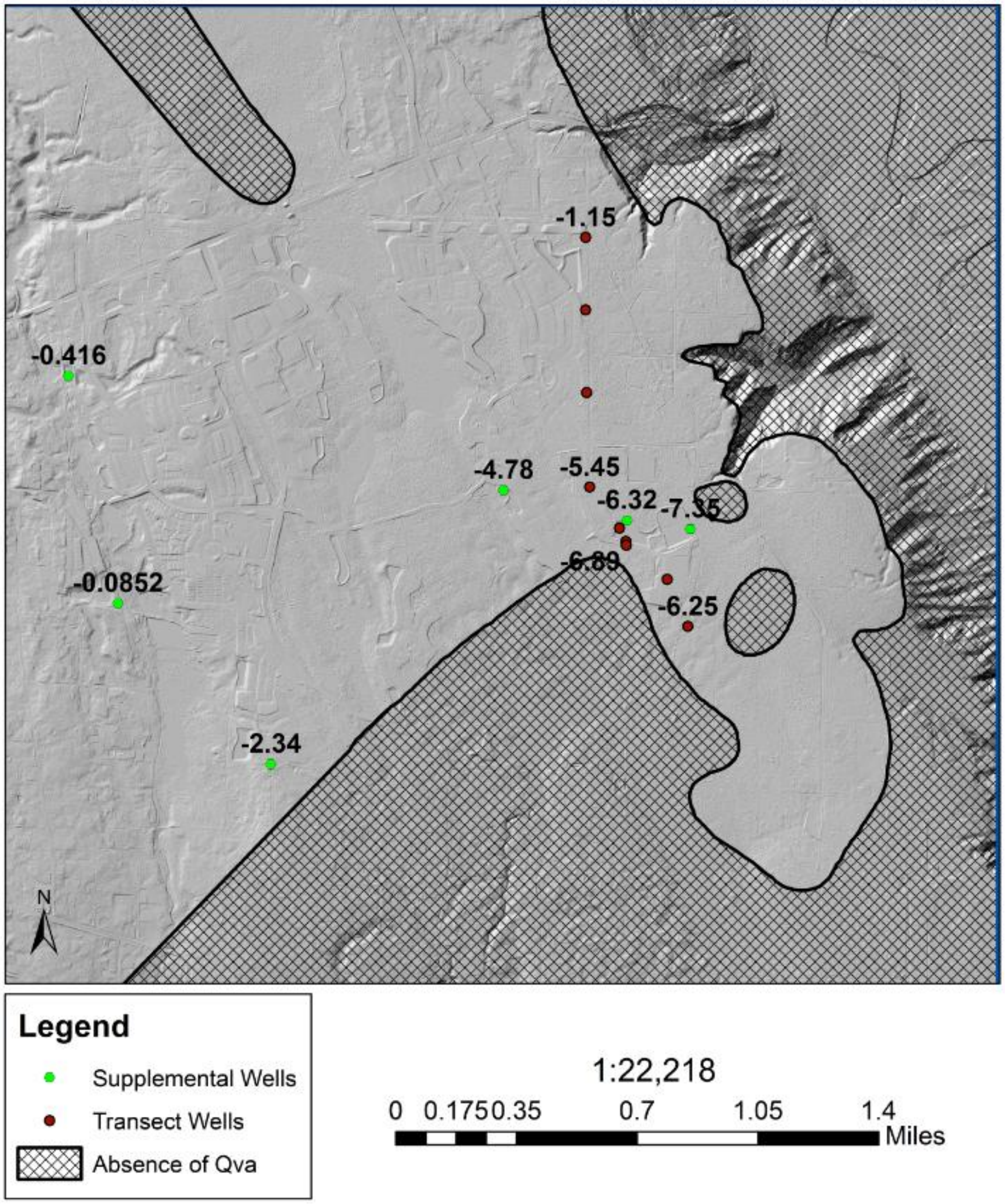


Figure 9 – The average observed ambient drainage values at each well in the RRE area

8.0 Tables

Table 1 – Summary of period of time over which selected wells were monitored

Well No.	Transducer Data		Hand Measurements	
	Start Monitoring	End Monitoring	Start Monitoring	End Monitoring
OBW-20	Jan-06	Present	Jan-03	Present
OBW-35	Jun-07	Mar-09	Apr-07	Jul-11
OBW-24	N/A	N/A	Feb-03	Aug-09
G-2	Nov-02	Jun-09	Oct-00	Aug-09
OBW-22	N/A	N/A	Feb-03	Aug-09
OBW-19	Apr-05	Present	Jan-03	Present
OBW-18	N/A	N/A	Jan-03	Present
OBW-16	Nov-02	Jan-06	Oct-00	Present
OBW-29	Apr-03	Present	Apr-03	Present

Table 2 – Summary of period of time over which supplemental wells were monitored

Well No.	Transducer Data		Hand Measurements	
	Start Monitoring	End Monitoring	Start Monitoring	End Monitoring
OBW-1R	Sep-98	Present	Apr-98	Present
OBW-4R	Nov-98	May-12	Oct-98	May-12
OBW-11	Sep-98	May-12	Aug-97	May-12
OBW-12	Nov-98	Present	Sep-98	Present
OBW-32	Jun-07	Jul-13	Apr-05	Jul-13
OBW-32R	Oct-13	Feb-14	Oct-13	Present
OBW-34	Jun-07	Jun-09	Apr-07	Jun-13

Table 3 – Summary of results for the analysis of the hydraulic head response to precipitation for each individual well. Where slope is in units of feet hydraulic head rise per foot of precipitation, 2σ represents a 95% confidence interval and threshold precipitation is in units of feet precipitation per week.

Well No.	Slope	2σ	R^2	Threshold Precipitation
G-2	9.5	1.6	0.82	0.74
OBW-20	6.7	1.0	0.75	0.83
OBW-19	6.9	0.9	0.75	0.82
OBW-29	1.5	0.3	0.62	0.82
OBW-1R	0.66	0.1	0.64	0.85
OBW-4R	1.7	0.3	0.60	0.83
OBW-11	2.3	0.4	0.54	0.79
OBW-12	5.8	0.6	0.70	0.89
OBW-32 OBW-32R	5.8	1.4	0.58	0.87
OBW-34	9.3	1.9	0.82	0.73

Table 4 – *summary of the linear regression trend lines for the relationship between weekly rainfall and weekly hydraulic head fluctuation using only wells having data for both pre- and post-development conditions*

Well No.	Slope	2σ	R^2	Threshold Precipitation
Pre Dev	4.2	0.5	0.54	0.87
Post Dev	3.1	0.4	0.45	0.84

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Appendix

Appendix 1 – GIS Data Sets

The data sets that are currently being used are:

- *Washington Base map (Washington)* – This data set is a base map of the state of Washington. The map was published by the Washington State Department of Ecology in 1994. The map is projected in the NAD_1983_HARN_StatePlane_Washington_South_FIPS_4602_Feet coordinate system.
- *King County Base map (King County)* – This data set is a base map of King County, WA. The map was published by the U.S. Department of Commerce, U.S. Census Bureau, Geography Division in 2010. The map is projected in the NAD_1983_HARN_StatePlane_Washington_South_FIPS_4602_Feet coordinate system.
- *King County Major Roads (King Co Roads)* – This data set is the inter-state and state route (major) roads in King County, WA. This data set was clipped from a layer showing all roads in Washington State to show only select routes in King County. The map was published by the Washington State Department of Transportation 2014. The map is projected in the NAD_1983_HARN_StatePlane_Washington_South_FIPS_4602_Feet coordinate system.
- *King County Major Cities (King Co Cities)* – This data set shows cities within select cities in King and Pierce Counties, WA. This data set was clipped from a layer showing all cities in Washington State to show only select cities. The map was published by the U.S. Department of Commerce, U.S. Census Bureau, Geography Division in 2010. The map is projected in the NAD_1983_HARN_StatePlane_Washington_South_FIPS_4602_Feet coordinate system.
- *Qva Boundary (Absence of Qva)* – This feature is a set of polylines that was created through the digitization of a previously existing map created by AESI. The map was published on 10/16/2014 and has been reprojected in the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4602_Feet coordinate system. This layer contains polylines delineating locations within the area where the Qva does not exist.

- *Potential Groundwater Flow Divides (Potential_GW_Flow_Divides)* – This feature is a set of polylines that was created through the digitization of a previously existing map created by AESI. The map was published on 10/16/2014 and has been reprojected in the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4602_Feet coordinate system.
- *Hand Drawn Water Level Lines (ElevationHeadLines)* – This feature is a set of polylines that was created through the digitization of a previously existing map created by AESI. The map was published on 10/16/2014 and has been reprojected in the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4602_Feet coordinate system.
- *Project Boundary (Boundary)* – This layer is a project boundary polygon that was created in editor to serve as an extraction mask for the LiDAR and Hillshade data sets.
- *Redmond LiDAR Data* (Novelty_Hill_6ft) – The LiDAR data was taken from the Puget Sound LiDAR Consortium and is part of the 2014 Cedar River Watershed LiDAR Project. The LiDAR data is projected in the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4602_Feet coordinate system. The LiDAR data was then clipped using the Boundary polygon.
- *Filtered Redmond LiDAR Data (Novelty_Hill_6ft_Filtered_20X20)* – The 2014 Cedar River Watershed LiDAR data was filtered using focal statistics. The original LiDAR data was too rough to perform a reasonable contour analysis and needed to be smoothed. The smoothing process used was a 20X20 averaging of the mean elevation
- *Redmond Hillshade (Novelty_Hillshade_6ft)* – This hillshade was created using the 2014 Cedar River Watershed LiDAR data. The hillshade was then clipped using the Boundary polygon. The hillshade serves as a background for the maps and figures created in this project.
- *Transect Wells (Transect Wells)* – These wells were created by converting a KMZ file into a node layer which is usable in ArcGIS. The well coordinates were reprojected into the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601_Feet coordinate system. The attribute table was then trimmed to display only those wells being used as part of the cross section analysis.

- *Supplemental Wells (Supplemental Wells)* – These wells were created by converting a KMZ file into a node layer which is usable in ArcGIS. The well coordinates were reprojected into the NAD_1983_HARN_StatePlane_Washington_North_FIPS_4601_Feet coordinate system. The attribute table was then trimmed to display only those wells being used as part of the cross section analysis.
- *Novelty Hill 15ft Contours (Novelty_Contour_15ft_Smoothed)* – This is a contour layer created using the filtered 2014 Cedar River Watershed LiDAR data. The layer informs potential flow paths of precipitation on the surface prior to infiltration.

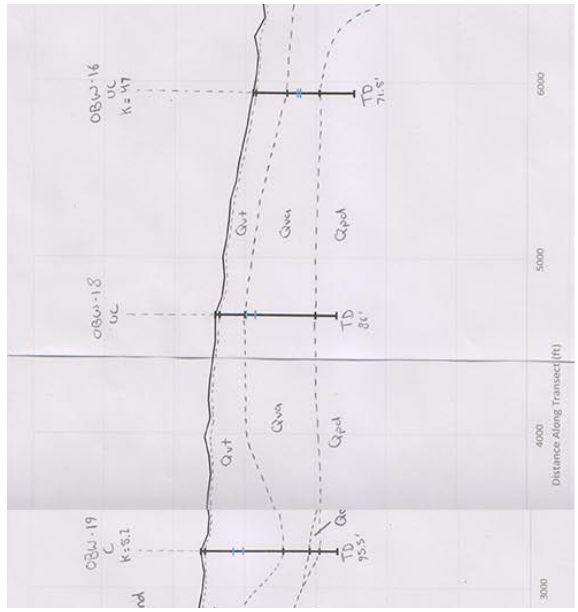
**Unless otherwise noted all layers have been projected or reprojected into the* NAD_1983_HARN_StatePlane_Washington_North_FIPS_4602_Feet coordinate system.

Appendix 2 – Cross-Section

Well Table – summary of observation wells used to create the cross-section

Well No.	Well Elevation (fmsl)	Ground Surface (fmsl)	Total Depth (ft)	Depth to Qvt (ft)	Top of Qvt (fmsl)	Depth to Qva (ft)	Top Qva (fmsl)	Depth to Qo (ft)	Top of Qo (fmsl)	Depth to Qp (ft)	Top of Qp (fmsl)
OBW-20	604.59	602.4	75.4	2	600.4	15.5	587	not pres	na	40.5	561.9
OBW-35	603.11	601.3	60.5	3	598.3	12	589	not pres	na	58	543.3
OBW-24	589.26	589.3	71	0.5	588.8	11.5	578	not pres	na	61.5	527.8
G-2	591.44	588.8	71.5	2	587	12	577	not pres	na	67	521.8
OBW-22	585.67	585.7	67.5	2	583.7	15	571	not pres	na	62	523.7
OBW-19	582.35	580.5	95.5	3	577.5	57.5	523	76	504.5	83	497.5
OBW-18	573.22	571.0	86	3	568.0	21	550	not pres	na	71	500
OBW-16	547.53	544.5	71.5	2	542.5	24	521	not pres	na	47	497.5
OBW-29	525.27	522.1	160	0.5	521.6	18	504	not pres	na	145	377.11

Cross-Section



Appendix 3 – Pump and Slug Testing

Results Table for Previous Pump Test – summary of results for 3 day constant rate pump test on OBW-25, run on 2/25/2003, analyzed by AESI

Well No.	Method	Conditions	T (ft^2/day)	K (ft/day)	Sy	Storativity
G-2	Neuman	Unconfined	129	3.2	3.98E-01	3.98E-05
OBW-22	Theis	Seasonally confined	2210	55		6.62E-04
OBW-24	Neuman	Unconfined	157	3.9	0.0226	2.26E-06
OBW-25	Neuman	Unconfined	133	3.5	0.018	

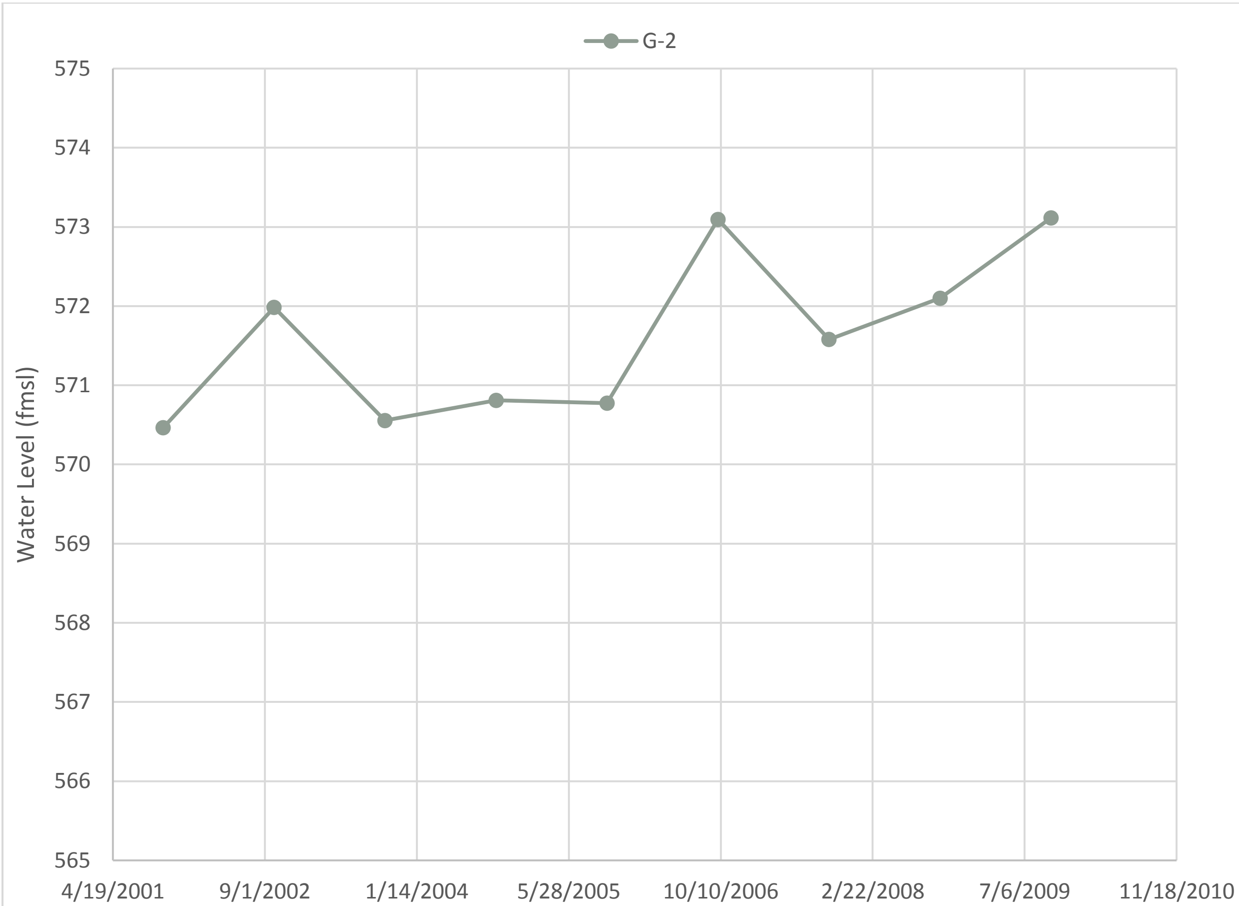
Results Table for reanalyzed Pump Test – summary of results for 3 day constant rate pump test on OBW-37, run on 5/21/2007, analyzed by Brandon Taft

Well No.	Method	Conditions	T (ft^2/day)	K (ft/day)	Sy	Storativity
G-2	Neuman	Seasonally Confined	988	18	8.93E-06	1.70E-06
OBW-19	Theis	Confined	3800	210		6.72E-06
OBW-22	Theis	Seasonally Confined	1020	22		1.65E-07
OBW-24	Neuman	Unconfined	1610	32	1.00E-06	1.43E-06
OBW-30	Hantush	Confined	856	42		2.90E-06
OBW-31	Hantush	Seasonally Confined	1700	37		6.37E-06
OBW-32	Hantush	Confined	1010	26		2.05E-05
OBW-33	Neuman	Unconfined	1550	32	1.59E-06	3.44E-06
OBW-34	Hantush	Confined	2210	200		6.66E-06
OBW-36	Hantush	Confined	985	25		1.98E-05

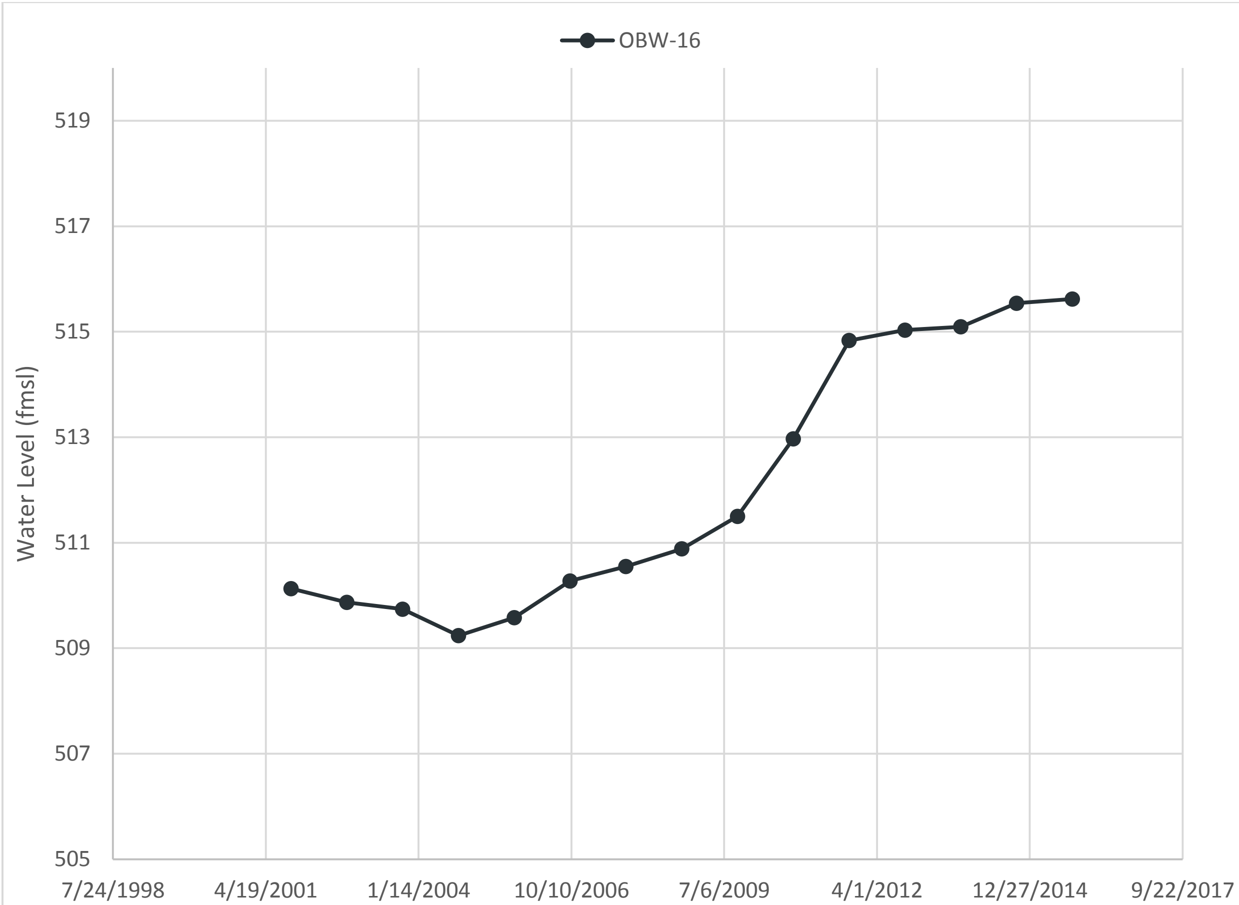
Results Table for Slug Tests – summary of slug test results, analyzed by AESI

Well No.	OBW-16	OBW-19	OBW-28
Method	KGS Model	KGS Model	KGS Model
	Unconfined	Confined	Confined
Kr (ft/day)	47	5.2	1.7
Ss (/ft)	8.8E-06	4.7E-05	0.011
Kz/Kr	0.1	0.1	0.1

Appendix 4 – Average Annual Hydraulic Head
Transect Wells
G-2

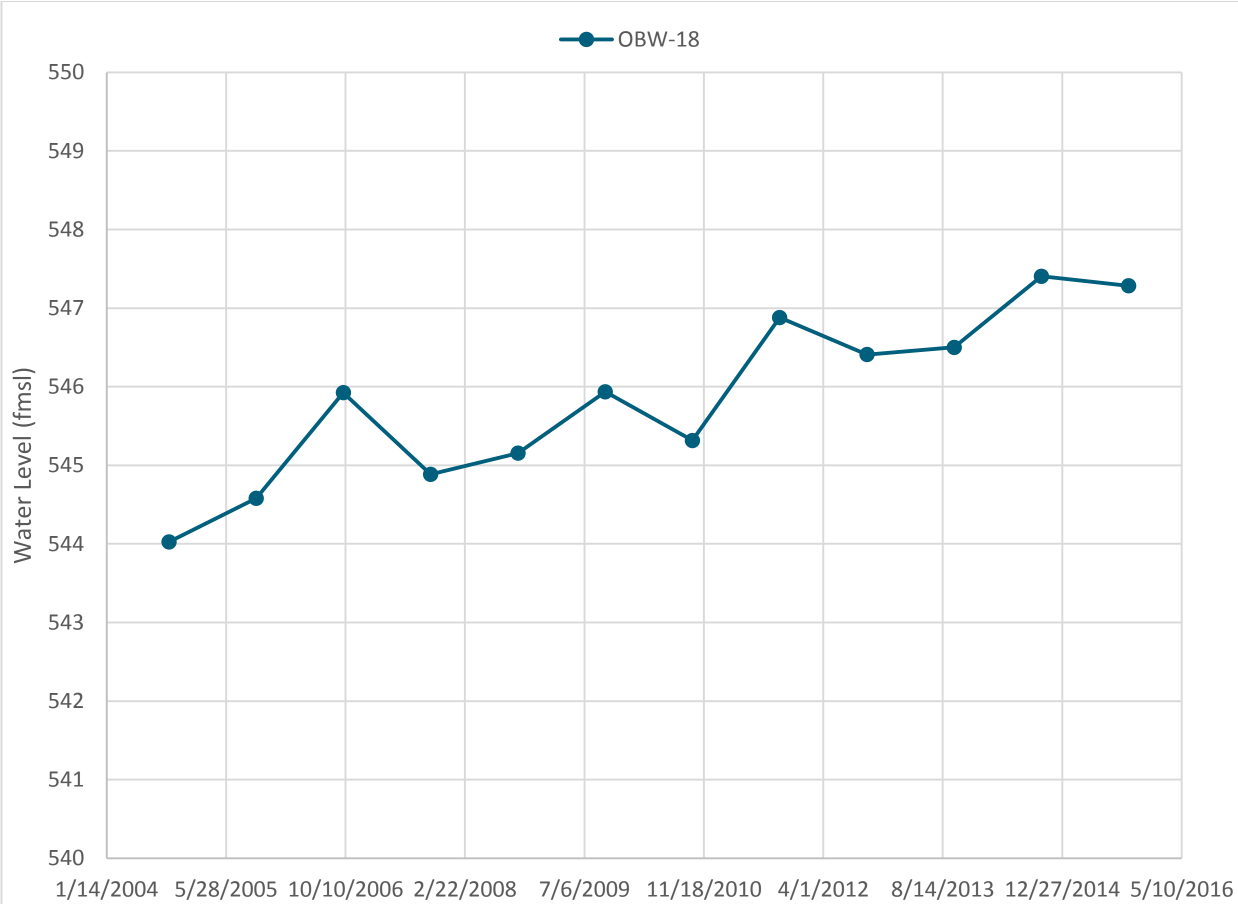


OBW-16



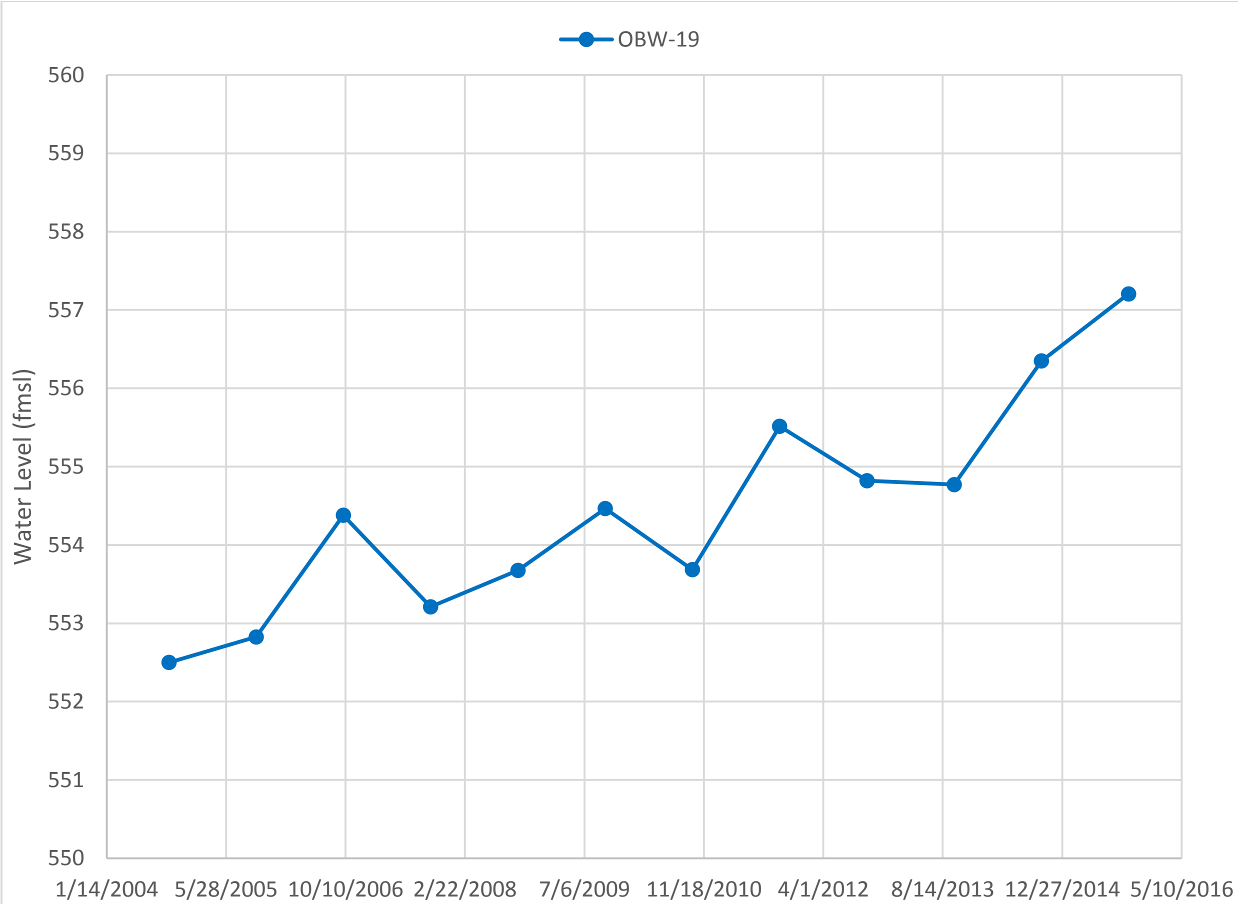
OBW-16
Water Level (fmsl)
519
517
515
513
511
509
507
505
7/24/1998
4/19/2001
1/14/2004
10/10/2006
7/6/2009
4/1/2012
12/27/2014
9/22/2017

OBW-18



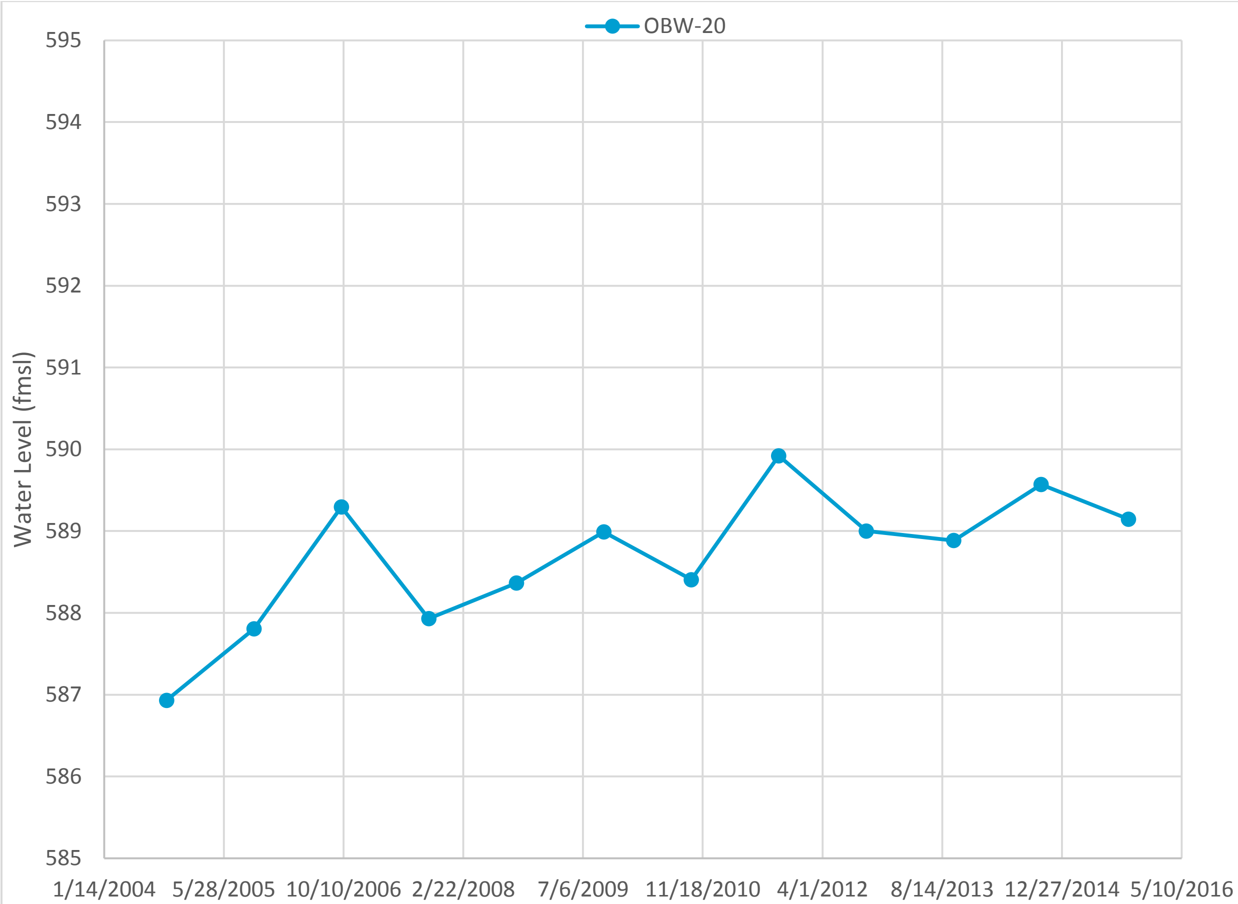
OBW-18
550
549
548
547
546
545
544
543
542
541
540
Water Level (fmsl)
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010
4/1/2012
8/14/2013
12/27/2014
5/10/2016

OBW-19



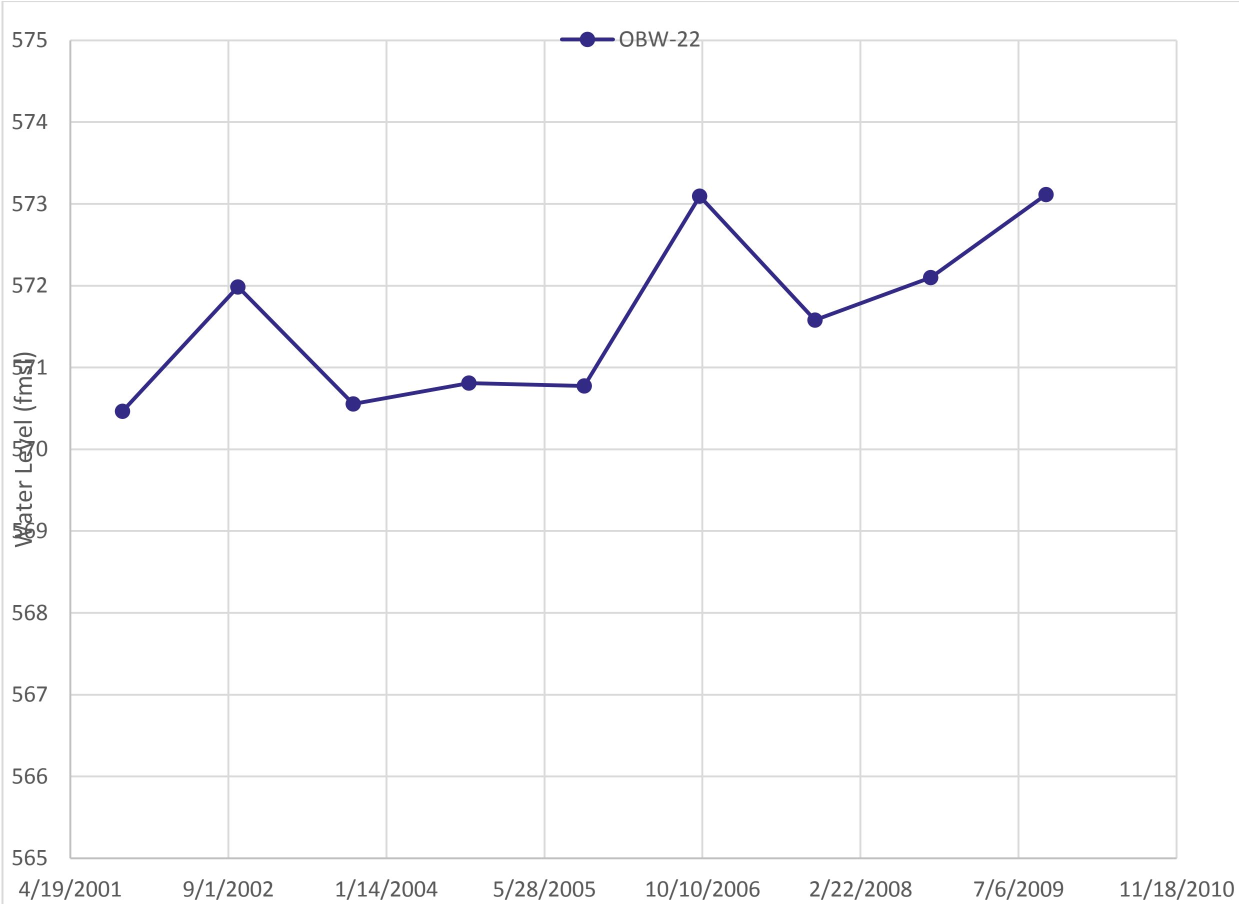
OBW-19
560
559
558
557
556
555
554
553
552
551
550
Water Level (fmsl)
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010
4/1/2012
8/14/2013
12/27/2014
5/10/2016

OBW-20



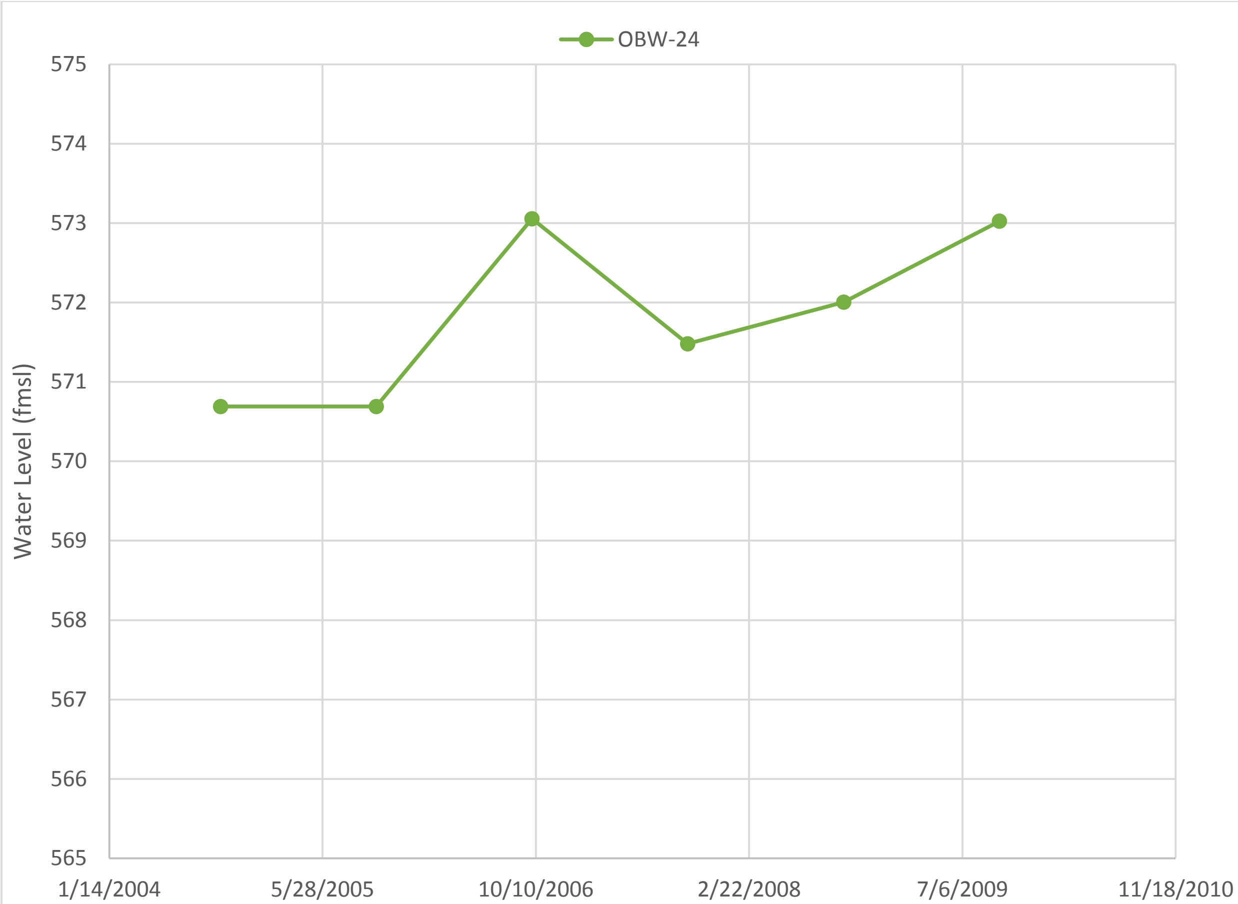
OBW-20
595
594
593
592
591
590
589
588
587
586
585
Water Level (fmsl)
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010
4/1/2012
8/14/2013
12/27/2014
5/10/2016

OBW-22

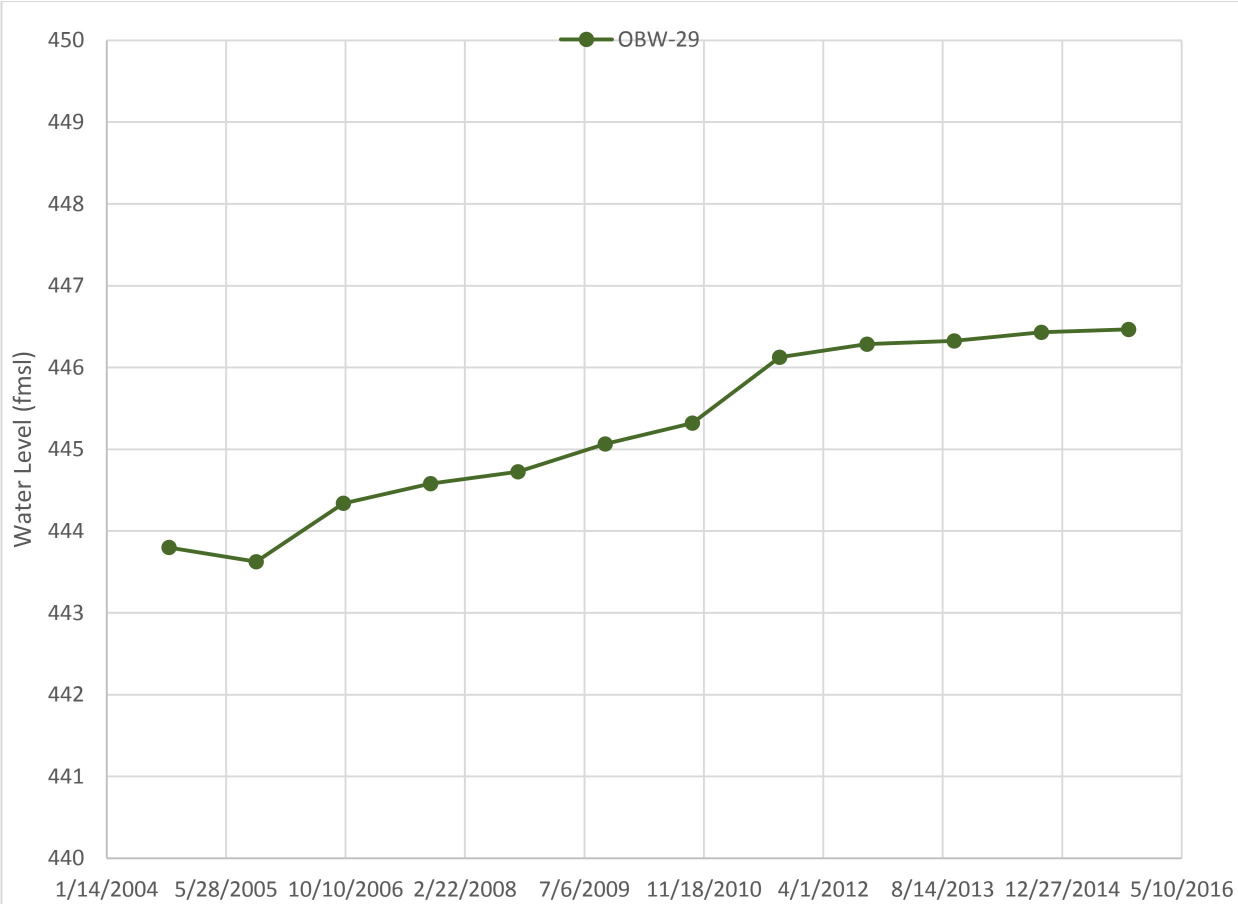


OBW-22
575
574
573
572
571
570
569
568
567
566
565
Water Level (fmsl)
4/19/2001
9/1/2002
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010

OBW-24

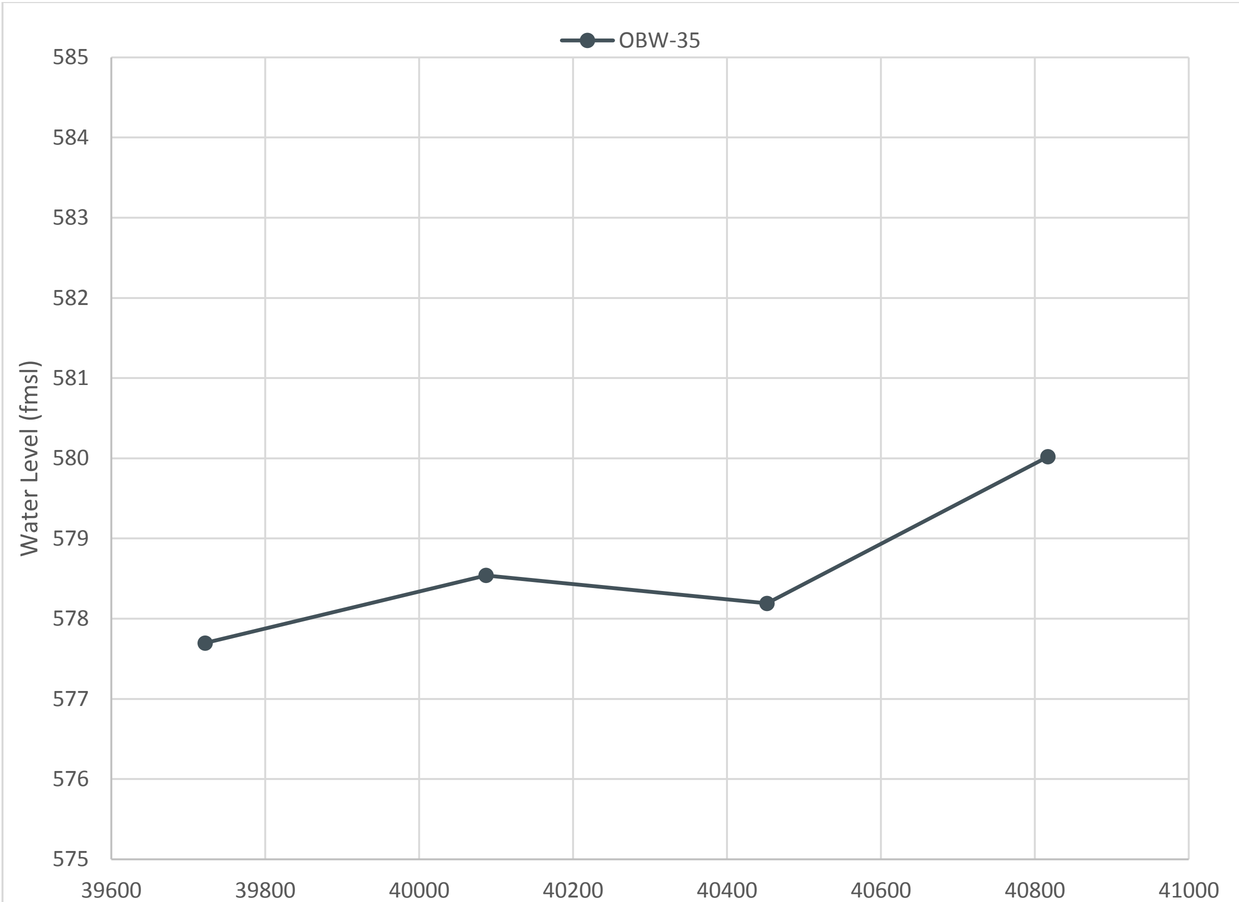

OBW-24
575
574
573
572
571
570
569
568
567
566
565
Water Level (fmsl)
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010

OBW-29



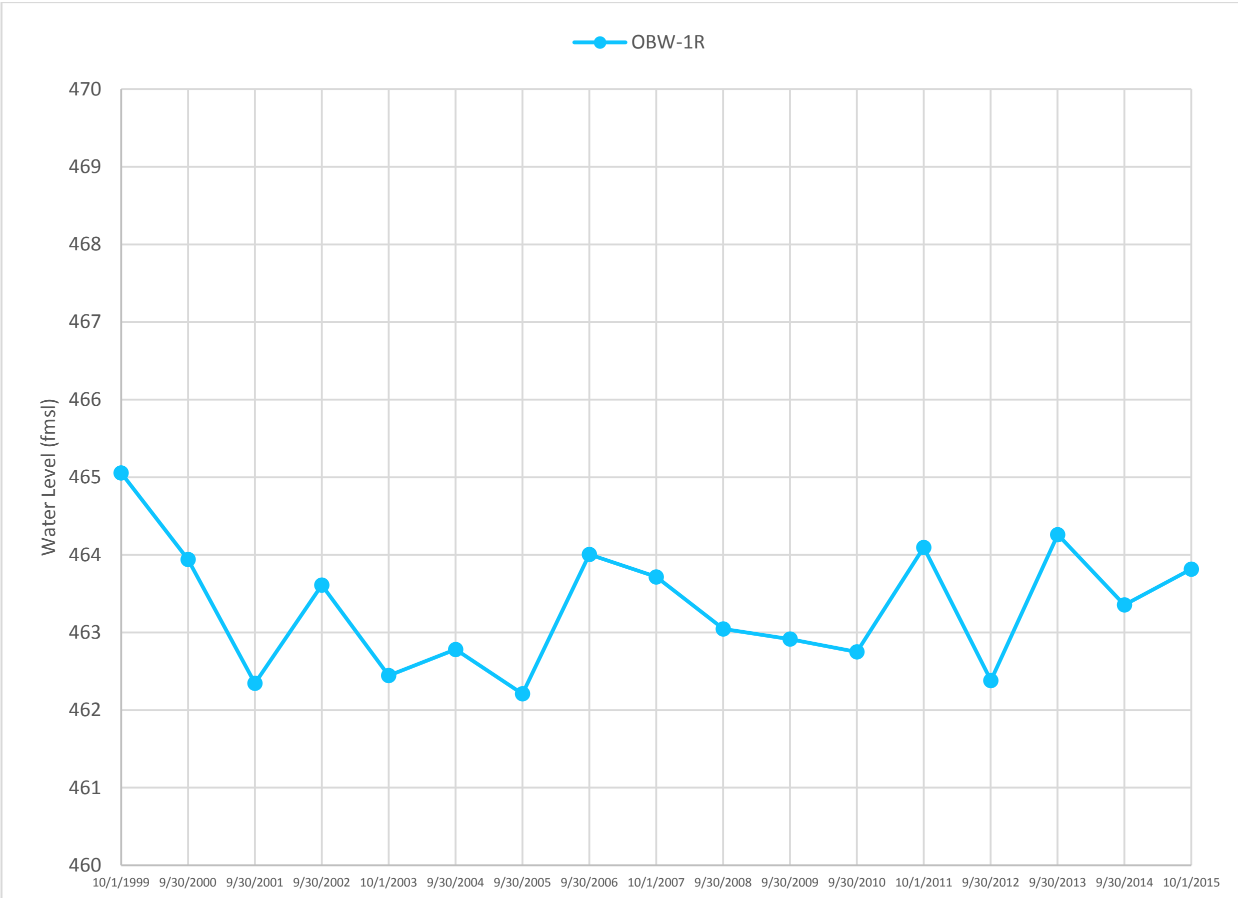
OBW-29
450
449
448
447
446
445
444
443
442
441
440
Water Level (fmsl)
1/14/2004
5/28/2005
10/10/2006
2/22/2008
7/6/2009
11/18/2010
4/1/2012
8/14/2013
12/27/2014
5/10/2016

OBW-35

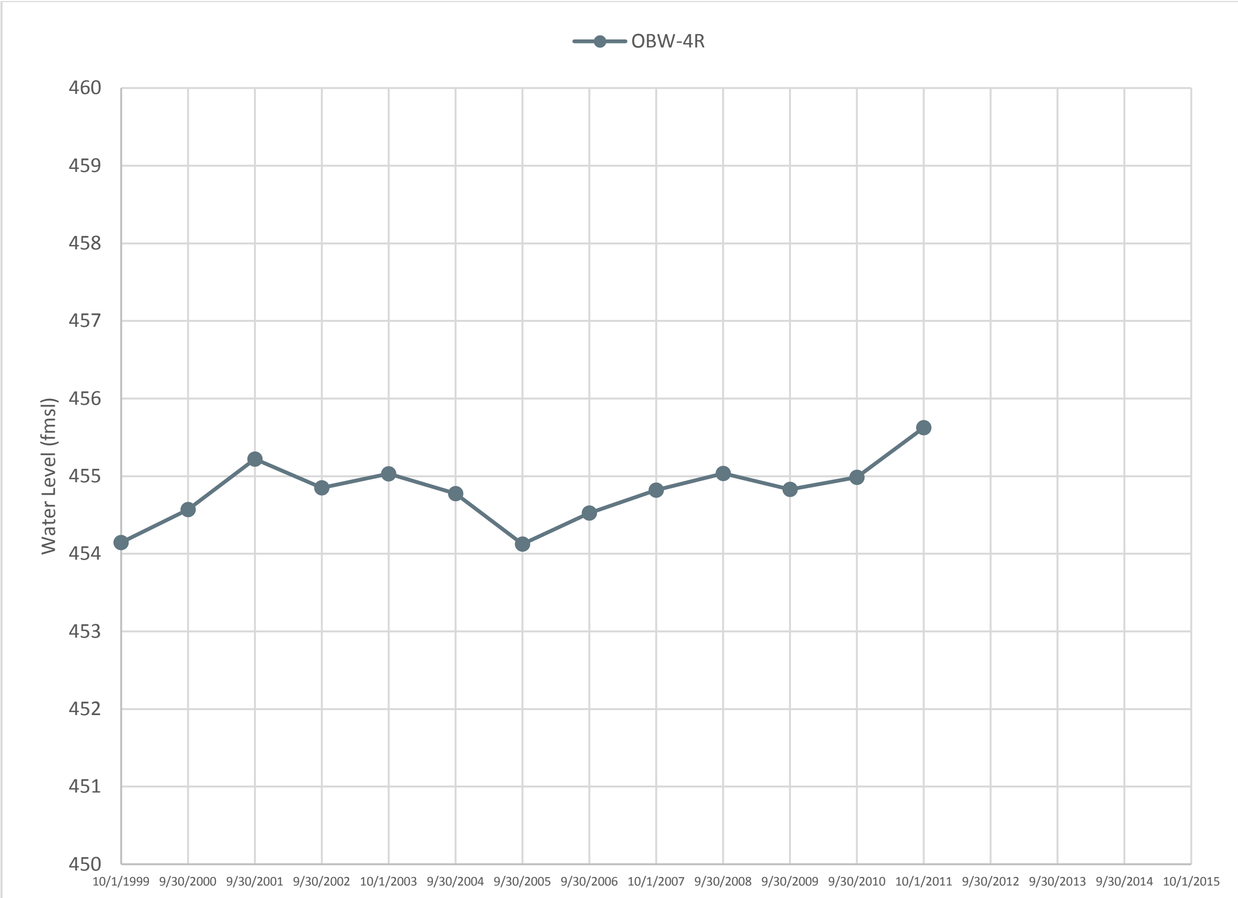

OBW-35
585
584
583
582
581
580
579
578
577
576
575
Water Level (fmsl)
39600
39800
40000
40200
40400
40600
40800
41000

Additional Wells

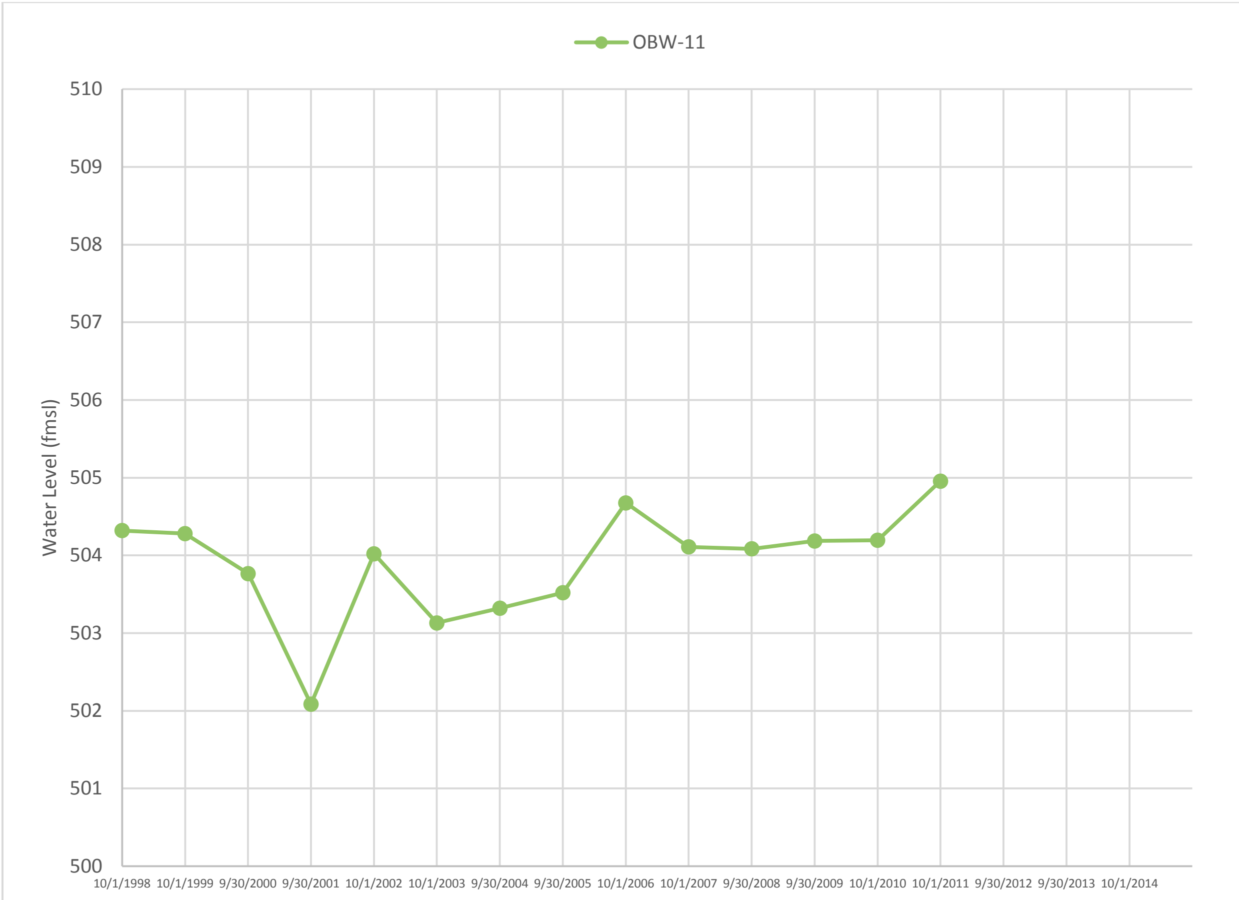
OBW-1R



OBW-4R

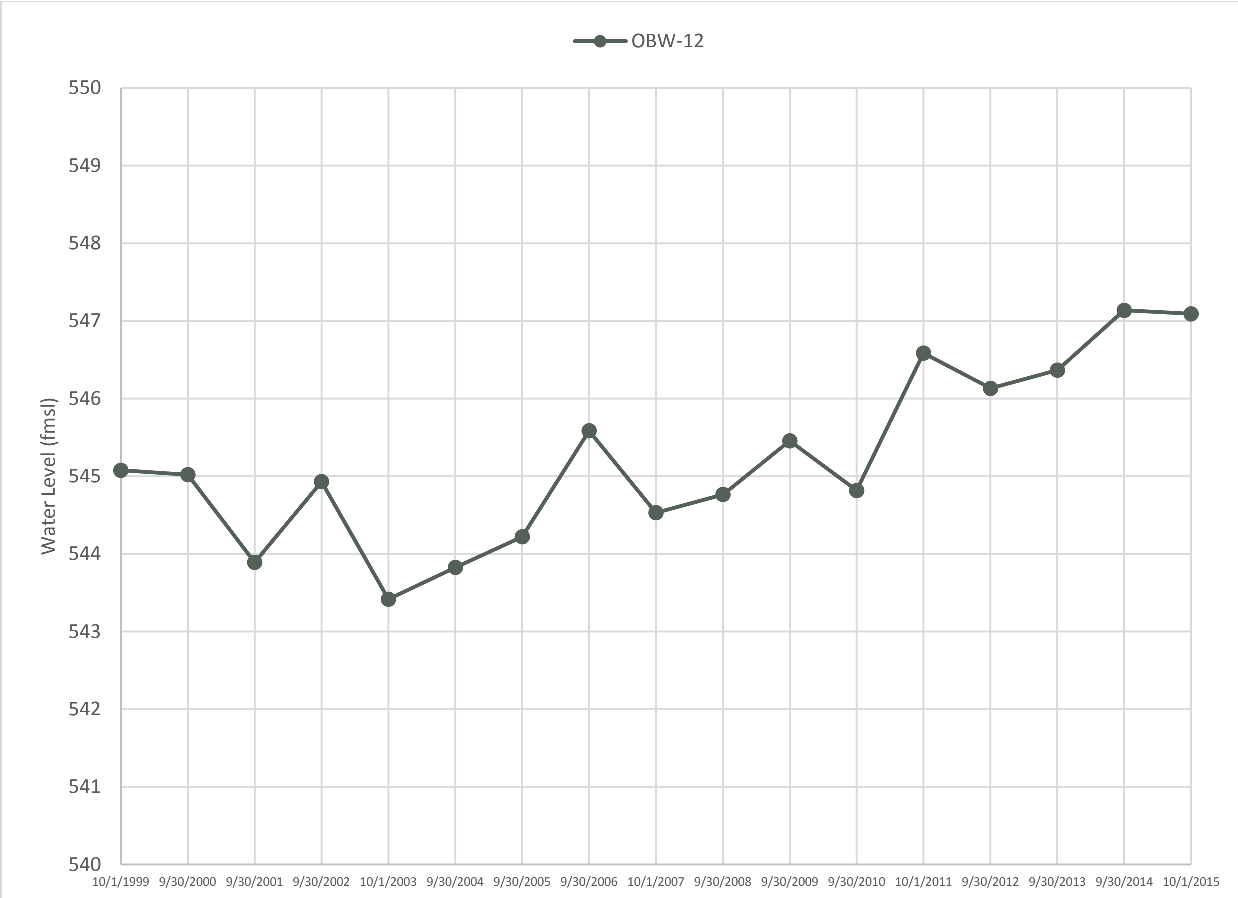

OBW-4R
Water Level (fmsl)
460
459
458
457
456
455
454
453
452
451
450
10/1/1999
9/30/2000
9/30/2001
9/30/2002
10/1/2003
9/30/2004
9/30/2005
9/30/2006
10/1/2007
9/30/2008
9/30/2009
9/30/2010
10/1/2011
9/30/2012
9/30/2013
9/30/2014
10/1/2015

OBW-11



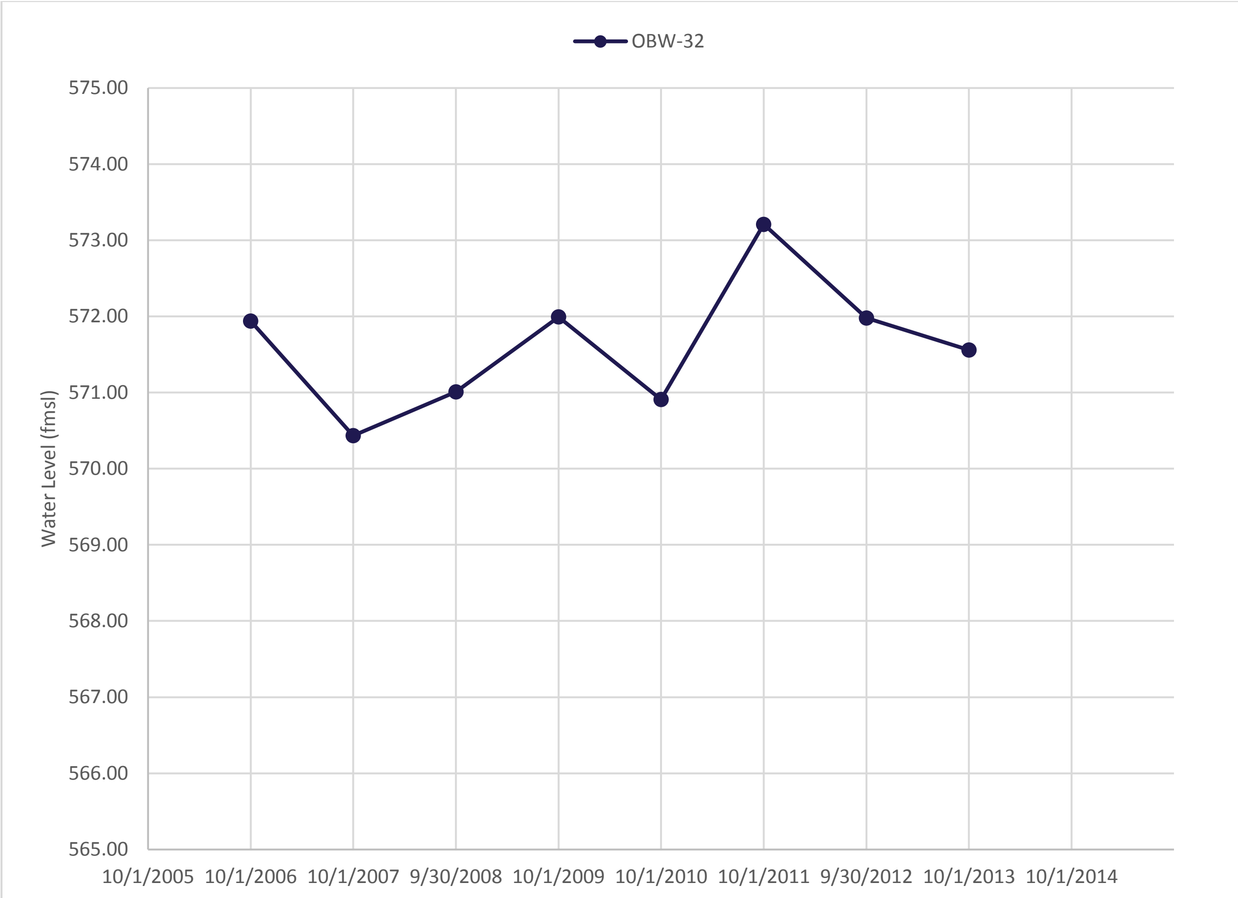
OBW-11
Water Level (fmsl)
510
509
508
507
506
505
504
503
502
501
500
10/1/1998
10/1/1999
9/30/2000
9/30/2001
10/1/2002
10/1/2003
9/30/2004
9/30/2005
10/1/2006
10/1/2007
9/30/2008
9/30/2009
10/1/2010
10/1/2011
9/30/2012
9/30/2013
10/1/2014

OBW-12

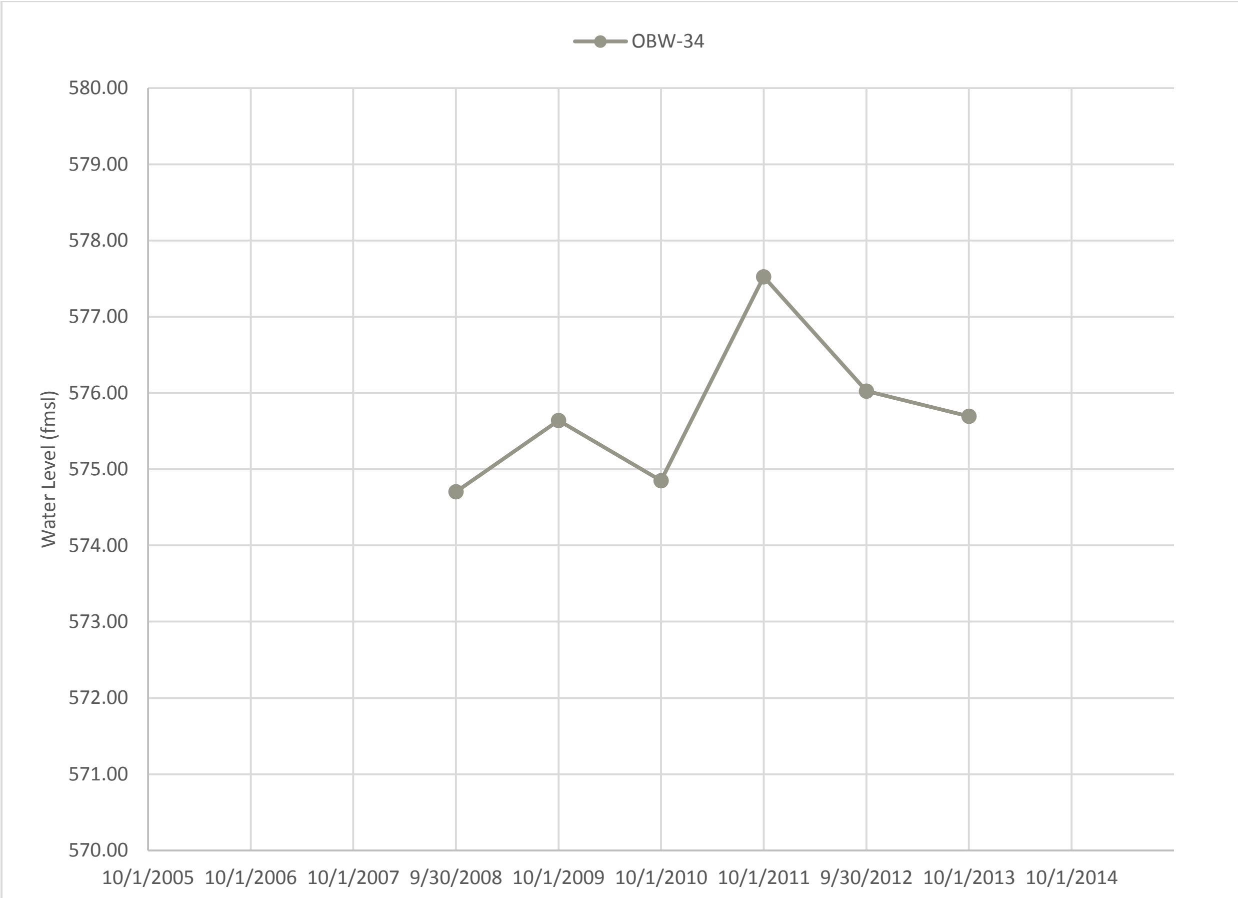


OBW-12
Water Level (fmsl)
550
549
548
547
546
545
544
543
542
541
540
10/1/1999
9/30/2000
9/30/2001
9/30/2002
10/1/2003
9/30/2004
9/30/2005
9/30/2006
10/1/2007
9/30/2008
9/30/2009
9/30/2010
10/1/2011
9/30/2012
9/30/2013
9/30/2014
10/1/2015

OBW-32


OBW-32
575.00
574.00
573.00
572.00
571.00
570.00
569.00
568.00
567.00
566.00
565.00
Water Level (fmsl)
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

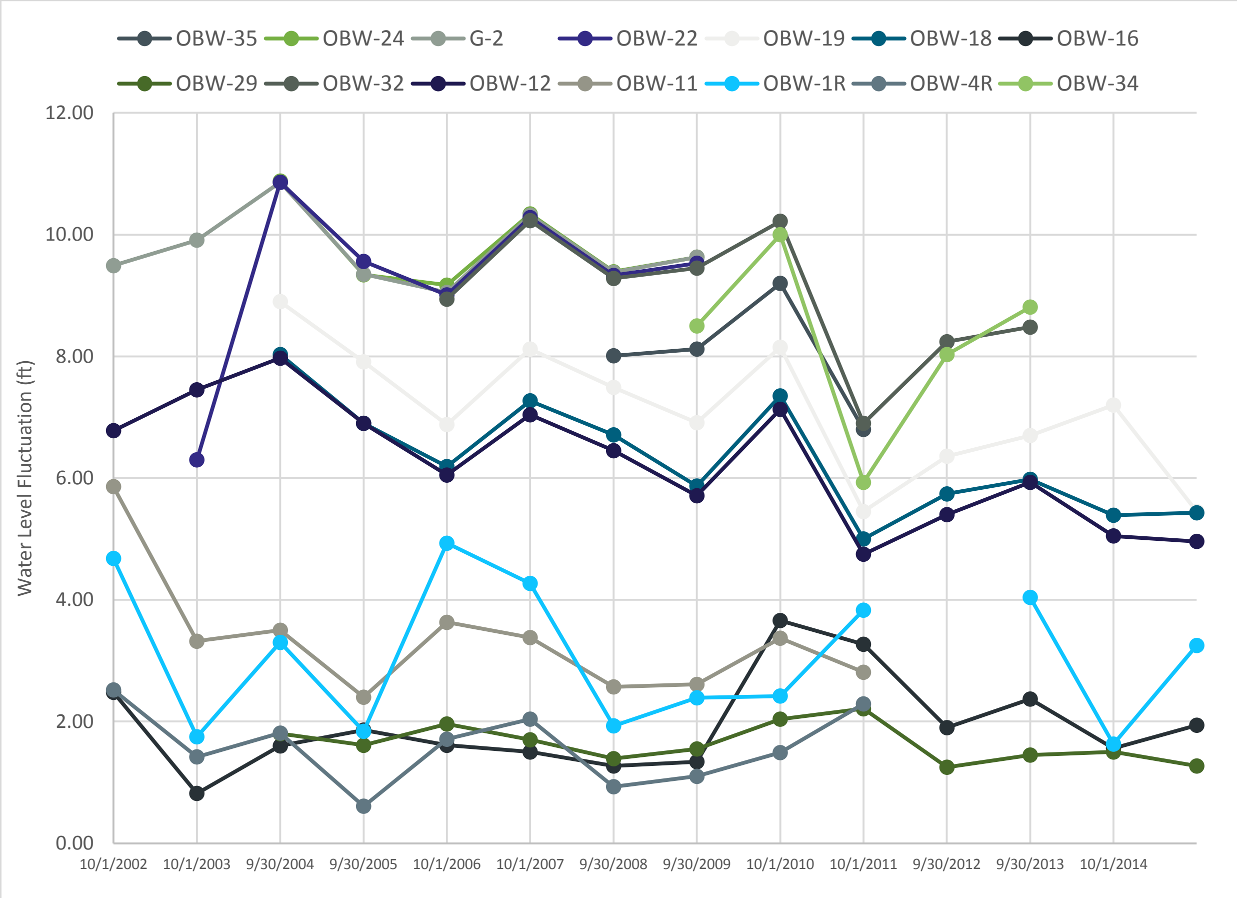
OBW-34



OBW-34
580.00
579.00
578.00
577.00
576.00
575.00
574.00
573.00
572.00
571.00
570.00
Water Level (fmsl)
10/1/2005 10/1/2006 10/1/2007 9/30/2008 10/1/2009 10/1/2010 10/1/2011 9/30/2012 10/1/2013 10/1/2014

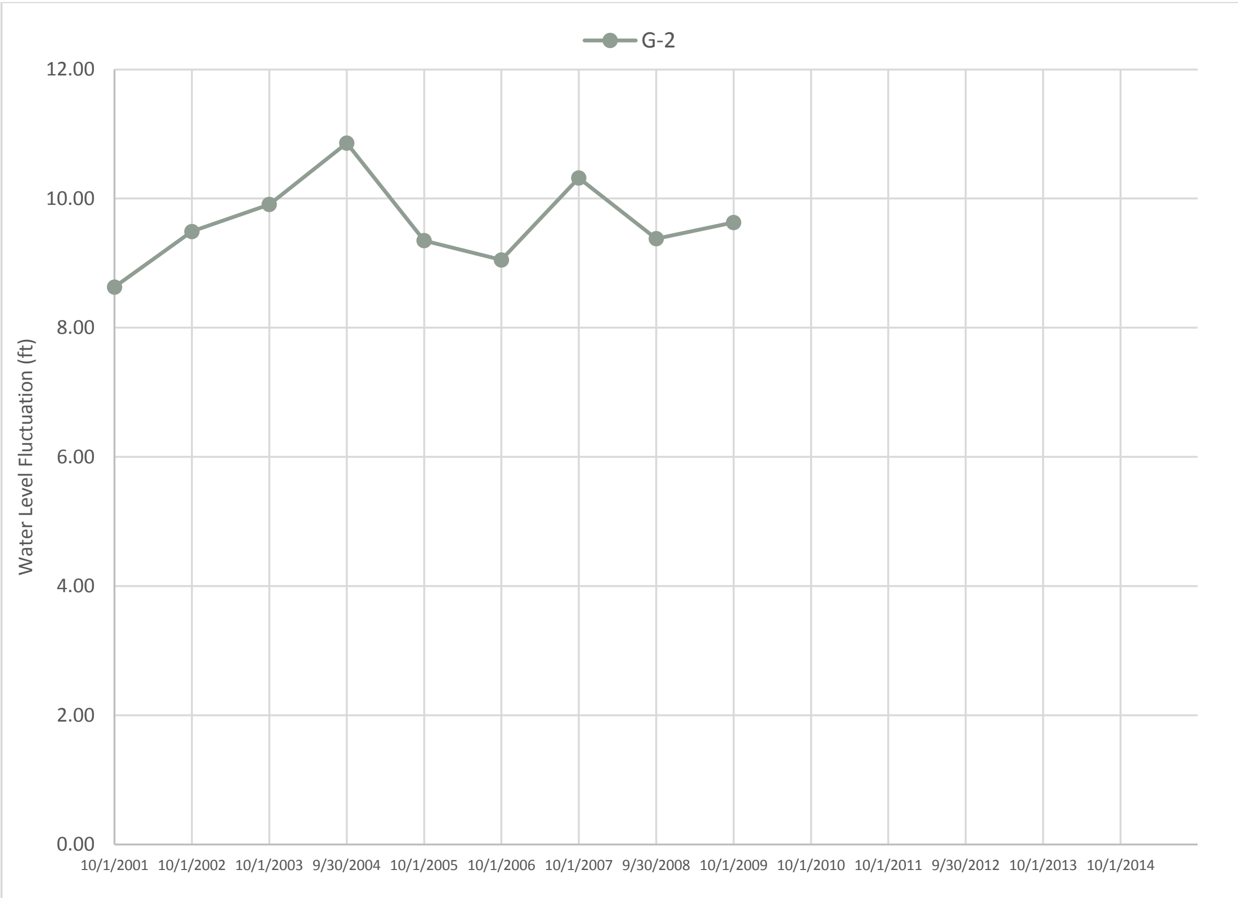
Appendix 5 – Annual Water Level Fluctuations

All Wells

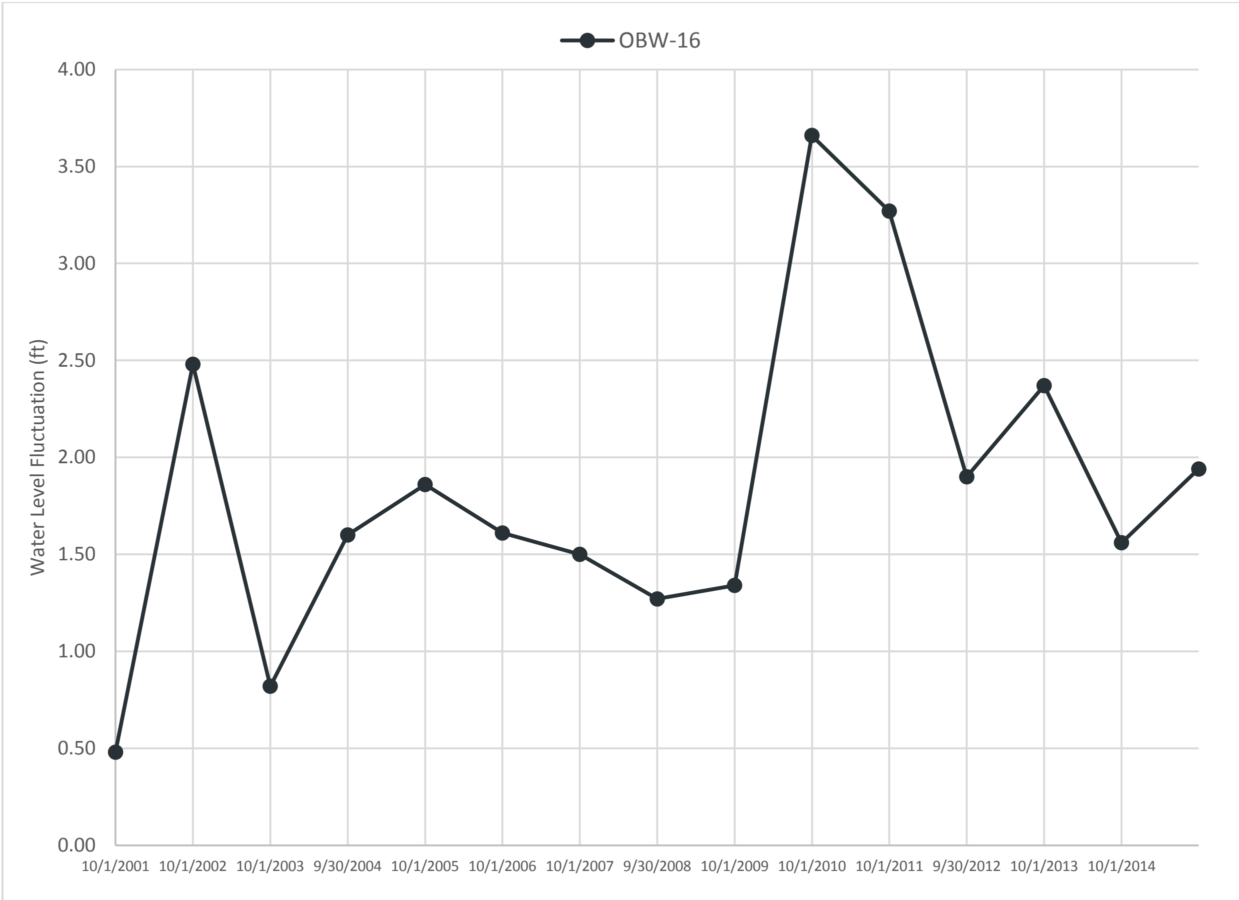


Transect Wells

G-2

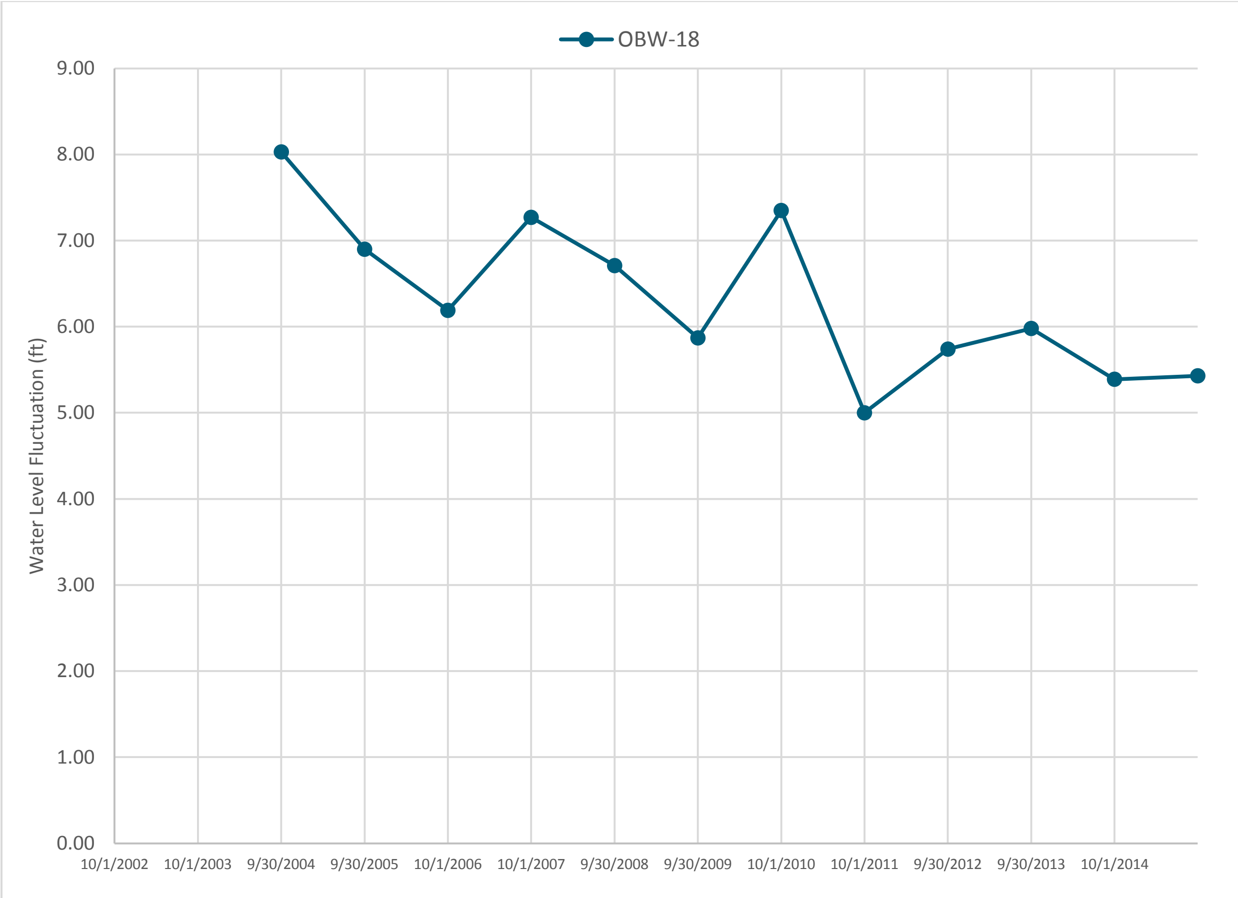


OBW-16



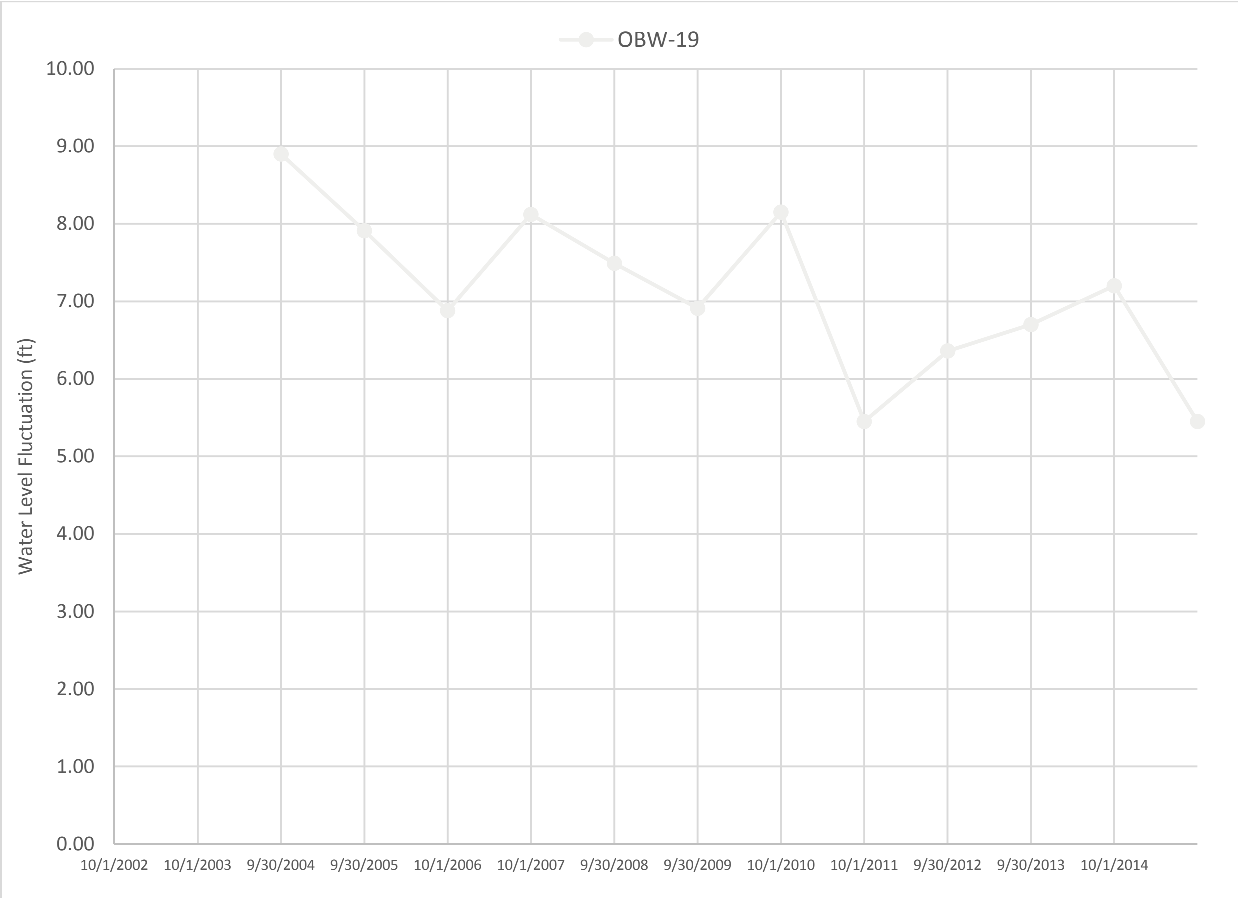
OBW-16
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

OBW-18



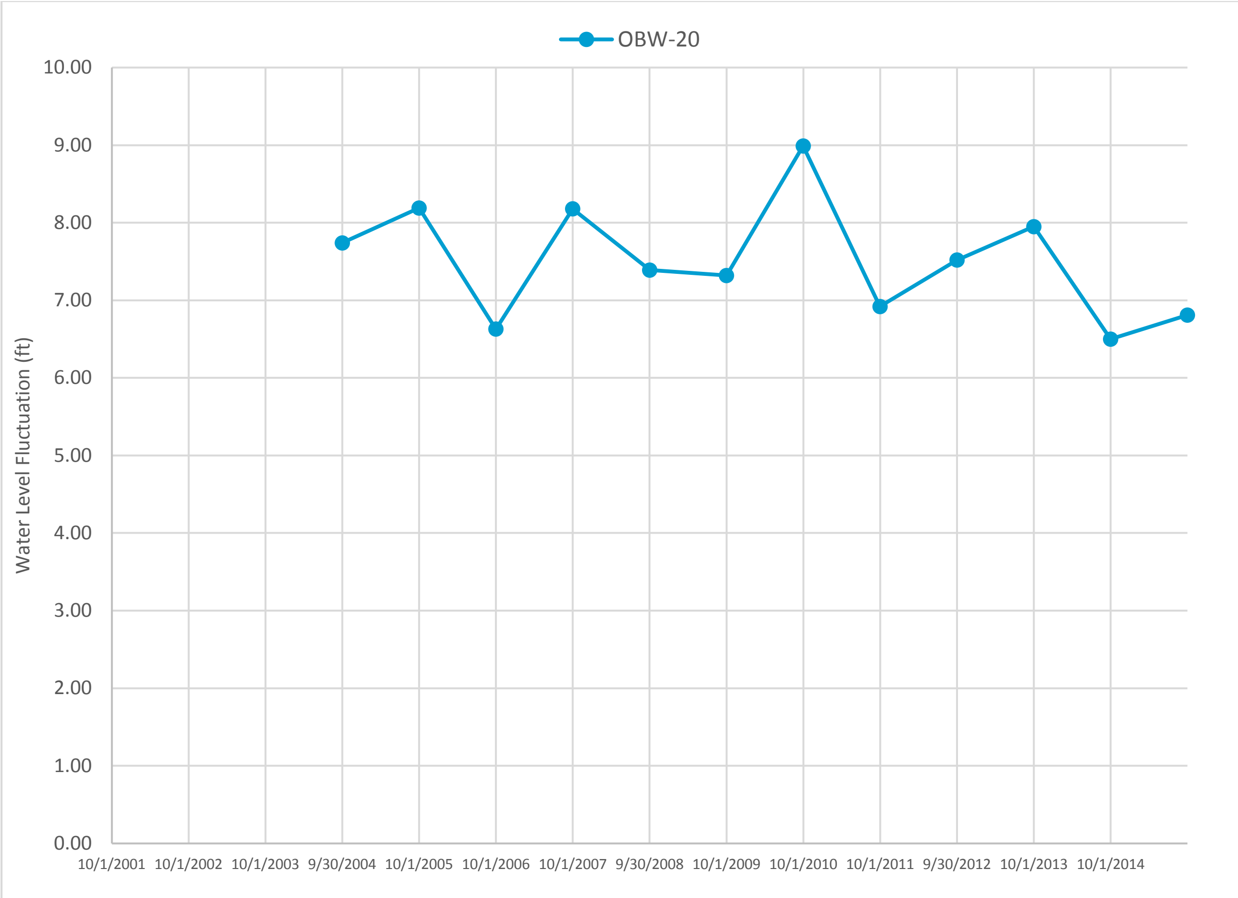
OBW-18
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Water Level Fluctuation (ft)
10/1/2002
10/1/2003
9/30/2004
9/30/2005
10/1/2006
10/1/2007
9/30/2008
9/30/2009
10/1/2010
10/1/2011
9/30/2012
9/30/2013
10/1/2014

OBW-19

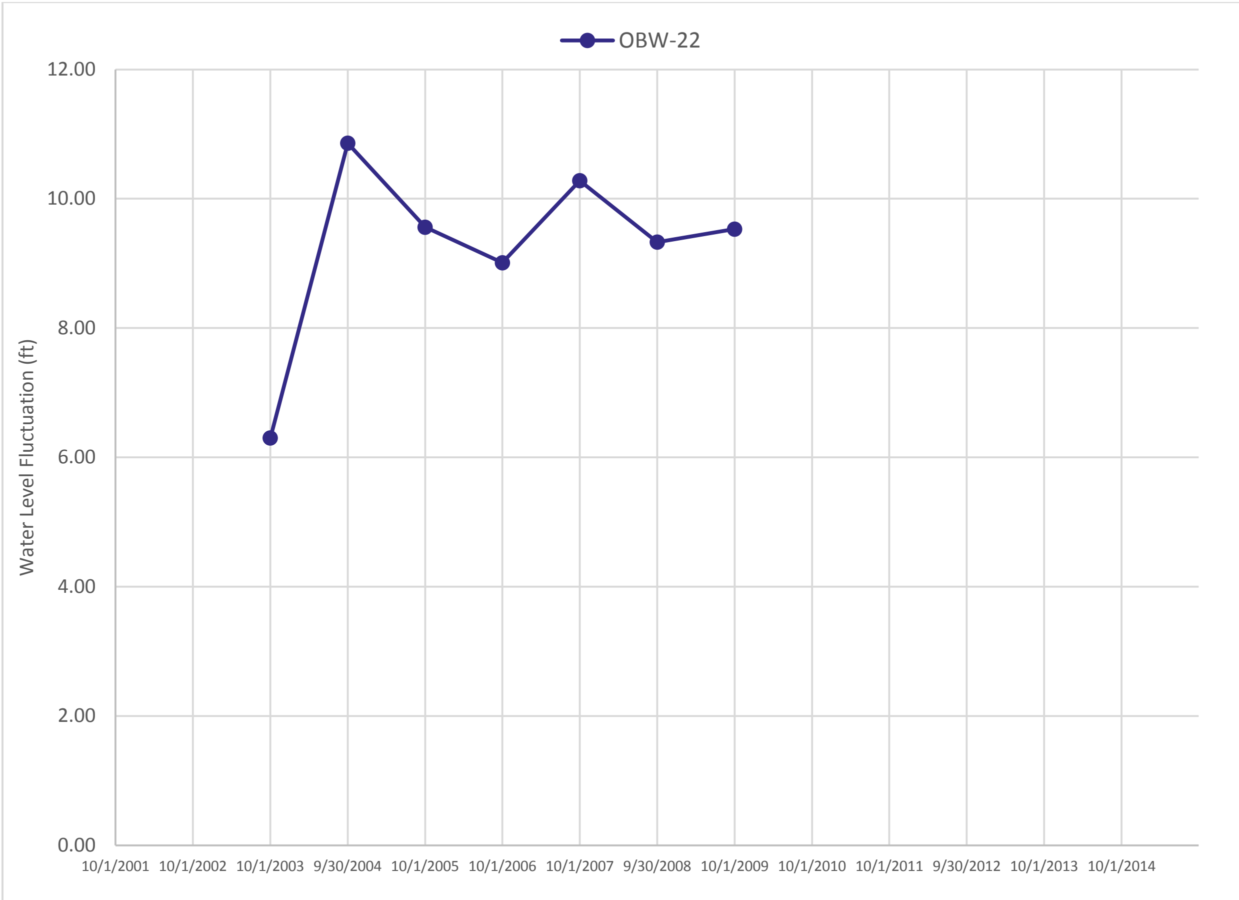


OBW-19
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Water Level Fluctuation (ft)
10/1/2002
10/1/2003
9/30/2004
9/30/2005
10/1/2006
10/1/2007
9/30/2008
9/30/2009
10/1/2010
10/1/2011
9/30/2012
9/30/2013
10/1/2014

OBW-20

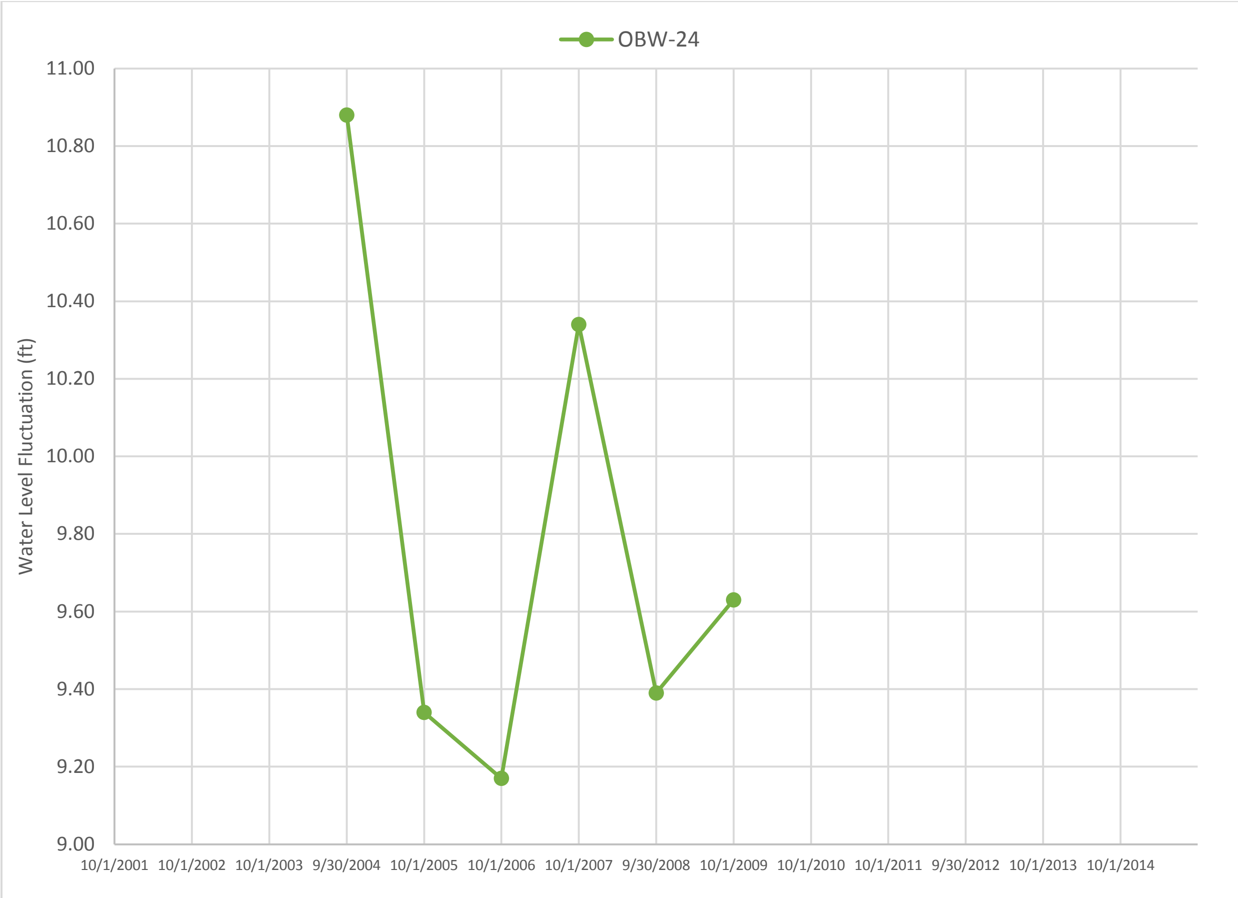

OBW-20
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

OBW-22



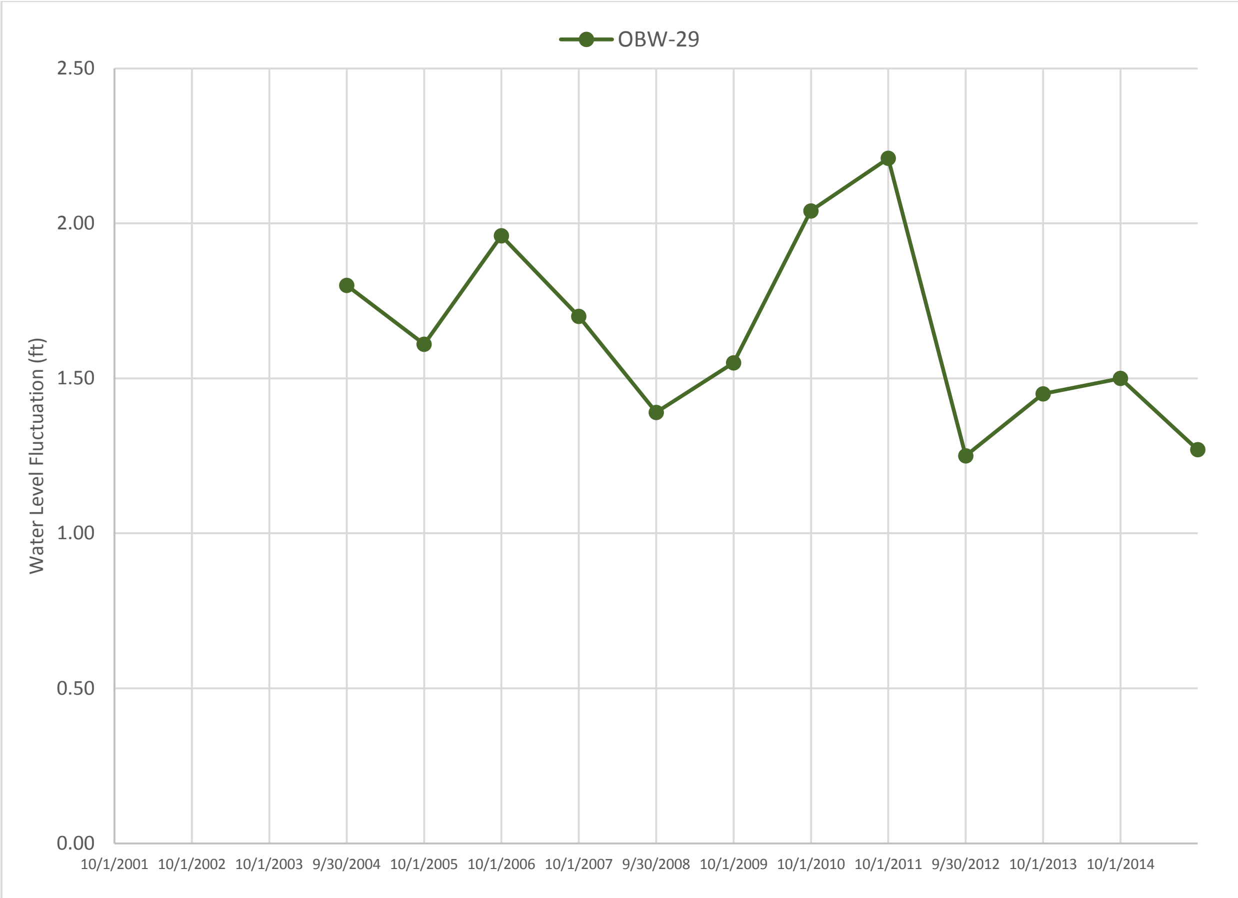
OBW-22
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

OBW-24

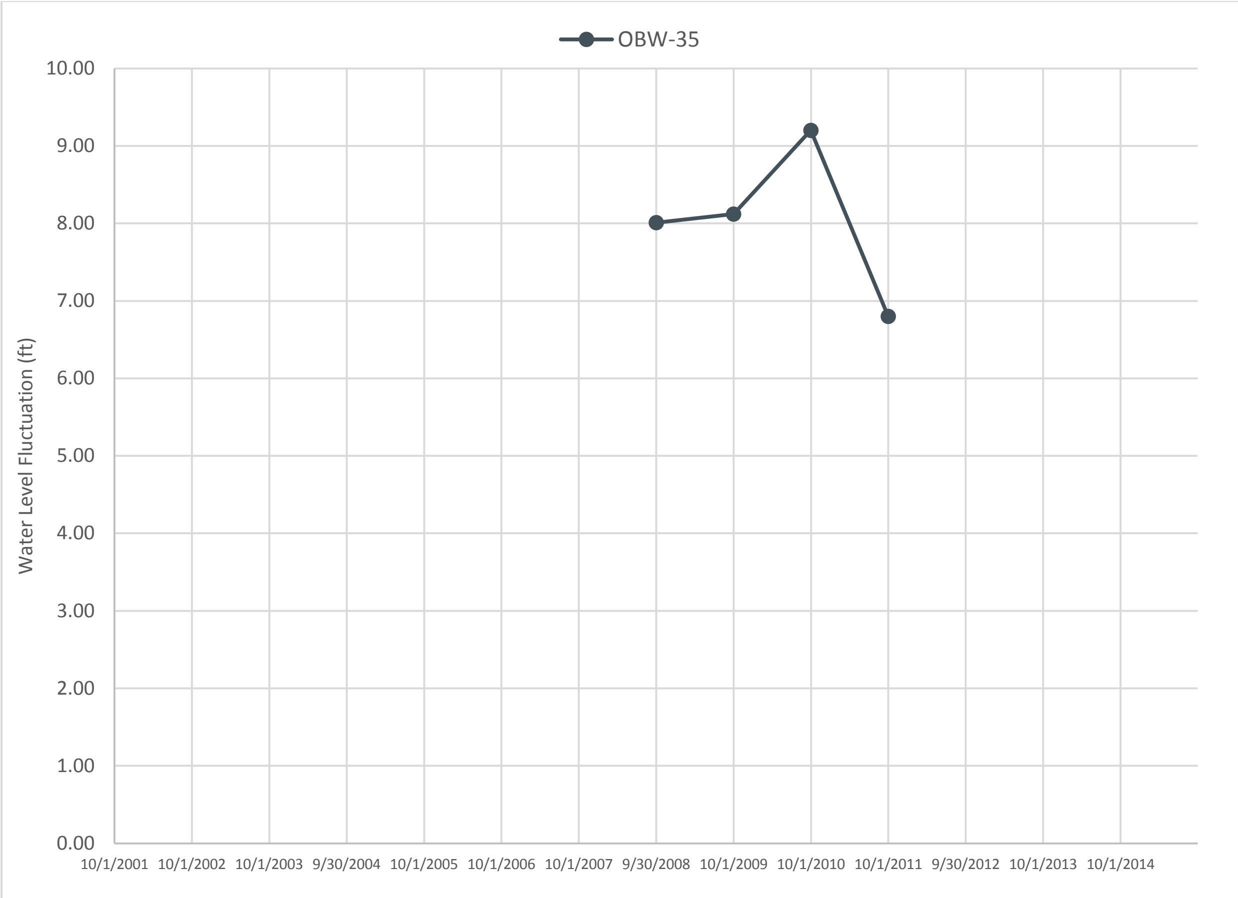


OBW-24
11.00
10.80
10.60
10.40
10.20
10.00
9.80
9.60
9.40
9.20
9.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

OBW-29


OBW-29
Water Level Fluctuation (ft)
2.50
2.00
1.50
1.00
0.50
0.00
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

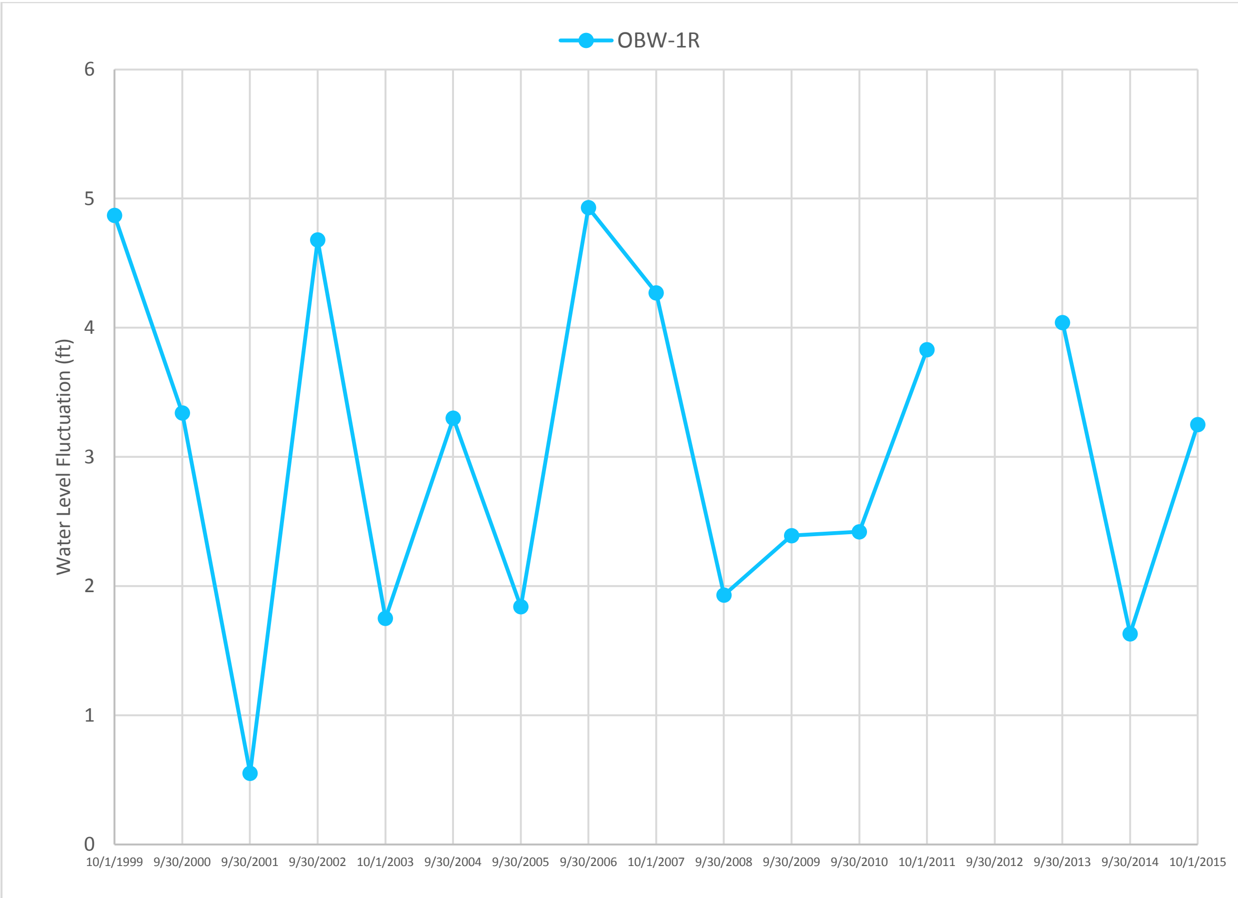
OBW-35



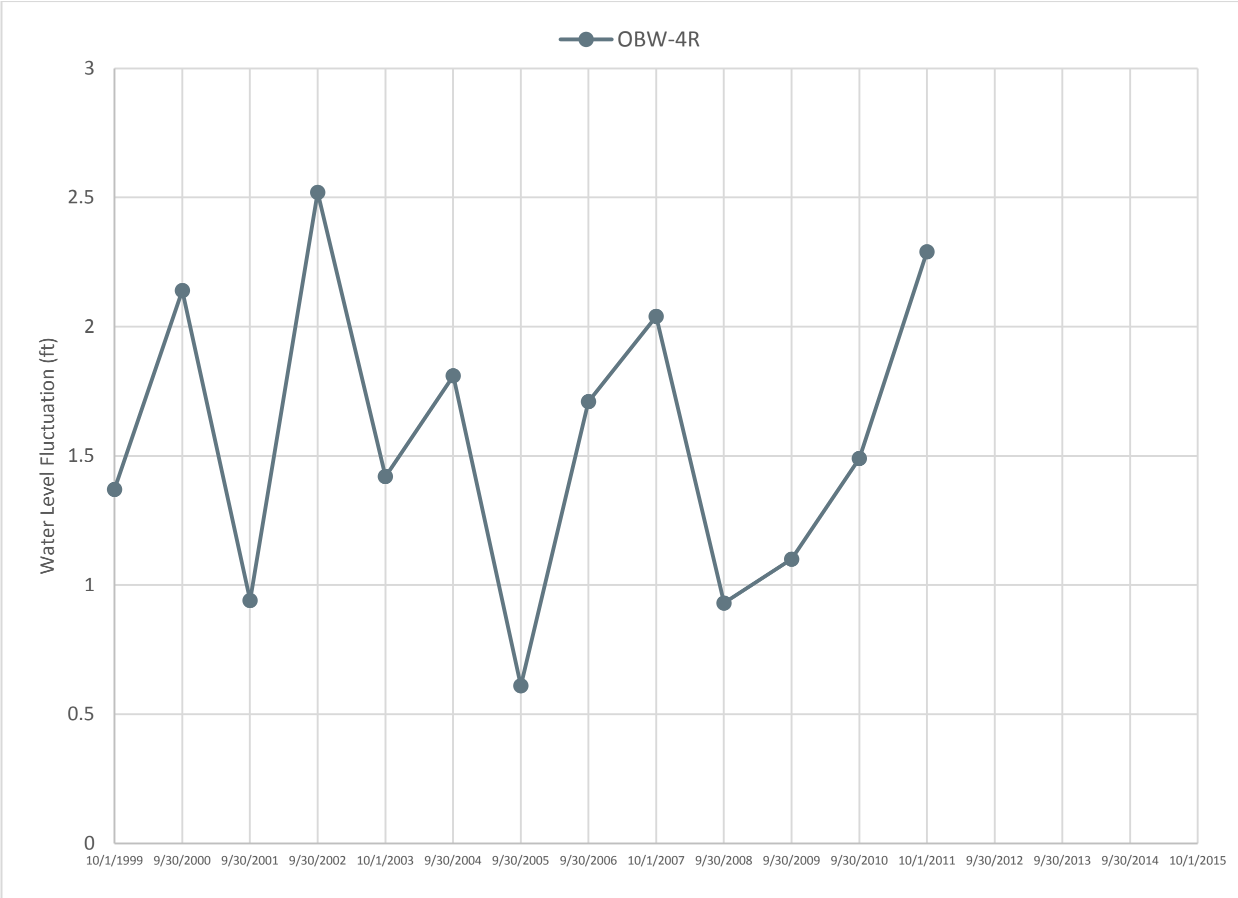
OBW-35
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

Supplemental Wells

OBW-1R

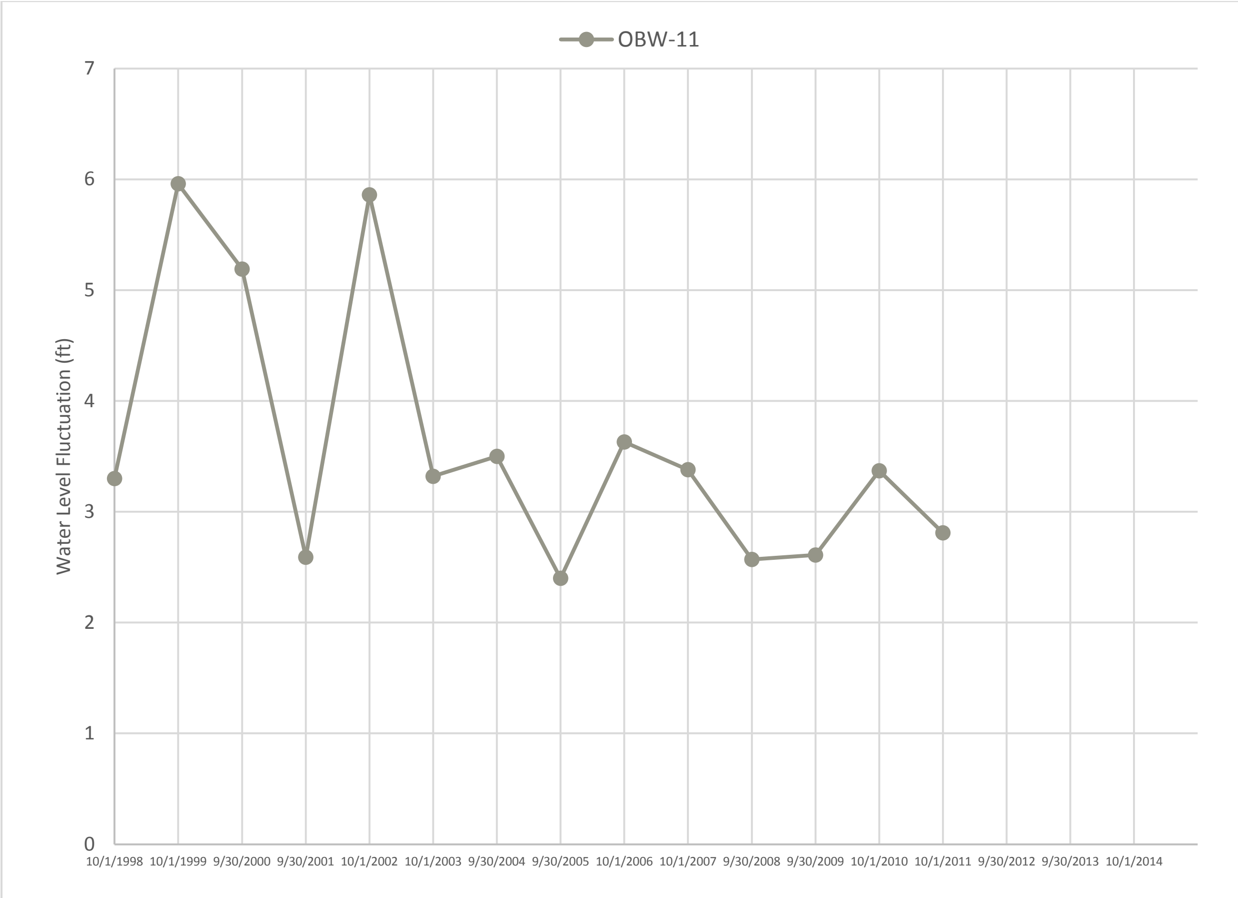


OBW-4R



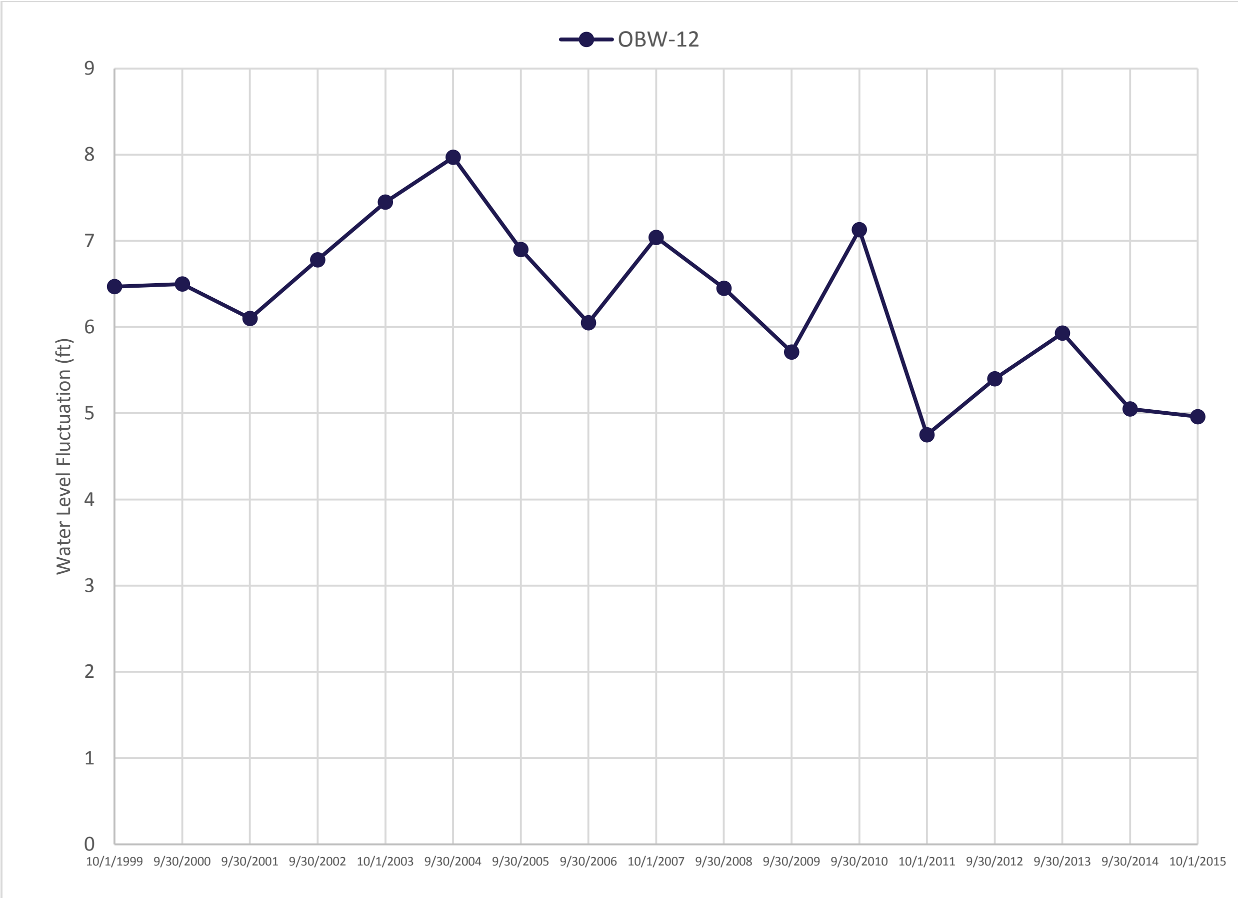
OBW-4R
3
2.5
2
1.5
1
0.5
0
Water Level Fluctuation (ft)
10/1/1999
9/30/2000
9/30/2001
9/30/2002
10/1/2003
9/30/2004
9/30/2005
9/30/2006
10/1/2007
9/30/2008
9/30/2009
9/30/2010
10/1/2011
9/30/2012
9/30/2013
9/30/2014
10/1/2015

OBW-11



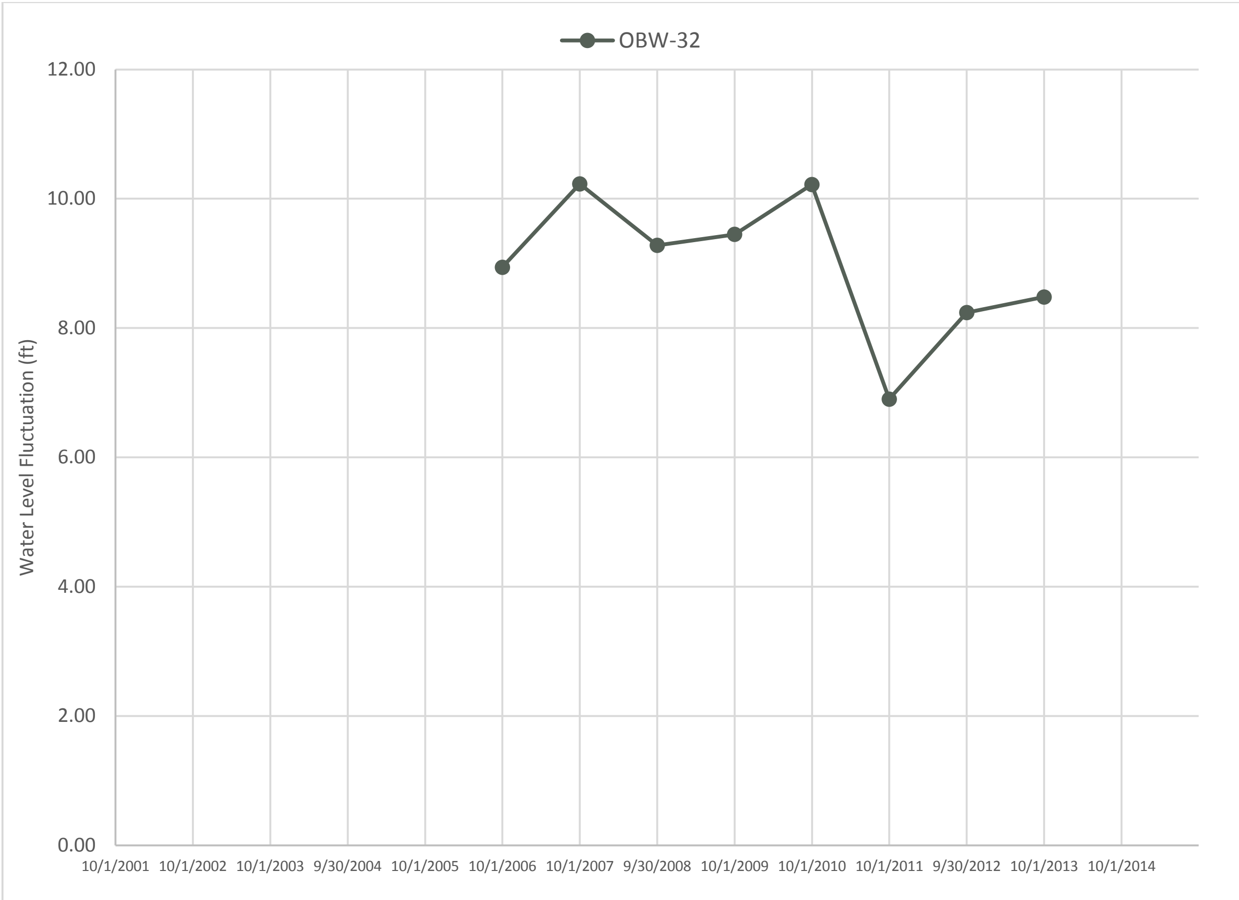
OBW-11
Water Level Fluctuation (ft)
0
1
2
3
4
5
6
7
10/1/1998
10/1/1999
9/30/2000
9/30/2001
10/1/2002
10/1/2003
9/30/2004
9/30/2005
10/1/2006
10/1/2007
9/30/2008
9/30/2009
10/1/2010
10/1/2011
9/30/2012
9/30/2013
10/1/2014

OBW-12

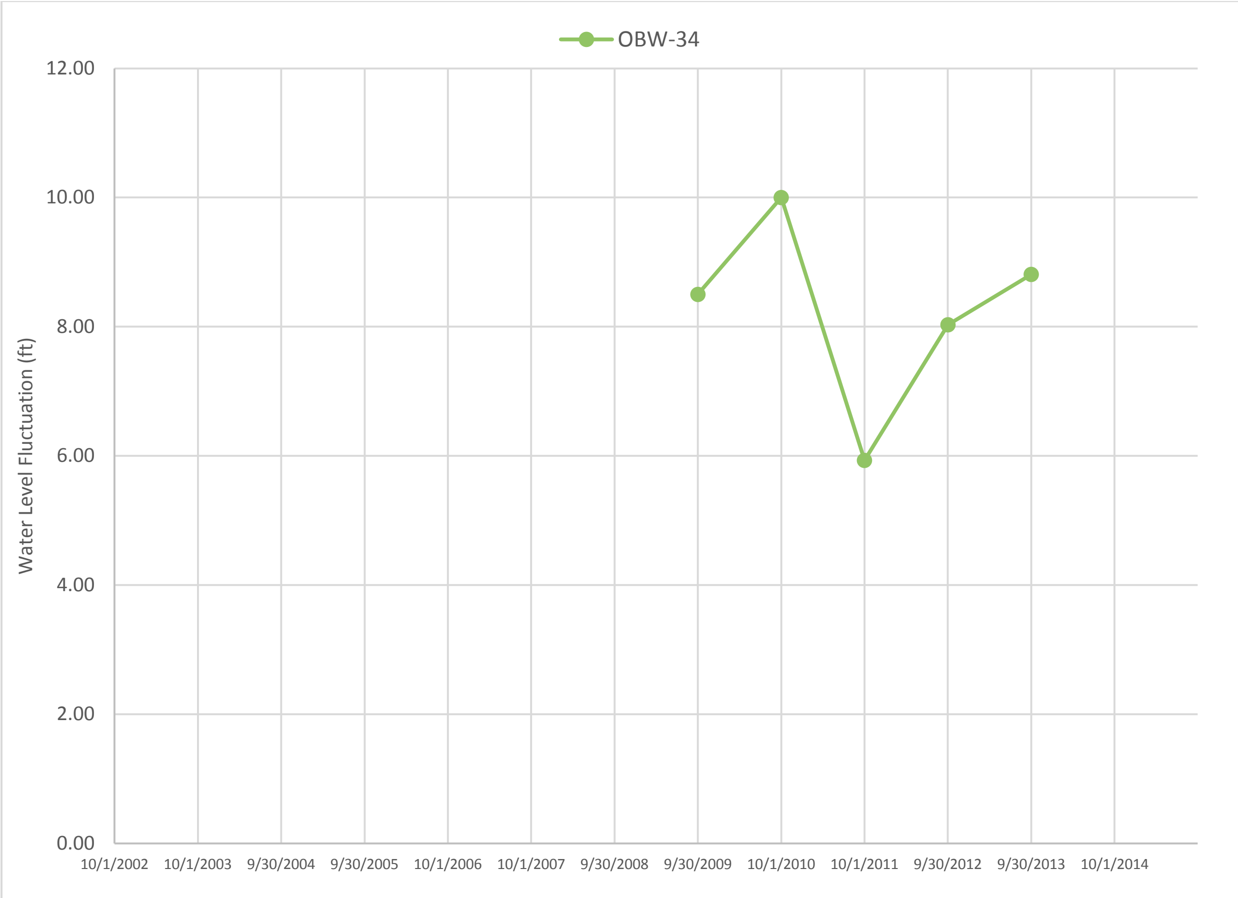


OBW-12
Water Level Fluctuation (ft)
9
8
7
6
5
4
3
2
1
0
10/1/1999
9/30/2000
9/30/2001
9/30/2002
10/1/2003
9/30/2004
9/30/2005
9/30/2006
10/1/2007
9/30/2008
9/30/2009
9/30/2010
10/1/2011
9/30/2012
9/30/2013
9/30/2014
10/1/2015

OBW-32


OBW-32
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Water Level Fluctuation (ft)
10/1/2001
10/1/2002
10/1/2003
9/30/2004
10/1/2005
10/1/2006
10/1/2007
9/30/2008
10/1/2009
10/1/2010
10/1/2011
9/30/2012
10/1/2013
10/1/2014

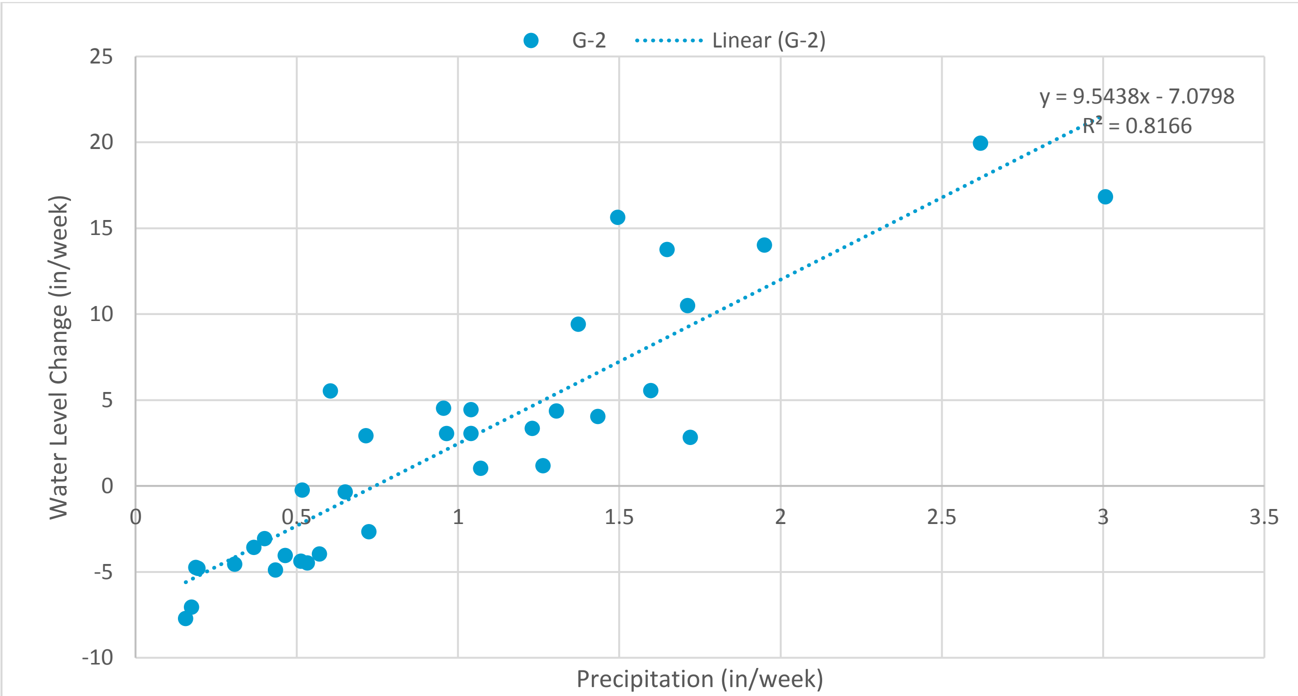
OBW-34



OBW-34
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Water Level Fluctuation (ft)
10/1/2002
10/1/2003
9/30/2004
9/30/2005
10/1/2006
10/1/2007
9/30/2008
9/30/2009
10/1/2010
10/1/2011
9/30/2012
9/30/2013
10/1/2014

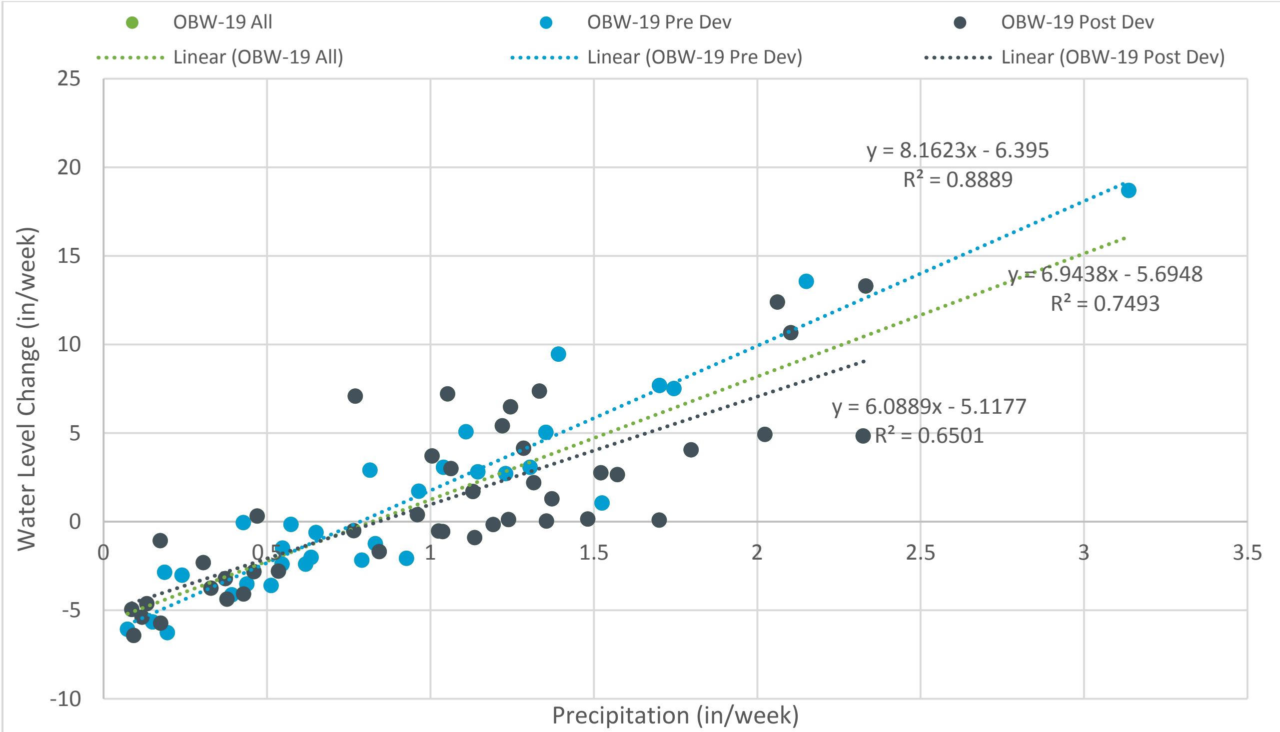
Appendix 6 - Hydraulic Head Response to Precipitation

G-2

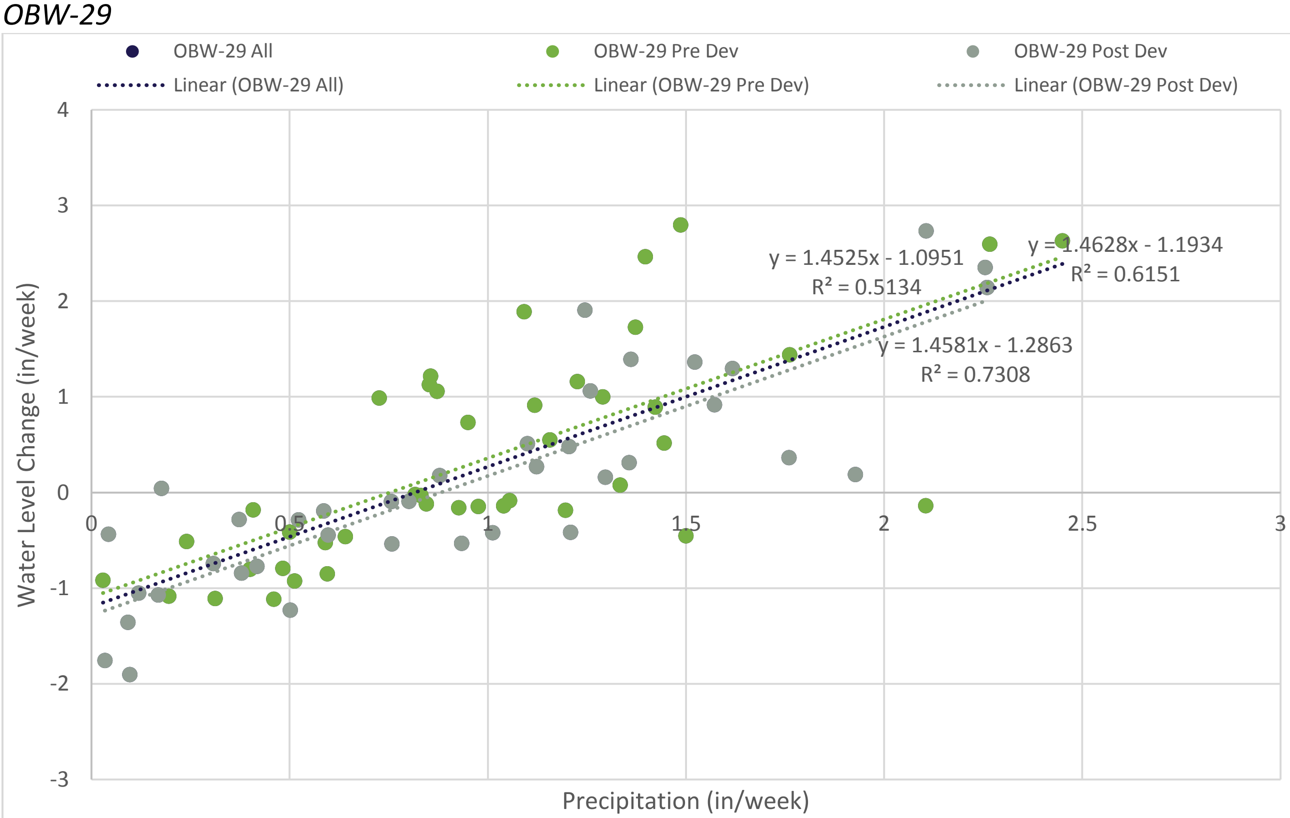


OBW-20

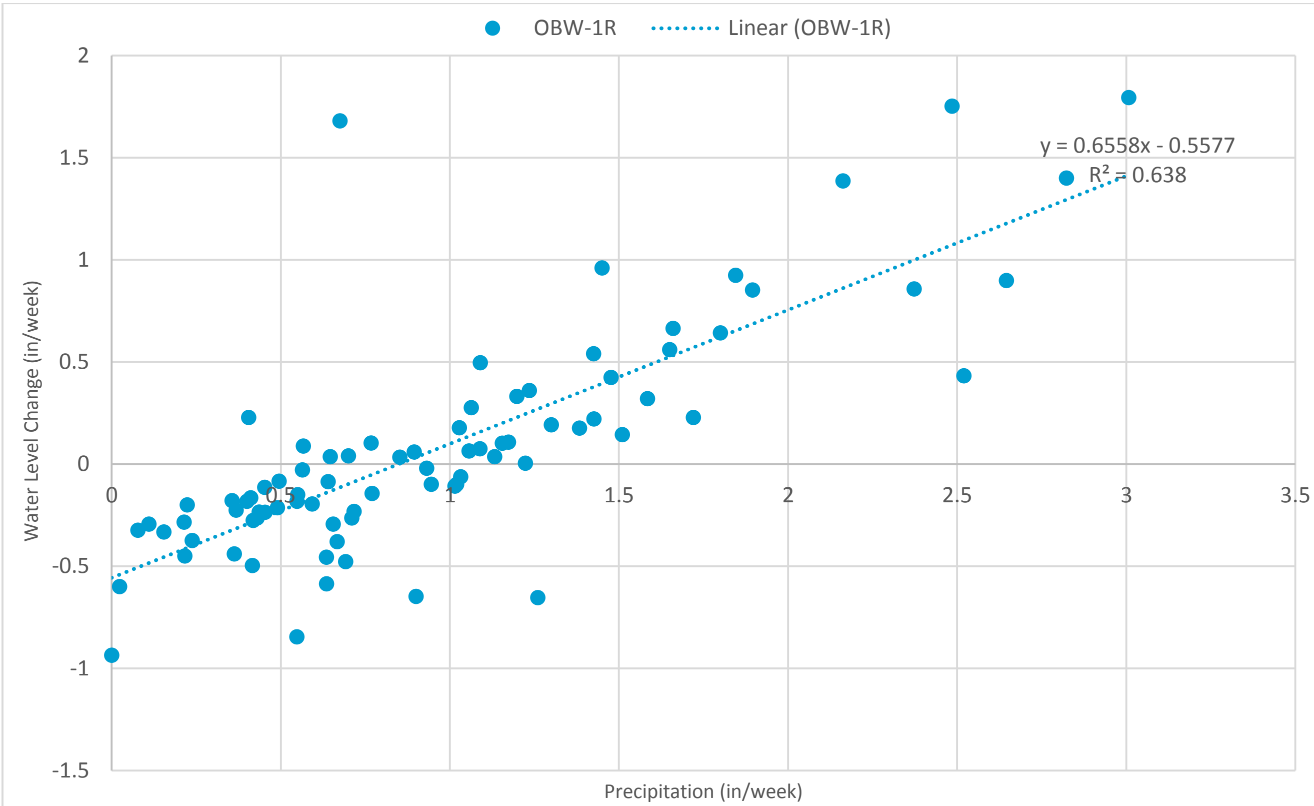
OBW-19


OBW-19 All
OBW-19 Pre Dev
OBW-19 Post Dev
Linear (OBW-19 All)
Linear (OBW-19 Pre Dev)
Linear (OBW-19 Post Dev)
y = 8.1623x - 6.395
R² = 0.8889
y = 6.9438x - 5.6948
R² = 0.7493
y = 6.0889x - 5.1177
R² = 0.6501
Water Level Change (in/week)
Precipitation (in/week)

OBW-29

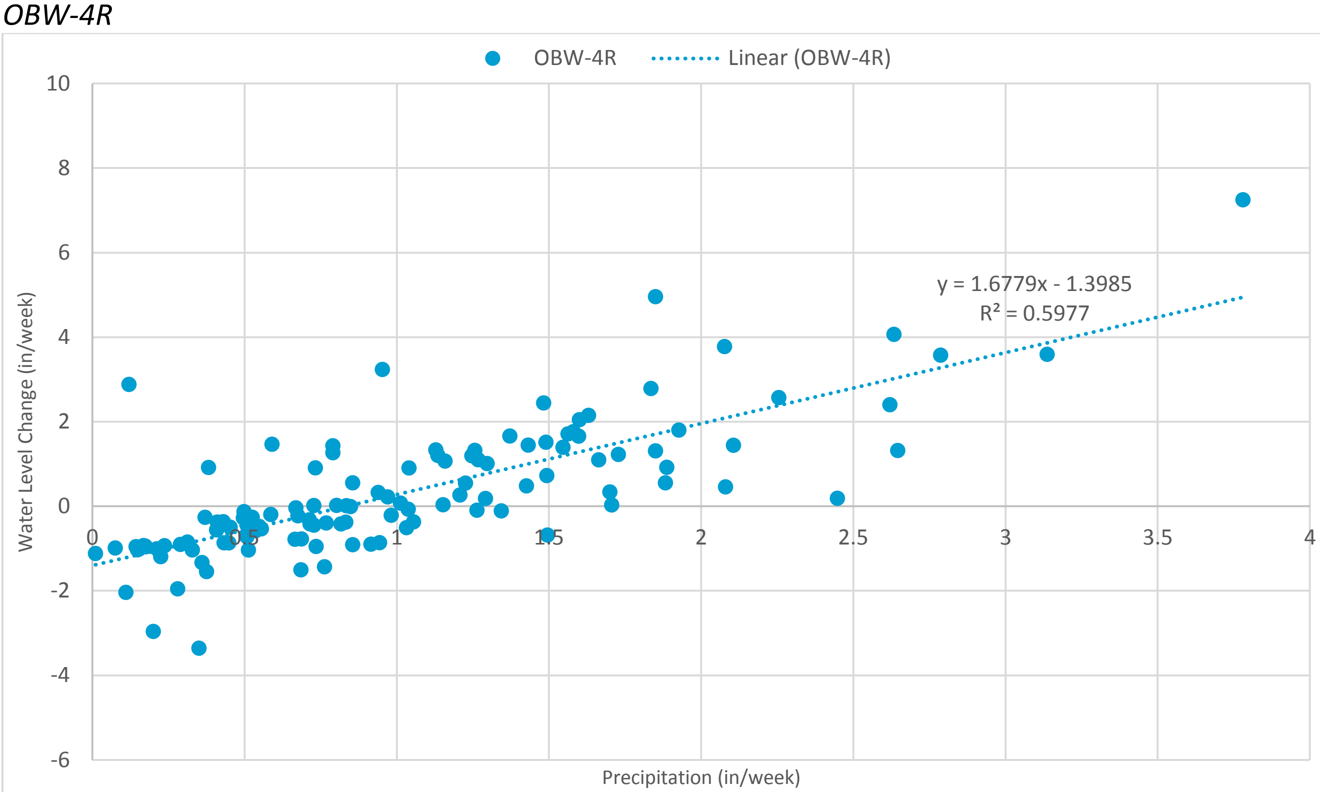

OBW-29 All
OBW-29 Pre Dev
OBW-29 Post Dev
Linear (OBW-29 All)
Linear (OBW-29 Pre Dev)
Linear (OBW-29 Post Dev)
y = 1.4525x - 1.0951
R² = 0.5134
y = 1.4628x - 1.1934
R² = 0.6151
y = 1.4581x - 1.2863
R² = 0.7308
Water Level Change (in/week)
Precipitation (in/week)

OBW-1R



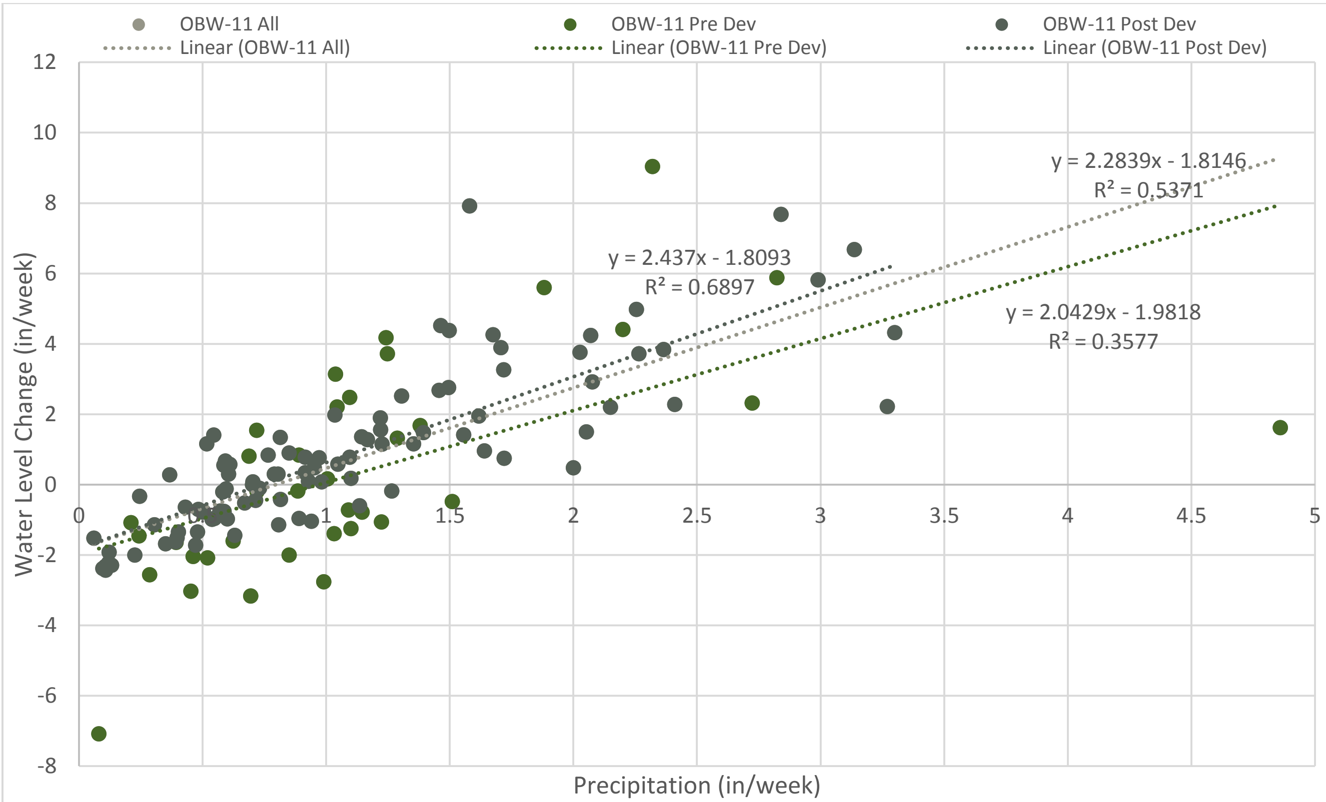
OBW-1R
Linear (OBW-1R)
y = 0.6558x - 0.5577
R² = 0.638
Water Level Change (in/week)
Precipitation (in/week)
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.5
1
1.5
2
2.5
3
3.5

OBW-4R



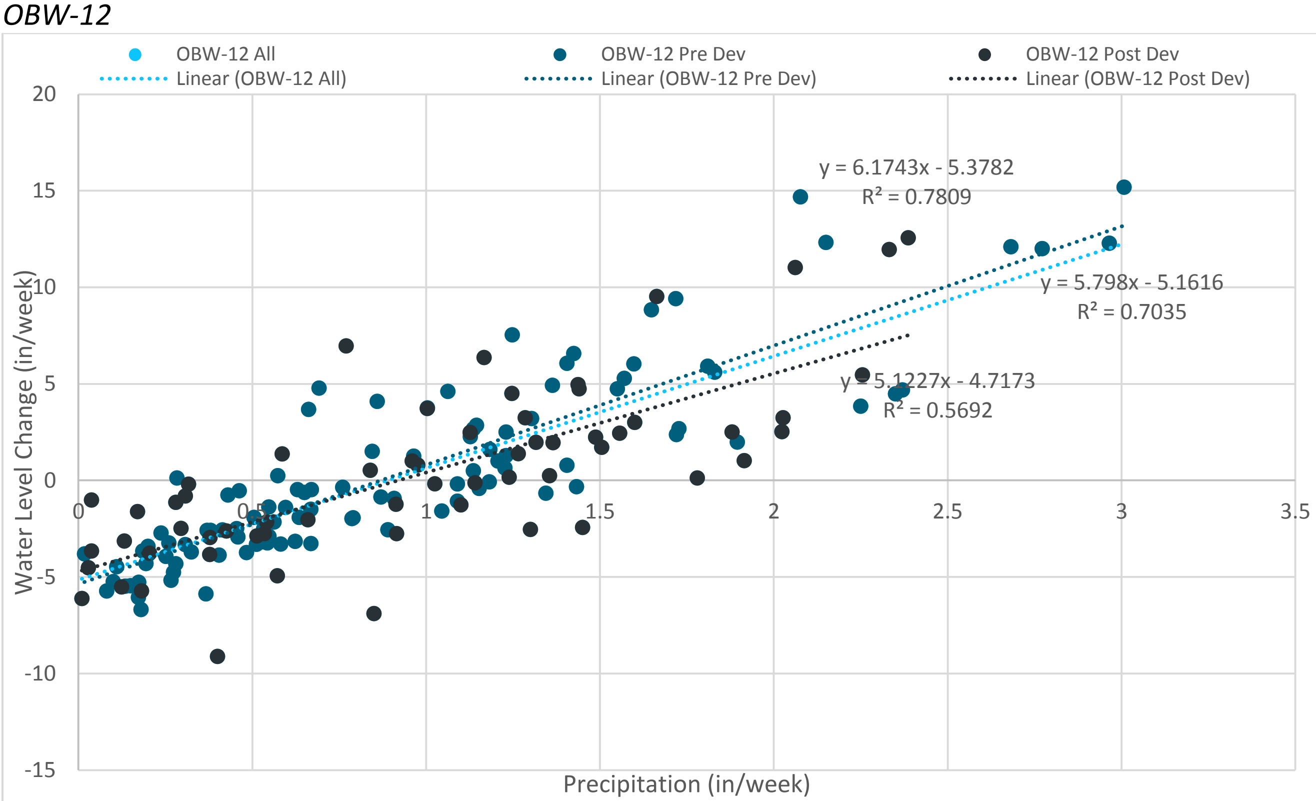
OBW-4R
Linear (OBW-4R)
y = 1.6779x - 1.3985
R² = 0.5977
Water Level Change (in/week)
Precipitation (in/week)
10
8
6
4
2
0
-2
-4
-6
0
0.5
1
1.5
2
2.5
3
3.5
4

OBW-11



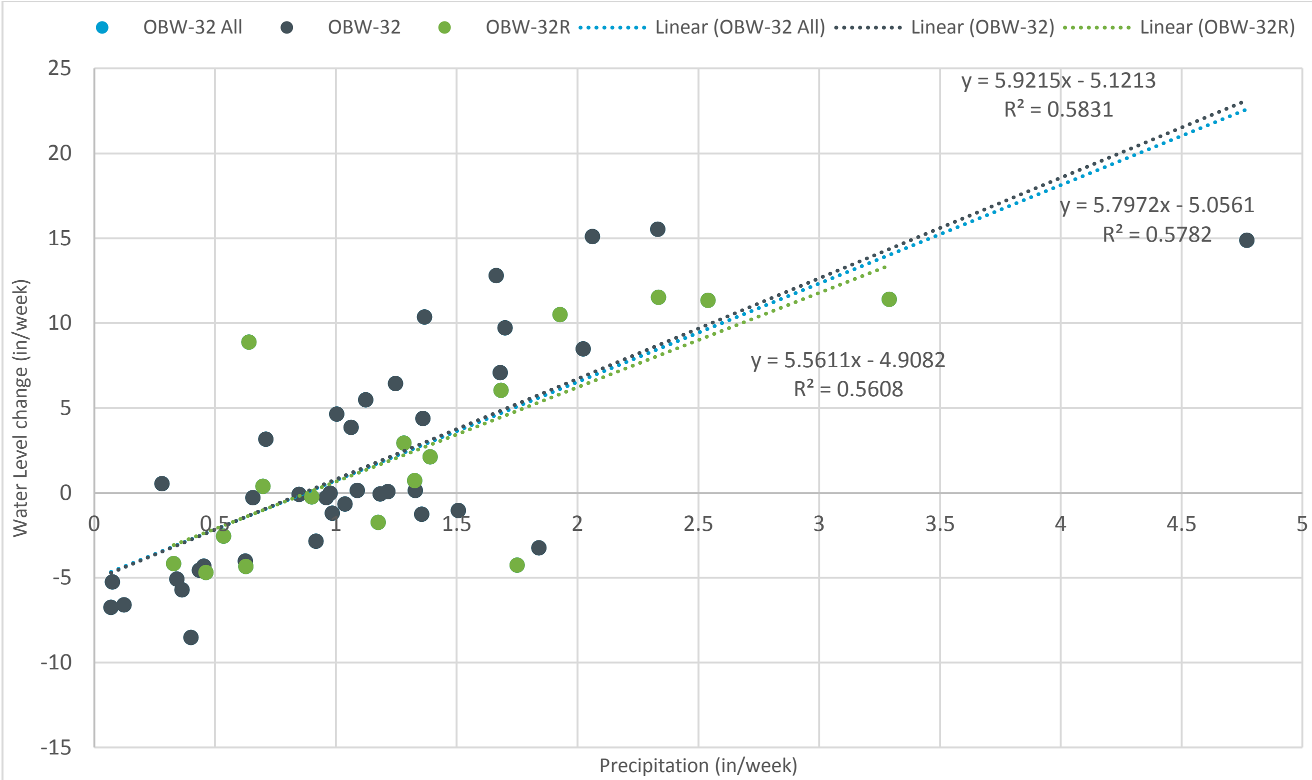
OBW-11 All
Linear (OBW-11 All)
OBW-11 Pre Dev
Linear (OBW-11 Pre Dev)
OBW-11 Post Dev
Linear (OBW-11 Post Dev)
y = 2.2839x - 1.8146
R² = 0.5371
y = 2.437x - 1.8093
R² = 0.6897
y = 2.0429x - 1.9818
R² = 0.3577
Water Level Change (in/week)
Precipitation (in/week)
12
10
8
6
4
2
0
-2
-4
-6
-8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

OBW-12

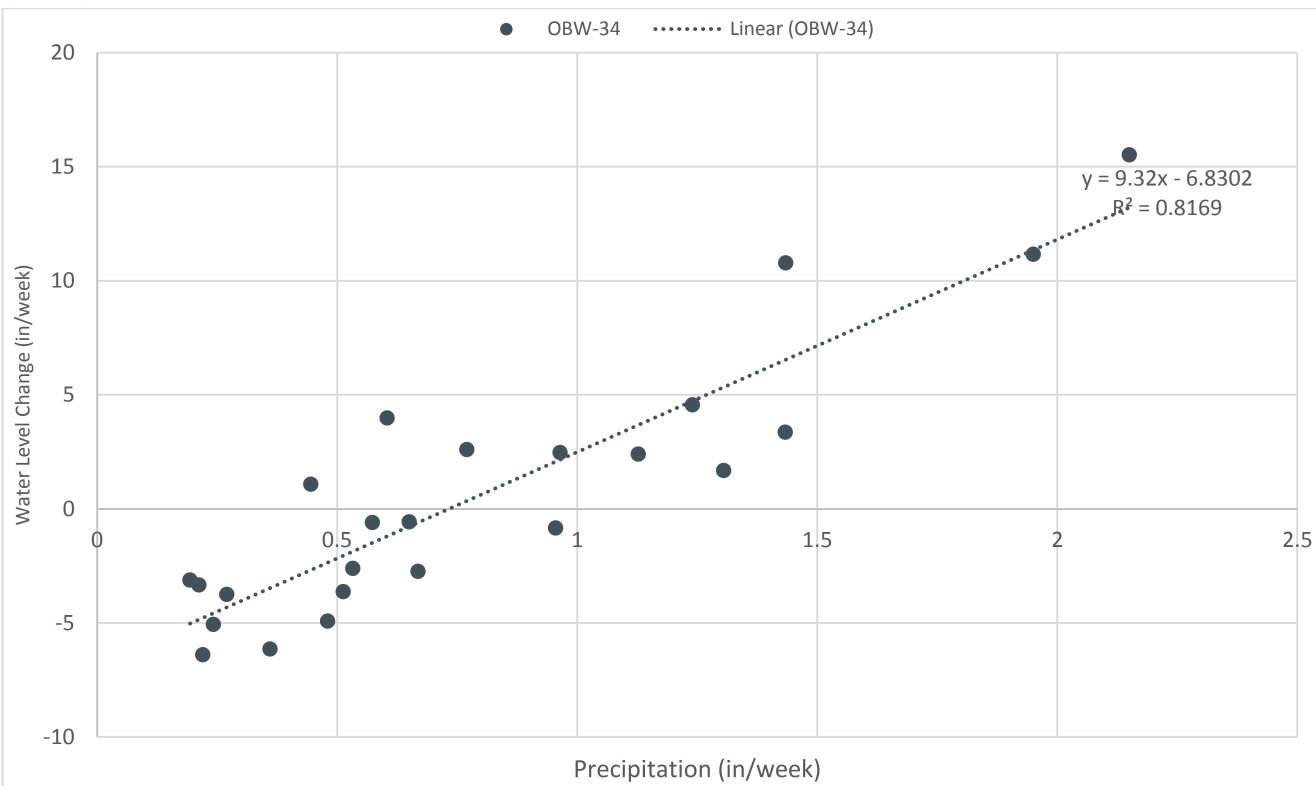


OBW-12 All
Linear (OBW-12 All)
OBW-12 Pre Dev
Linear (OBW-12 Pre Dev)
OBW-12 Post Dev
Linear (OBW-12 Post Dev)
y = 6.1743x - 5.3782
R² = 0.7809
y = 5.798x - 5.1616
R² = 0.7035
y = 5.1227x - 4.7173
R² = 0.5692
Water Level Change (in/week)
Precipitation (in/week)
20
15
10
5
0
-5
-10
-15
0
0.5
1
1.5
2
2.5
3
3.5

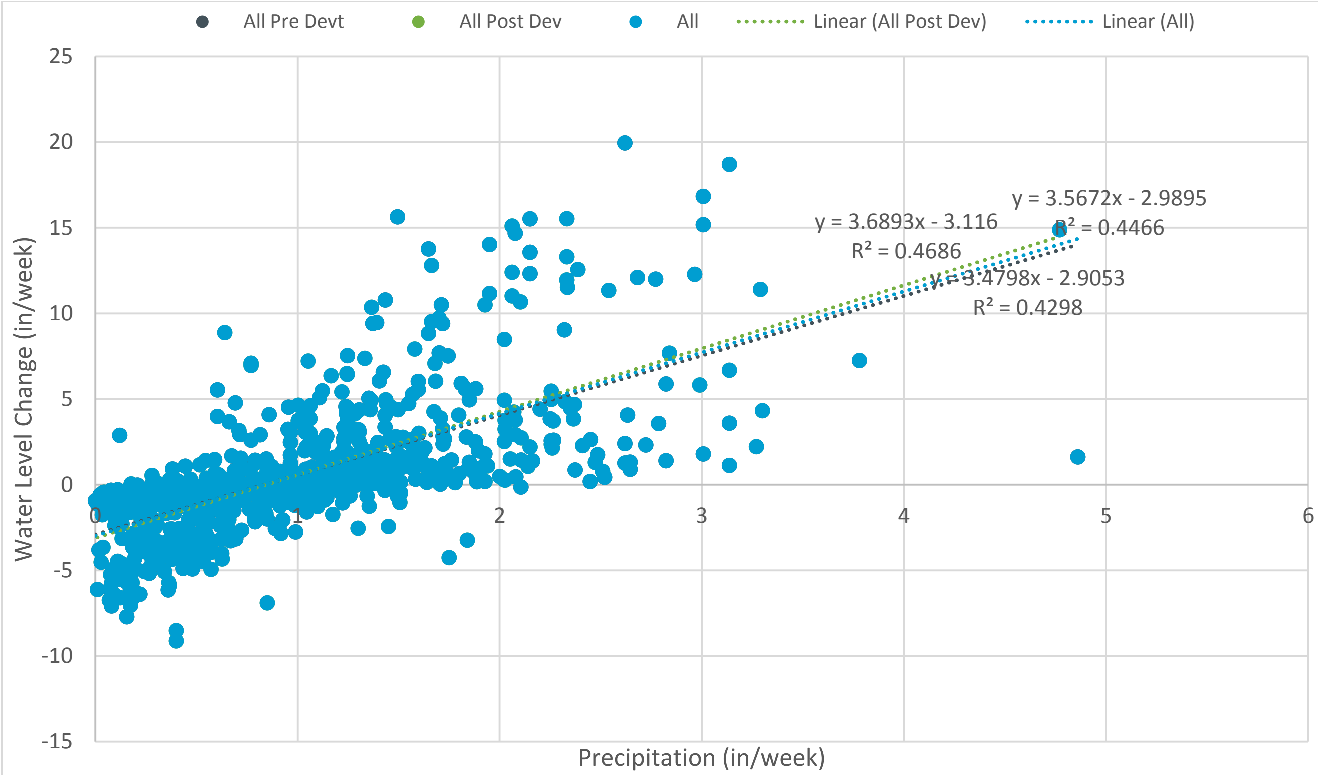
OBW-32 and OBW-32R



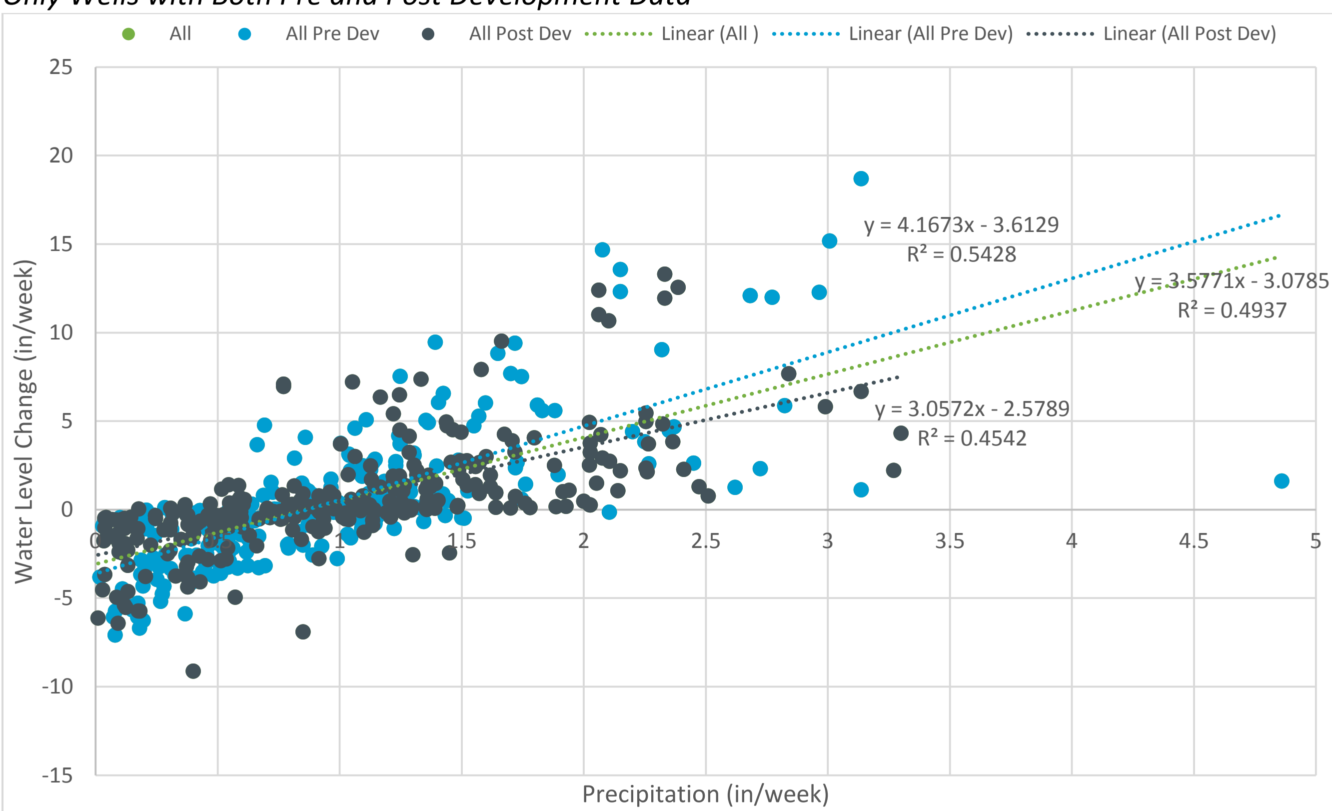
OBW-34



All Wells All Data



Only Wells with Both Pre and Post Development Data



Results Table 1– summary of regression equations derived for all wells and the threshold precipitation

Well No.		All data
G-2	Equation	y = 9.5x - 7.1
	RSQ	0.82
	Threshold	0.74
OBW-20	Equation	y = 6.7x - 5.6
	RSQ	0.75
	Threshold	0.83
OBW-19	Equation	y = 6.9x - 5.7
	RSQ	0.75
	Threshold	0.82
OBW-29	Equation	y = 1.5x - 1.2
	RSQ	0.6151
	Threshold	0.8158326
OBW-1R	Equation	y = 0.66x - 0.56
	RSQ	0.638
	Threshold	0.850411711
OBW-4R	Equation	y = 1.7x - 1.4
	RSQ	0.60
	Threshold	0.83
OBW-11	Equation	y = 2.3x - 1.8
	RSQ	0.54
	Threshold	0.79
OBW-12	Equation	y = 5.8x - 5.2
	RSQ	0.70
	Threshold	0.89
OBW-32	Equation	y = 5.8x - 5.1
OBW-32R	RSQ	0.58
	Threshold	0.87
OBW-34	Equation	y = 9.3x - 6.8
	RSQ	0.82
	Threshold	0.74

Results Table 2 – summary of regression equations for wells with both pre- and post-development data and the threshold precipitation

Well No.		m	2σ m	b	2σ b	RSQ	Threshold
OBW-20	All Data	6.7	1.0	-5.6	1.2	0.75	0.83
	Pre Dev	7.0	1.2	-5.2	1.4	0.87	0.75
	Post Dev	6.7	1.4	-5.9	1.7	0.69	0.89
OBW-19	All Data	6.9	0.9	-5.7	1.1	0.75	0.82
	Pre Dev	8.2	1.1	-6.4	1.2	0.89	0.78
	Post Dev	6.1	1.4	-5.1	1.7	0.65	0.84
OBW-29	All Data	1.5	0.3	-1.2	0.3	0.62	0.82
	Pre Dev	1.5	0.4	-1.1	0.5	0.51	0.75
	Post Dev	1.5	0.3	-1.3	0.3	0.73	0.88
OBW-11	All Data	2.3	0.4	-1.8	0.5	0.54	0.79
	Pre Dev	2.0	0.9	-2.0	1.4	0.36	0.97
	Post Dev	2.4	0.3	-1.8	0.4	0.69	0.74
OBW-12	All Data	5.8	0.6	-5.2	0.7	0.70	0.89
	Pre Dev	6.2	0.7	-5.4	0.8	0.78	0.87
	Post Dev	5.1	1.2	-4.7	1.4	0.57	0.92

Appendix 7 – Drainage Coefficients

Results Table – This table shows the hydraulic head response to…

Well No.	Pre-Development Rate Decline (in/week)			Post Development Rate Decline (in/week)			All Data Rate Decline (in/week)		
	Modeled	Observed	% Error	Modeled	Observed	% Error	Modeled	Observed	% Error
G-2	-7.1	-6.9	2.7				-7.1	-6.9	2.7
OBW-20	-5.2	-6.5	19	-5.9	-6.1	3.5	-5.6	-6.3	9.9
OBW-19	-6.4	-6.0	6.8	-5.1	-5.1	0.06	-5.7	-5.5	4.5
OBW-29	-1.1	-1.2	6.67	-1.3	-1.1	13	-1.2	-1.2	
OBW-1R	-0.56	-0.42	34				-0.56	-0.42	34
OBW-4R	-1.4	-0.85	64				-1.4	-0.85	64
OBW-11	-2.0	-2.1	6.7	-1.8	-2.4	25	-1.8	-2.3	23
OBW-12	-5.4	-5.0	8.0	-4.7	-4.4	6.2	-5.2	-4.8	7.9
OBW-32				-5.1	-6.3	20	-5.1	-6.3	20
OBW-34	-6.8	-7.4	7.1				-6.8	-7.4	7.1
All Data	-2.9	-4.0	28	-3.1	-4.3	27	-3.0	-4.2	28

Appendix 8 – Annual Precipitation and Recharge

Results Table – summary of the estimated annual recharge based on annual precipitation and equation (2)

Precipitation Yearly Total	Total Precip (in)	Estimated Recharge (in)	Recharge Efficiency (%)	Estimated Recharge (ft)
97/98 Water Year	41.07	16.20	39.4	1.350
98/99 Water Year	58.95	25.89	43.9	2.158
99/00 water Year	54.36	23.40	43.1	1.950
00/01 Water Year	38.63	14.88	38.5	1.240
01/02 Water Year	51.88	22.06	42.5	1.838
02/03 Water Year	36.02	13.46	37.4	1.122
03/04 Water Year	45.27	18.48	40.8	1.540
04/05 Water Year	43.51	17.52	40.3	1.460
05/06 Water Year	41.81	16.60	39.7	1.383
06/07 Water Year	46.52	19.15	41.2	1.596
07/08 Water Year	39.74	15.48	39.0	1.290
08/09 Water Year	36.94	13.96	37.8	1.163
09/10 Water Year	48.44	20.19	41.7	1.683
10/11 Water Year	47.37	19.61	41.4	1.635
11/12 Water Year	45.87	18.80	41.0	1.567
12/13 Water Year	56.01	24.30	43.4	2.025
13/14 Water Year	47.16	19.50	41.4	1.625
Average	45.86	18.79	40.7	1.566

Appendix 9 – Specific Yield

Results Table – This table shows inferred Specific Yield for wells in unconfined locations of the Qva aquifer

Well No.	Sy
G-2	0.14
OBW-20	0.21
OBW-29	0.90
OBW-1R	3.9
OBW-4R	1.0
OBW-11	0.41
OBW-12	0.24
OBW-32/32R	0.19