Establishing Metrics to Quantify the Vulnerability of Municipal Supply Wells to Contaminants from Surface Water Sources

by

Cailin Elizabeth Hillier

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences

Waterloo, Ontario, Canada, 2014

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This study was completed in conjunction with the Regional Municipality of Waterloo and the Southern Ontario Water Consortium, with assistance from the Canadian Water Network and Grand River Conservation Area with the main focus of the field study in the Alder Creek Watershed, near Kitchener, Ontario. The main objective of this study was to evaluate the utility of a broad range of field site characterization techniques designed to assess the vulnerability of public supply wells to water quality impacts from surface water sources. This was carried out through detailed field investigations at the site of an existing supply well, managed by the Regional Municipality of Waterloo. Focus was placed on determining which data would be most useful to collect to evaluate well vulnerability during extended pumping tests. Connections between different parameters were also important in this investigation for their potential to act as data surrogates, where easier to measure and more inexpensive parameters could advise on otherwise difficult to collect data. The main intention was to evaluate and streamline the process of field site assessment to determine well vulnerability without the need for or in concert with conventional predictive modeling approaches.

A 60-day pumping test was conducted on a newly installed public supply well located within the Regional Municipality of Waterloo adjacent to a perennial stream, Alder Creek, in order to gather hydrogeological and water quality information to assess well vulnerability. A network of groundwater monitoring wells was installed and instrumented at the site in the vicinity of the supply well, which included multilevel wells at several locations and drive point piezometers in the stream bed. Additional instruments were also placed within Alder Creek itself to measure surface water characteristics. A multitude of parameters were measured during the course of the test, including hydraulic head, temperature, general chemistry, metals, stable water isotopes, electrical conductivity, turbidity, and climatic data from drive points in Alder Creek, the pumping well, surrounding monitoring and multi-level wells, along with Alder Creek itself. It is rare to have such an extensive data.

Stratigraphic information from drill records indicated the subsurface was dominated by glacial sands and gravels and identified an isolated lower permeability unit of silty clay above the depth of the supply well screen separating a shallow and deeper groundwater system. The hydraulic data collected during the pumping test were processed through standard pump test

analysis methods to determine hydrogeologic parameters and understand the subsurface behaviour. The analysis indicated the subsurface responded as an unconfined system suggesting that the lower permeability unit did not significantly restrict the hydraulic connection between the shallow and deep systems. In this instance, the early, intermediate, and late time drawdown response indicative of the unconfined sand aquifer required six days of pumping to become apparent, providing evidence of the value for extended time pumping tests. Both the data from the stratigraphic mapping and the aquifer test analysis indicated the potential for a high degree of vulnerability of the supply well to surface sources of contamination.

The groundwater water level data illustrated a fairly rapid response to the influx of recharge following significant precipitation events throughout the entire monitored subsurface region, again suggesting a high degree of hydraulic connection. Mapping of the drawdown cone resulting from the long term pumping from the supply well based on regional hydraulic head data illustrate that Alder Creek was situated within the capture zone of the well and that the influence of pumping passed beneath the creek and was clearly observable on the side opposite to where the pumping well is situated. These combined observations based on the hydraulic head data provide more evidence of a high degree of vulnerability of the supply well.

Alder Creek and shallow groundwater beneath the streambed did not respond to the pumping process and this may be due to a low permeability bed under the stream or perched conditions. A strong downward gradient was measured across the streambed that indicates downward flow below the creek; however, additional information is required to quantify the groundwater-surface water interaction in the stream.

Water quality and temperature data were collected for their potential to act as tracers of groundwater flow and groundwater-surface water interaction. Based on the relatively low average concentrations of hardness and calcium in the shallow system, they were identified as shallow tracers that decreased concentration in the pumping well during the pumping test below those levels in the intermediate and deeper groundwater systems. Higher concentrations of iron and sulphate were attributed to deeper groundwater contributions as a result of aquifer materials weathering in the subsurface. These data indicate that both shallow and deep groundwaters were captured by the pumping well.

Temperature was an excellent indicator of precipitation influxes, which could be observed as pulses of higher temperature water in the wells after a given time lag. Variations in groundwater temperature distributions resulting from transient groundwater flow could be correlated to geologic heterogeneity. At the site, a silt layer in the subsurface caused a difference in temperature, where multi-level ports above the silt layer were considerably warmer than the ports screened below the silt layer. Water temperature from the pumping well became colder during the test, likely a result of deep groundwater being drawn up to the well screen. Additionally, pumping caused temperature increases in the shallower multilevel ports indicating that warmed water was also been drawn downward as a result of pumping. This deep and shallow groundwater movement matches the geochemical data analysis. The multilevel well between Alder Creek and TW2-13 showed the largest degree of change in groundwater temperatures, with shallower ports becoming warmers throughout the test, which might be a result of some surface water infiltration from the creek.

The 50-day time of travel distance, a common method to assess well vulnerability, was determined for the groundwater flow system; Alder Creek is contained well within this estimated distance, once again increasing the vulnerability at the site. Several different vulnerability index calculations were performed, with a mixture of results ranging from moderately to extremely vulnerable. It is evident that there is room for improvement when it comes to establishing the vulnerability of an aquifer, where there is a specific need for indexing methods which focus on well vulnerability.

Correlation coefficient and covariance calculations were applied to compare the different continuous and discrete data parameters available. The statistical analyses found correlation coefficients effective in determining the surface water level and turbidity correlation, pump well water level and temperature correlation, and the inverse relationship between conductivity and turbidity for the data sets available. Once again, sodium, chloride, anions and cations, and electrical conductivity were correlated to one another. Calcium, manganese, and hardness also correlated, indicating the mineral signature of the subsurface. Manganese and iron concentrations correlated positively to each other. Correlation coefficients are helpful in indicating groundwater flow direction and water sources based on quality parameter connections, where shallow or deep groundwater systems can be attributed to having certain qualities allowing for trend analyses to indicate groundwater movement. Statistically, surface water temperature can also act as a surrogate for air temperature, however there was no data available that would act as a reasonable surrogate for precipitation data. Given its usefulness, precipitation information should be gathered during longer duration pumping tests where the groundwater system is potentially connected to the surface. These statistical analyses are extremely easy to perform on existing or newly collected data sets, allowing for quick connections at the site to be identified. The statistical analysis can provide useful additional understanding of geochemistry associated with shallow or deeper groundwaters, assist in interpreting the movement of water in the subsurface and assess any response to surface changes.

Overall, lengthy data sets allow for the myriad of conclusions to be made regarding long term water quality changes and impacts of seasonality, precipitation events, and shallow and deep groundwater mixing on the vulnerability of a public supply well. In the event of a short test being run, the depth of information gathered would not have been possible. Long term monitoring, coupled with quantifiable changes and correlations are paramount in addressing well vulnerability to surface water sources. Although certain geochemical parameters are bound to be site specific, monitoring turbidity, and electrical conductivity are valuable starting points; however detailed water level, water chemistry, and temperature data, from drive points and multi-level wells, are most important in estimating groundwater-surface water interaction and well vulnerability.

Acknowledgements

I am so thankful for the support of many people and organizations within the Waterloo community and across the country. To financial support from NSERC, the Regional Municipality of Waterloo, the Farvolden Award from the Earth and Environmental Sciences Department, and the Karl C. Ivarson Scholarship through the Agricultural Institute of Canada: you made this happen and allowed me to focus on the task at hand without worry.

For all of your expertise, huge thank you goes to the members of the Rudolph Group that I have had the privilege of working with. Thank you Andrew Wiebe for showing me the ways of grad school, helping me with all things computer related, and for answering my endless questions. To Paul Johnson and Bob Ingleton, your amazing skills and positivity made anything possible!

To the team at the Region, Eric Hodgins, James Hutton, Tammy Middleton, and Richard Wootton: thank you for being open to information sharing, for giving me the freedom and support to conduct this study, and for providing me with that amazing office space for my thesis writing – my highly productive Mondays were the best. Lesely Veale, Angie Ducharme, and Roger Freymond: you were great supports throughout this project. Thank you for all of those email replies over the last year! And for your constant willingness to help, thank you Sue Fisher, Mary Bland, Chris Gerrits, Brewster Conant, Marcelo Sousa, Rob McLaren, Odum Idka, and Gus Rungis!

Dave Rudolph, thank you for your endless positivity, great ideas, and clarifying insights. You have been such an inspiring supervisor. Your suggestions made this thesis much stronger and cohesive. Thank you for replying to all of those emails even while you travelled all over the globe these past few years! To my committee members, Walter Illman and Will Robertson, that you for your quick responses and willingness to help!

To those who helped with field work under all conditions, thank you! Sage McKay, Kristen Blowes, Jamie Dickout, Lauren Harrison, Jack Robertson, and James Elliot: you made working in 40 °C temperatures and freezing rain wonderful. Your attention to detail and friendship is greatly appreciated!

To my teachers over the years: thank you for passing along your knowledge and wisdom and for showing me that those are two different things. Special mention must go to Paul Van Zant for helping me find my passion for earth sciences and to believe in myself. To my more recent mentors, Mario Coniglio and Rob de Loë, thank you for sharing your positive attitudes and appreciation for organization – they did not go unnoticed.

To the support system at the University of Waterloo: friends of SWIGS, the ESGA, and the Engineering Society, thank you for always being so welcoming and reminding me to have fun. Special mention goes to my support network over these past two years: Allison Bawden, Lizanne Pharand, Steve Holland, Jason Davison, and Peter Robertson – thank you for helping me keep things in perspective and enjoy things outside of school. Your unconditional friendship has meant so much this year.

Dedication

This is dedicated to my family, you quirky loveable bunch you: thank you for always encouraging me to do what I love and to live like anything is possible. David and Les Hillier: your belief in keeps me going. And to my mummsie, Laurie Laughlin-Hillier, thank you for being the first person to read this monstrous thing. Thank you for really listening when I needed you, regardless of the time, and for rescuing me from Waterloo when I needed to get away. You have always been there no matter what and that means the world to me.

Table of Contents

List of Figures

List of Tables

Chapter 1 – Introduction

Source water protection, both of surface water and groundwater, is a crucial component in ensuring the integrity and sustainability of Canada's water resources is maintained. Source protection strategies for groundwater supplies are based around determining aquifer and well vulnerability, at a regional and local scale. This requires a multidisciplinary knowledge of geology, hydrology, geochemistry and contaminant transport in order to gain a sufficient understanding of the conditions in a specific setting that control the vulnerability of a groundwater source or supply.

The conventional assessment of the vulnerability of a public supply well to surface sources of contamination relies primarily on several methods. These include predictive modeling (wellhead protection areas), indexing methods (ISI, AVI, SAAT) and computational estimates of contaminant travel times (GUDI). It has been challenging to verify these types of quantitative estimates of degree of vulnerability through direct field measurement and as such a significant degree of uncertainty is associated with all of these conventional approaches (Frind et al. 2006). Vulnerability analysis is relevant to hydrogeologists who strive to improve their ability to advise municipal groundwater managers on the security and sustainability of wells and well fields long-term water quality. Attempts are currently being made to evaluate the potential impacts on groundwater quality in wells that extract groundwater under the direct influence of surface water (GUDI). This has been primarily based on estimation of times of travel between surface water source and the intake of a supply well, which rely on intrinsic characteristics of the site conditions and the application of analytical approaches to estimate travel time (Ontario Ministry of the Environment, 2002). However, seasonal climatic variability complicates the understanding of the spatial and temporal distribution of water and subsequently the assessment of groundwater quality and vulnerability. This is not routinely incorporated into conventional vulnerability analysis. In addition, this can be further complicated by the effects of climate change, manifesting itself through a higher frequency of high-intensity hydrologic events (Treidel, Martin-bordes, & Gurdak, 2012).

There is a paucity of field-scale investigations focused on evaluating methodologies to quantify the vulnerability of public supply wells (Frind et al., 2006). In order to improve our approach in this regard, additional guidance into how field testing should be conducted, which parameters provide the most insight into the vulnerability of public supply wells, and how the combined field observations can be most appropriately evaluated to quantify this vulnerability would be of value. This represents the overall objective of the current study.

1.1 Objectives

This project attempts to examine the utility of different data sources and investigative techniques to help inform well vulnerability assessment through field work. The focus of this study is a newly drilled production (TW2-13) well near the town of Mannheim, within the Alder Creek watershed to the west of Kitchener-Waterloo through an extended hydraulic testing and monitoring program. The production well is within 11 m of Alder Creek, making it potentially very susceptible to contamination from potential pollutants within the surface water. Through collaboration with the Regional Municipality of Waterloo (the Region) who manage the groundwater supply system, this research aims to provide insight into approaches for quantifying the vulnerability of wells that are very close to surface water bodies and to understand the dynamic interaction between the surface water and groundwater systems in the vicinity of these types of wells. The Region, along with the Grand River Conservation Authority (GRCA), assisted in providing land access within the site, facilitating access to existing data, and offering technical direction in many aspects of the study.

The objective of this study, to quantify well vulnerability, includes a series of sub-goals. The ability to clearly assess vulnerability will allow for an ease in the hydrogeologic assessment process. Given a well with uncertain vulnerability, the metrics established could be checked against any existing data to make initial predictions about a given well's safety and help to prioritize what data should be collected as part of a field study. The aim is to determine what parameters are most pertinent to measure over the course of a vulnerability assessment, either for the information they provide or because they can act as a surrogate for other worthwhile parameters that indicate vulnerability. This way, data collection can be streamlined and made more cost effective. A quantitative approach to well vulnerability assessment might also allow for better certainty in the processing of data, rapidity in determining results, and allow for information to be more easily and definitively conveyed to other parties, such as policy makers and water treatment operators. The first step in this process was to collect a wide variety of site-specific data in order to determine what should be measured in the field and what type of evidence it can provide relative to vulnerability.

The project assessed aquifer and well vulnerability at the K22A site, the location of one of the Region's public supply wells, through the implementation of a 60-day pumping test, involving spatial and temporal monitoring of meteorologic, hydrologic, and geochemical parameters through networks of sensors, samplers, and monitoring wells. A plethora of parameters were measured, including water level, temperature, conductivity, turbidity, water quality, stratigraphy, and climate data, in order to determine what parameters are most valuable to measure during a pumping test in order to assess vulnerability. The lengthy period of data collection will also be assessed specifically to determine if and how an extended time pumping test is more beneficial for vulnerability assessment than a more conventional and shorter term 72-hour pumping test. Statistical analyses were implemented to determine which of the data sets gathered showed significant correlation, inferring that different measurements may be able to act as surrogate for other parameters. This will help to prioritize information gathering when attempting to quantify local vulnerability.

Vulnerability at the site was considered in several ways. Mainly, the potential for surface water and surface sources of contamination to reach the production well quickly and be deleterious to the water quality was analyzed. As a secondary motivation, the possibility for aquatic ecosystem effects due to pumping and the potential impacts of climate change on the aquifer longevity were assessed. The interpretation of these combined data sets demonstrate the transient nature of groundwater and surface water interaction at the site, establish an understanding of the well vulnerability, and assess the value of these various data streams in quantifying well vulnerability.

1.2 Thesis Organization

This thesis is comprised of six chapters in total, including 1) Introduction, 2) Background, 3) Methodology, 4) Results and Discussion, 5) Conclusions, and 6) Recommendations. The references for all chapters, figures, tables, and appendices are included in the Bibliography. There are 36 appendices included, which consist of the collected data from the duration of the field study, permits obtained from the Ministry of the Environment for pumping, and additional figures generated from the data sets. Also included within the appendices are AquiferTest analysis reports and drawdown contours and Surfer generated drawdown contour maps based on kriging of piezometric data. Funding for this project was also provided by the CWN as part of a project titled "Influence of Dynamic Hydrology on Groundwater Source Security (Rudolph, 2011)."

Chapter 2 – Background

2.1 Literature Review

2.1.1 Groundwater Surface Water Interaction

The interaction of groundwater and surface water is complex, creating a relationship that may have negative impacts on water quantity and quality within both water bodies. With water mixing, there is potential for water quality degradation. This is a particularly important consideration for aquatic health and drinking water safety. Many different sources of contamination pose risks to the drinking water supply and ecosystem health, forming a long list of possible contamination threats. In southern Ontario, this list is extensive; examples of such threats include waterborne pathogens, algal toxins, pesticides, nutrients, municipal wastewater effluent, industrial point source discharge, and urban runoff. Through an understanding of contaminant fate and transport, along with general risk assessment regarding hazardous chemicals that are introduced into the environment, water degradation issues can be reduced or remediated more effectively.

Pathogens can originate from wastewater effluent, urban and agricultural runoff, and wildlife (National Water Research Institute, 2001). Pathogens include disease causing bacteria, viruses, and protozoa. Four commonly monitored indicator bacteria used to determine pathogen presence are total coliform, fecal coliform, Esherichia coli (E. coli), and Enterococci, although there is considerable debate regarding the utility of these indicator species in assessing pathogen impacts (Emelko et al., 2010). These bacteria are prevalent in the feces of livestock, wildlife, pets, and humans (Karamous et al, 2013). Knowledge about pathogen transport and fate is lacking and understanding of pathogen impacts on ecosystem health also needs further development.

Algal toxins impact water taste and odor, yet more seriously, they can impede liver and nervous system function and irritate the skin. Synthetic chlorinated pesticides are increasingly harmful to surface water and groundwater, and their long term impacts on human and environmental health are not well known.

High nutrient levels, involving nitrogen, phosphorous, and their associated compounds, have notoriously caused eutrophication of many water bodies around the world (National Water Research Institute, 2001). Excessive nitrogen concentrations are linked to methemoglobinemia, or blue baby syndrome, cancer, hypertension, respiratory infections, and other diseases. The Canadian limit is 10 mg NO3-N/L for nitrate in drinking water. Municipal wastewater effluent introduces endocrine disrupting substances, pharmaceuticals, and other contaminants into surface water bodies. The assimilative capacity of surface water bodies to accept this effluent are uncertain due to climate change influences, which is further complicated by rising populations. Urban runoff may include storm water, sewage, fuel, and road salt in non-negligible quantities. Specific ecosystem threats and potential climate change impacts are discussed below (National Water Research Institute, 2001).

Physical water properties can offer information regarding water quality changes. Temperature can be an indication of photosynthesis rate, the metabolic rate of aquatic organisms, and the sensitivity of organisms to degraded water quality. Salinity levels can provide information about the dissolved oxygen capacity of the water. Suspended materials and turbidity levels, a measure of water clarity or the ability of the water to transmit light, occur naturally as a result of erosion, runoff, and plant growth. However, they can also indicate excessive erosion due to development, excessive organic growth due to nutrient enrichment, and discharge from industrial or waste water treatment facilities. Precipitation volumes can explain changes to water quality parameters. Chemical constituents of water offer an even clearer assessment of quality. Dissolved oxygen has a direct correlation to aquatic life survival. Photosynthesis increases the availability of oxygen to support life whereas the decomposition of organic material depletes oxygen. When light is unavailable, perhaps due to high sediment load within the water, photosynthesis is hindered and aquatic life can suffer. Dissolved oxygen can also influence the pH of a water body, which can have additional chemical consequences for the water (Karamous et al., 2013). All of these threats have compounded to inspire a source water protection movement that aims to control point and non-point pollution in an effort to maintain good water quality.

Quantitatively, surface water encompasses any above ground water such as streams, lakes, springs, reservoirs, snow reserves, and overland flow resulting from precipitation events.

Infiltrated water within the unsaturated and vadose zones is neither surface water nor groundwater. Once the water makes its way to the water table, it is termed recharge and falls into the groundwater category (Karamous et al., 2013). The mixing behaviour of surface water and groundwater is governed by the volume of water involved and the characteristics of the subsurface. The ground surface has a specific infiltration capacity based on soil chemistry, vegetation coverage, soil moisture, temperature, and hydraulic conductivity. Initial infiltration capacity is governed by soil moisture content, with the saturated hydraulic conductivity of the soil determining final infiltration capacity. If precipitation exceeds infiltration capacity, water will flow overland to lower elevations, eventually pooling on the surface and then infiltrating or making its way to a surface water body (Karamous et al., 2013). Impermeable surfaces, including roads, buildings, and parking lots, obviously generate greater runoff volumes than other soil-covered, gravel-covered, or vegetated surfaces.

If the hydraulic gradient of an aquifer induces flow towards the stream, groundwater will discharge into the stream creating a gaining stream segment. A hydraulic gradient resulting in flow away from the stream will cause the stream to lose water through the streambed, contributing to the groundwater system. The volume of water interchanged within these gaining and losing segments is controlled by hydraulic conductivity, the magnitude of the hydraulic gradient, and the depth of the water table. If the surface water body has the same elevation as the water table, they are very clearly hydraulically connected. Should the surface water be perched above the water table, an unsaturated zone would exist between the surface water and underlying regional water table, separating the two water bodies. Water may infiltrate through the unsaturated zone to reach the deeper water table, however the two water bodies are not in direct contact with one another and will interact differently. Seasonal conditions also influence these areas which can change throughout the year (Karamous et al., 2013). The overall interaction between the groundwater and the surface water systems are also influence by the subsurface stratigraphy which can control groundwater velocity and time of travel between ground surface and a receptor, such as a water well.

There a many methods for estimating the nature and potential impact of groundwater surface water interaction, including water balances, the use of tracers, thermal profiling, seepage meters, miniature piezometers, and numerical modelling. Water balances involve the simple evaluation of all inputs, outputs, and changes in storage in order to determine an unknown component, such as evaporation or runoff. The limitation of performing a water balance is the amount of uncertainty associated with its component parts; evaporation, net groundwater flux, and direct runoff are the main areas for such uncertainty. For streams, a simple comparison of flow from two locations can determine if the length between them is gaining or losing. Chemical or isotope tracers can be used to determine water sources and their relative contributions by either introducing a known quantity into the environment or measuring a chemical already present at a particular site and collecting surface water and groundwater samples for comparison over time. Once again, this result is limited by parameter uncertainty, particularly if there is lack of understanding regarding local isotopic trends and the influence of seasonality on data (Hunt et al., 2005). Thermal profiling can be used to quantify vertical groundwater velocity and flux. Streambed temperature monitoring is an accurate and unobtrusive method to characterize spatial variability groundwater surface water interaction. Essentially, heat is utilized as a natural tracer and streambed temperatures taken at a uniform depth can be mapped to assist with hydrogeological characterization. The surface and subsurface temperature differences relate to advective heat transport by flowing water and conductive heat flow through the solid and liquid phase of the streambed sediments, allowing for groundwater flux across the streambed to be calculated (Schmidt et al., 2007). Seepage meters and miniature piezometers function by measuring the volume exchange across an area of the streambed over a period of time, resulting in location-specific groundwater flux information. It can be a challenge to extrapolate these measurements over a larger area (Schmidt et al., 2007). Lastly, numerical modelling can be used to develop a regional representation of a surface water and groundwater system. However, a large amount of geological and hydrological data is needed to establish an accurate representation of the natural environment.

2.1.2 Regulatory Framework

In response to the Walkerton tragedy in 2001, the Ontario government has developed a regulatory framework in order to ensure the safety of municipally supplied drinking water. Notably, the 2002 Nutrient Management Act, a comprehensive nutrient management framework for Agriculture and Municipalities; the 2006 Clean Water Act, which takes a watershed-based approach to source water protection and addresses all sources of drinking water; and the 2012 Water Opportunities and Conservation Act, which promotes the large scale conservation of water throughout the province, are some of the key pieces of legislation regarding Ontario's water. Most relevant to this current study are the Ministry of the Environment Terms of Reference documents regarding wells that are potentially sources of groundwater under the direct influence of surface water (GUDI). The main shift from before and after Walkerton was the need for legislation that rigidly defined the responsibilities for drinking water providers, overall strengthening language from guidelines into strict laws, standards, and regulations. The GUDI Terms of Reference delineate the requirements of a groundwater study, specify methods to determine aquifer susceptibility, define the need for Wellhead Protection Area Studies, and stipulate the reporting requirements and minimum data standards for the entire province (Ontario Ministry of the Environment, 2002).

In addition to the GUDI regulations in place, wellhead protection areas and capture zone areas are used as a way to map groundwater vulnerability through the application of subsurface understanding and potential contamination sources that could impact groundwater systems. Section 3.7 outlines the methodologies relevant to this study. Based on the time of travel for groundwater to reach the well, a corresponding zone number is be assigned; zones 1, 2, and 3, symbolize travel times from zero to two years, two to ten years, and ten to 25 years, respectively. Zone 1 is most sensitive, requiring careful land use management to avoid risk of potential sources, including bacteria, viruses, hazardous chemicals, and other possible contaminants. Additionally, a 50 day time of travel area should be added within Zone 1 to specify where the highest potential for risk exists, which is of particular interest in the event of spills or other incidents requiring rapid response by the water utility (Ontario Ministry of the Environment, 2004). There are a lot of factors which influence the interaction of groundwater and surface water. In the GUDI guidelines, this includes if a well is screened within 15 m of the ground surface, if the source aquifer is unconfined, if nearby surface water changes in response to pumping, or if the water quality is closer to that of the surface water than the surrounding groundwater or the quality changes in response to climatological or surface water conditions (Ontario Ministry of the Environment, 2004).

One of the current challenge regarding drinking water governance in Ontario stems from the need to update the approaches to assessing well vulnerability and specifically the GUDI designations based on new knowledge. Advances in the scientific understanding of groundwater surface water interaction call for improvements to legislation governing these concepts. The health and environmental risks associated with GUDI wells are better understood now than prior to 2001. New pathogen indicators are being suggested as monitoring tools over the current standard. Modifications to treatment requirements are proposed based on a new class system. Environmental data is necessary to this process yet it can be very challenging to obtain, requiring expensive monitoring programs and subsequent data management to make the information accessible to the public. However, it is imperative that any changes that are made related to the GUDI guidelines are backed by scientific fact. The municipal capacity to ensure the water supply is safe must be maintained; the extra caution and conservative treatment measures introduced by legislation since 2001 must be upheld. The Walkerton tragedy is now many years behind us, yet this powerful lesson cannot be forgotten.

2.1.3 The Influence of Pumping Wells on Streams

Groundwater contributions are very important for aquatic ecosystem health. Environment water allocation means that certain volumes of water are made available for stream flow throughout the year in order to sustain aquatic life. When it comes to providing water for the environment, the quantity and timing of water dynamics is crucial given seasonal and annual irregularity in natural systems. Frequent or lengthy low flow conditions can result in increased temperature and reduced dissolved oxygen concentration, whereas unnaturally high flows can be negative ecological effects as a result of flooding. Effective water monitoring networks should be established to ensure that data are available to make water allocation decisions. Accurate and sustainable planning would be best conducted at a sub-watershed level (de Loë, 2009). During warmer months, much of the surface water in these environments is due to groundwater contributions, known as baseflow. Baseflow is typically estimated via stream flow hydrograph separation. Additional complex, computational methods to determine baseflow are available, which consider groundwater storage, bank infiltration, and overall water balance models (Karamous et al., 2013). The other common method involves tracer separation, using isotopes for instance (Clark & Aravena, 2005). Environmental flow requirements for a given stream are based on its hydrologic character, sediment load, water quality and temperature, channel geomorphology, and habitat diversity. An environmental threshold can be defined as the minimum or maximum level an ecosystem can sustain under stress, without long-term consequences (Maunder & Hindley, 2005). In the Grand River Watershed, 60 % to 70 % of wetlands have been drained, limiting the capacity of the environment to self-regulate during flood and drought conditions. Approximately 9.2 m^3/s of surface water is taken from the Grand River to meet municipal, agricultural, and industrial needs. The environmental flow threshold for the Grand River Watershed is based on the magnitude of monthly means, the magnitude and timing of annual extremes, the frequency and duration of high and low pulses, and the frequency of change in conditions. This information is summarized in terms of mean monthly flow in Table 1 (Grand River Conservation Authority, 2005).

Common water allocation practises allow for groundwater to be extracted based on safe yield. Safe yield is defined as the long-term balance between the amount of groundwater withdrawn annually and the amount of recharge, where the upper limit of groundwater extraction is based on the volume of precipitation and surface water seepage anticipated. However, safe yield does not consider that aquifers discharge this water into surface water bodies as baseflow in other locations (Sophocleous, 2000). Extracting water to the safe yield limit will impact surface water levels; beyond the safe yield, groundwater extractions will deplete aquifer storage. When pumping from a well commences, the drawdown cone will expand outwards until a new equilibrium is reached in the system. Should the cone encompass a surface water body, a reversal in the hydraulic gradient would cease discharge from the aquifer to the surface water and surface water will begin to flow into the aquifer. Ultimately, this safe yield approach fails to address groundwater discharge, the potential impacts on surface water and its ecosystems, and changes in yield based on vegetation cover, land use practices, pumping well dynamics, or climate change. An appreciation for nature's tendency towards randomness, variability, and the need for disturbances, such as flooding events, have begun to expand sustainability concepts. Integrated water resource management encourages considering the good of both people and the environment with the inclusion of societal participation. This tactic will rely on dynamic and iterative policy, with ongoing monitoring, analysis, and revision (Sophocleous, 2000).

Ultimately, groundwater and surface water are connected; groundwater pumping can decrease the flow in those rivers and streams that they are connected to, known as stream flow depletion by wells. Understanding the effects of stream flow depletion is challenging because of the significant time delays between when pumping commences and when the effects of pumping start to impact streams. Several key concepts regarding stream flow depletion are pertinent to this study: individual wells have the ability to influence stream flow conditions; it may take days or years to observe the effects of groundwater pumping on stream flow; stream flow depletion can continue after pumping stops, as the system slowly stabilizes; reductions in groundwater discharge into surface water bodies can cause surface water temperatures to fluctuate more dramatically; and lastly, sustainable groundwater extraction rates must include total flow rates required to maintain stream health, not simply the amount recharge introduced to the groundwater system (Barlow & Leake, 2012).

2.1.4 Vulnerability of Pumping Wells

Vulnerability is a function of hazard, exposure, and adaptive capacity, which can indicate if exposure to a hazard forms the basis of a risk which could result in disaster. In terms of groundwater, understanding vulnerability is inherent to drinking water safety (Karamous et al., 2013). Groundwater vulnerability can be defined in many ways and considers a range of factors pertaining to the subsurface, the water resource, and possible contaminants involved. Frind et al. (2006) summarizes much of the terminology regarding the definition of vulnerability. The use of intrinsic, specific, and source vulnerability help to specify the reason for concern. Intrinsic vulnerability is based on the geological, hydrological, and hydrogeological characteristics of the subsurface, including hydraulic conductivity, porosity, gradients, tortuosity, and dispersivity, independent from contaminants. Specific vulnerability accounts for the fate and transport of contaminant groups and their potential impact on groundwater, involving mixing, sorption, and toxicity. Source vulnerability is based on mapping potential contaminant pathways, both vertically and horizontally. Additionally, aquifer and well terms provide additional meaning, with aquifer vulnerability referring to the entire aquifer source and well vulnerability referring to a specific receptor or well point (Frind et al., 2006). The main message is that all groundwater is vulnerable, to an extent. Everything from depth to groundwater, soil texture, potential for contaminant loading, and land use practises involving population density or pesticide use is relevant when considering vulnerability (Committee on Techniques for Assessing Ground Water Vulnerability, 1993).

The terms risk, susceptibility, and sensitivity have also been used interchangeably with vulnerability in reference to groundwater, however they fundamentally mean different things. Risk is a much broader term, including hazards, exposure, and vulnerability beneath its umbrella. In order for there to be risk, an exposure to a hazard will have a certain probability of occurring (McBean & Rovers, 1998). Where risk is a category above vulnerability, susceptibility and sensitivity are a vulnerability subset. Susceptibility encompasses the physical aquifer properties listed above, like porosity, hydraulic conductivity, and hydraulic gradients, however stress on the system is considered as well. This includes recharge, interaction with surface water, travel through the unsaturated zone, and well discharge (Frind et al., 2006). Similarly, sensitivity pertains to the potential for contamination based on aquifer properties (Committee on Techniques for Assessing Ground Water Vulnerability, 1993).

Over the past 20 years, the concept of vulnerability has gone from being purely qualitatively to taking on a semi-quantitative approach. Instead of determining a relative degree of vulnerability, there is a need to provide a numerical value for well vulnerability in order to indicate treatment requirements, assess potential hydrologic event-based problems, and plan for a safe and sustainable water supply for the future. Many methods have been developed in order to adequately quantify vulnerability. In order from least to most complex, these include index methods based on time of travel techniques, statistical methods, and modelling.

Time of travel is used to develop a vulnerability index, where the longer the travel time is, the higher the index value and the lower the vulnerability. Advective travel time is commonly used throughout North America and Europe to generate groundwater protection mapping. A more advanced surface to aquifer advection time (SAAT) approach was introduced by the MOE which considers hydraulic gradients and transport in the unsaturated zone. When both advective and dispersive transport of contaminants are considered, time of travel can be used to determine a well capture zone, dispersion-related concentration reductions, the expected arrival time of a contaminant, and the time required to surpass a water quality objective. Overall, time of travel methods can be difficult to apply due to heterogeneity of the subsurface, complexity of the non-point contamination sources, and the scale of the investigation (Frind et al., 2006).

Statistical methods are frequently used to assess groundwater vulnerability. Generally, probability distributions are used to describe uncertainty for any measured variable of interest for a given site. Simple or multiple regression analysis can be used in a predictive fashion, along with analyses of variance and geostatistical analyses such as kriging, which is essentially linear interpolation of variables over space and time given point measurements. Many statistical approaches, whether parametric or not, can help to provide estimates of concentration breakthrough points, cumulative concentration probabilities, and criteria for effluent concentration based on tolerance intervals. As with any statistical approaches, it can be difficult to determine whether a trend indicates a correlation or is simply a coincidence (Committee on Techniques for Assessing Ground Water Vulnerability, 1993).

Numerical modelling has the capacity to combine measured parameter data to produce scenario-based predictions. There is a variety of software that is applicable to time of travel assessments. FEFLOW, MODLFOW, and WATFLOW software was used to determine time-lag within the unsaturated zone, forward and reverse particle tracking, and estimate capture zone delineation. Models can prove to be limiting, with multiple software sets being both costly and time consuming. Accurate data and proper interpretation is needed in order to construct and make sense of model results (Sousa, 2013).

2.1.5 Climate Change Impacts on Water Resources

Climate change and water resources are highly intertwined. Increasing climatic variability is set to have many adverse impacts on water quality and quantity. Ontario-specific climate models predict high air and water temperatures, more precipitation with high regional and seasonal variability, shorter winters, and reduced snow and ice coverage. This would potentially result in higher rates of evaporation and transpiration, a longer growing season, and an increased potential for extreme weather events. Higher intensity, shorter duration rainfall events can be expected, causing higher runoff volumes, less time for water infiltrate the subsurface, increased erosion, and enhanced contaminant and sediment transport. Average snow pack may be reduced and the spring melt could occur earlier, resulting in less groundwater recharge at the end of the winter and a possible lowering of the water table in the summer. Lower flow levels during summer months would then diminish the assimilative capacity of surface water bodies to accept waste water effluent (Cameron, 2010). The sustainability of groundwater resources is at risk. With groundwater being replenished more slowly due to climate changes, human extractions must not exceed the renewable supply (Treidel et al., 2012). Additionally, efforts must be made to obtain the required scientific knowledge to address these emerging issues. Improvements must be made to climate forecasting models, especially on a regional scale. More knowledge regarding current water quantity and quality is needed through the use of sophisticated monitoring networks and database sharing (National Water Research Institute, 2001).

Aquifers will respond to climate change differently, depending on their size, recharge changes, and subsurface materials. Smaller, unconfined aquifers are anticipated to experience a greater variability in their water levels in comparison to larger, confined aquifers, making predictions about water availability difficult. In the context of well vulnerability, highly variable stream levels and mid winter melt events pose risk. Warmer winter temperatures will reduce soil frost, causing the opportunity for more recharge and less overland flow during the winter months; however, this can also increase the risk of leaching contaminants during the winter, amplifying problems associated with land use, such as agriculture and road salt application. High intensity rainfall events result in higher runoff volumes, introducing land surface contaminants into the water and degrading its quality. Alternatively, under reduced flow conditions over summer months, the assimilative capacity of the surface water will be reduced and the concentration of contaminants will increase. Further information is required by the scientific community in order to make sophisticated predictions regarding the impacts of climate change on groundwater (Kløve et al., 2013).

2.2 Field Study Site

The opportunity to perform an extensive well vulnerability field study was made possible by the Region who allowed for this research to be conducted on one of their new municipal supply wells.

2.2.1 The Alder Creek Watershed

The Alder Creek Watershed is located to the west of Kitchener-Waterloo, in the south-central portion of the Waterloo Moraine. This watershed drains approximately 79 km^2, spanning the Region and Oxford Country. Land use within the watershed is varied. Although primarily agricultural, there are some areas within the watershed with aggregate extraction operations. Settlements within the watershed include Shingletown, St. Agatha, Petersburg, Mannheim, and New Dundee. The villages of New Dundee, Mannheim, and a small trailer park on Witmer Road rely on onsite sewage disposal systems. At the north eastern boundary of the watershed lies the Erb Street Landfill. Subdivision development has taken place to the east of Mannheim, near the Region's Mannheim Water Treatment Plant located at Trussler Road and Ottawa Street South. There are transportation and infrastructure corridors spanning the Alder Creek Watershed, including Highway 7/8, the CN railway, and Ontario Hydro lines. Figure 1 shows a map of the watershed, including land use and settlement locations (CH2MHILL, S. S. Papadopulos & Associates, 2003).

2.2.2 Climate

Southern Ontario experiences four distinct seasons throughout the year, with relatively mild winters and hot humid summers. Precipitation is generally fairly uniform throughout the year, with no wetter or drier seasons. On average, between 700 and 900 mm of precipitation falls each year, with 400 mm estimated to recharge into the subsurface (Environment Canada, 2014). Notably, there are frequently mid-winter melt events, which contribute to recharge throughout the winter, with a significant amount of groundwater recharge happening as a result of the spring freshet. The warmest months, June through August, experience an average temperature of approximately 29 °C, with colder temperatures occurring in January and December, at around -8 °C (Environment Canada, 2014).

2.2.3 Geology and Topography

The Region lies on the eastern rim of the Michigan Basin, with a bedrock dip toward the southwest. This Palaeozoic rocks of the area overlies Precambrian rocks at an approximate depth of 850 m. The Salina Formation occurs next in the stratigraphic sequence, consisting of dolomites and limestones, interbedded with grey shales and lenses of gypsum and anhydrite. This Upper Silurian Formation is irregular in depth due to glacial erosion (CH2MHILL, S. S. Papadopulos & Associates, 2003).

The overburden geology underlying the Alder Creek Watershed is thick. Glacial till was deposited generously during ice advance, followed by outwash, kame, and glaciolacustrine deposition during ice retreat. A series of individual sheets were deposited during different periods of glacial activity. The Glacial sequence is referred to as the Waterloo Moraine and is situated on the western edge of Kitchener-Waterloo. The overburden thickness varies throughout the watershed, approximately 140 m towards the north around St. Agatha to about 35 m nearing the Nith River confluence. The surface of the hummocky formation is irregular, with areas of steeply undulating ground and rolling landscape. As a result, topography ranges considerably throughout the watershed, from around 400 m above sea level (masl) at its northern boundary to roughly 320 masl in the Nith River valley (CH2MHILL, S. S. Papadopulos & Associates, 2003).

The surficial geology of the watershed is characterized by sand and gravel deposits over 60 % of its area. Ice contact sand and gravel dominates the central portion of the watershed, with outwash sand and gravel occupying its southern extent. The remaining surfaces are typified by Maryhill Till and Port Stanley Till. Maryhill Till is a clay till which runs along the eastern limit of the Waterloo Moraine within the watershed, extending from the headwaters to Mannheim. The Port Stanley Till is comprised of sand and gravel with some clay. It exists along the southwestern boundary of the watershed, near New Dundee. More specifically, the Mannheim West well field area is characterized by Maryhill Till with underlying ice-contact sand and gravel deposits, with the till creating a surficial aquitard (CH2MHILL, S. S. Papadopulos & Associates, 2003).

2.2.4 Surface Water

The main surface water feature of interest within the watershed is Alder Creek. Alder Creek flows roughly south, meandering throughout the watershed for almost 20 km, and emptying into Alder Lake in New Dundee and continuing south from Alder Lake into the Nith River, roughly 3 km downstream. Alder Creek is a perennial stream south of Highway 7/8 and frequently ephemeral to the north towards the headwaters (Figure 2). In this region of the stream, a series of unnamed tributaries feed into the main channel, most of which join Alder Creek south of the K22A area of study. Alder Lake is a man-made feature created by a dam constructed across Alder Creek valley. The water level within the lake is regulated by the GRCA and is typically 4 m above the creek downstream. Alder Creek's drainage channel is underlain by alluvium, till, and some swamp deposits, creating a highly heterogeneous environment.

There are several other more minor features of interest. These include several kettle ponds within the hummocky areas. During high intensity rainfall events, these ponds swell and permit regionally significant groundwater recharge necessary for the Region's municipal well fields. An additional pond is located at the Trout Farm by the Queen Street and Huron Street intersection. Multiple wetland complexes also exist throughout the watershed, many of which are protected as an Environmentally Sensitive Policy Area (CH2MHILL, S. S. Papadopulos & Associates, 2003).

2.2.5 Hydrogeology

The Kitchener-Waterloo municipal water supply is provided in large part from a series of well fields constructed in the sand and gravel aquifers of the Waterloo Moraine. Two major overburden aquifer sequences exist within the Waterloo Moraine, including the upper sequence Mannheim Aquifer and the lower sequence Greenbrook Aquifer (Figure 3). The sequences are comprised of sand and gravel deposits with interbedded silt and clay horizons. The Alder Creek Watershed is dominated by the upper Mannheim Aquifer, which supplies groundwater to the municipal wells in the area and provides discharge to the watershed's streams and wetlands. The Mannheim Aquifer is comprised of sand, gravel, cobbles, and boulders which can sustain high well yields year round. The unsaturated zone of the Mannheim aquifer consists of interbedded horizons of silt or clay and sand and gravel. This unconfined aquifer is directly recharged by precipitation, which infiltrates rather rapidly. Due to the hummocky terrain, runoff from upland areas collects in low-lying swale areas, allowing for this runoff to infiltrate the ground surface as high intensity recharge zones (Grand River Conservation Authority, 2000).

The regional groundwater flow patterns within the Alder Creek Watershed's Mannheim Aquifer have been studied thoroughly. Generally, groundwater flows from the higher recharge elevations at the boundaries of the watershed, mainly originating in the northwest and flowing southward. Groundwater converges on Alder Creek in many locations throughout the watershed, indicating groundwater is discharging into the creek. In the northern part of the watershed, groundwater flow is influenced by pumping from the Erb Street well field. At the watershed's eastern boundary, groundwater flow is influence by the Mannheim well field's pumping. Gaining and losing segments of Alder Creek are variable in time and location throughout the watershed, however north of the village of Mannheim Alder Creek is gaining groundwater discharge. South of this point, the water table may be several meters below the streambed, so the aquifer is not directly hydraulically connected to the creek. However, depending on the hydraulic conductivity of the streambed sediments and underlying deposits, the creek may be losing water through the unsaturated zone and recharging the aquifer (CH2MHILL, S. S. Papadopulos & Associates, 2003). Additional groundwater discharge sites have been identified north of Alder Lake, south of Petersburg along Highway 7/8, and along the Trout Farm Tributary (Grand River Conservation Authority, 2000).

Specific to the area surrounding the K22A site within the watershed, several more specific units were identified in Stantec (2013). Aquitard 1, consisting of low permeability, spatially discontinuous, and surficial till units, is found predominantly along the flanks of the Waterloo Moraine. Along the eastern flank of the moraine, Aquitard 1 corresponds to the Upper Maryhill and Port Stanley Tills. Within the Mannheim West well field, this unit is generally less than 10 m thick. Next is Aquifer 1, composed of layered silt, fine to coarse sand, and gravel. K22A is completed at the base of Aquifer 1, which is the main water supply aquifer within the Waterloo Moraine. Generally, this unit is between 30 and 40 m thick around Mannheim and overlies Aquitard 2. Aquitard 2 corresponds to the lower Maryhill Till (Stantec Consulting Ltd., 2013). Essentially, the Mannheim well field area is very complex, with many different sand and gravel aquifers that are interbedded with till units, creating a series of unconfined and semi-confined aquifers (Figure 3). Previous efforts have been undertaken to determine the hydraulic conductivity of the different aquifer units mentioned above (Table 2). For Aquifer 1, hydraulic conductivity is estimated to range from $3x10^{-4}$ to $8x10^{-4}$ m/s. These estimates match values expected for sand and gravel deposits (Stantec Consulting Ltd., 2013).

2.2.6 Production Wells within the Alder Creek Watershed

There are several well fields within the Alder Creek Watershed that supply water to Kitchener-Waterloo, St. Agatha, and New Dundee. The Mannheim West well field includes K22A, K23, K24, and K26. The Mannheim East well field is located east of the Mannheim Water Treatment Plant, which includes wells K21, K25, and K29. The Mannheim Water Treatment Plant includes several aquifer storage and recovery (ASR) wells. North of this is the peaking well field, containing wells K91 to K94. The Erb Street well field is comprised of wells W6A, W6B, W7, and W8. Wells SA3 and SA4 make up the St. Agatha well field, which supplied to that community. New Dundee's well field, at the southern end of the watershed, includes wells ND2, ND3, and ND4 (Figure 2).

Many of the production wells in the area draw water from confined or semi-confined aquifers. Wells W7, W8, K22A, K23, K26, ND2, and ND4 are adjacent to Alder Creek. Due to their proximity and the stratigraphy of the area, they are expected to be drawing some of their extraction volume from Alder Creek (CH2MHILL, S. S. Papadopulos & Associates, 2003).

The management and reliance on supply wells in this watershed are affected by several key groundwater issues. Areas of concern include expanding urban development and aggregate extraction in significant recharge areas, over-extraction concerns in order to sustain growth and non-point source contamination in high vulnerability areas, including fertilizers, manure, septic systems, road salt usage, and pesticide application (CH2MHILL, S. S. Papadopulos & Associates, 2003).

Particle tracking in a study of the Mannheim West well field showed that K22A and K23 may receive surface water contributions from Alder Creek, within a 50-day time of travel. A qualitative assessment of well vulnerability was undertaken in the Alder Creek Watershed, developed based on the surficial geology. More permeable deposits were assigned a higher vulnerability, including those outwash and ice-contact sands and gravels. Less permeable areas, such as silts and clay tills, were given a lower vulnerability designation. Well K22A is currently classified as GUDI based on the MOE's Terms of Reference, including time of travel, proximity to Alder Creek, and very little or no aquitard material present in the area (CH2MHILL, S. S. Papadopulos & Associates, 2003). The significance of this GUDI classification is the clear potential from groundwater quality to be directly impacted by the quality of the surface water in Alder Creek. Specifically, pathogen contamination of surface water has the ability to infiltrate into the groundwater table, posing a risk to the drinking water supply. Understanding the groundwater-surface water interaction in more detail is essential in assessing this level of risk and being able to quantify its vulnerability.

2.2.7 Previous Studies of the Alder Creek Watershed

Many studies of the Alder Creek Watershed have been conducted over the years by the Region and other institutions. This is attributed to its many supply well fields, the Erb Street Landfill, the Mannheim Water Treatment Plant and ASR, as well as development targets for the area and the environmentally protected status of its wetlands. Within this literature review, only those reports that are most relevant to this research have been included. These were obtained from the Region, the GRCA, and the University of Waterloo. Access to the Region library database was granted in order to attain the background information necessary to this research (Appendix A).

CH2M HILL was retained by the Region in 2003 to undertake an Alder Creek Groundwater Study. There were two primary objectives for this study. First was a goal to develop a conceptual model of the hydrogeologic setting of the Alder Creek Watershed. This information would be useful in the delineation of capture zones for the municipal wells throughout the watershed and ASR and recovery wells at the Mannheim Water Treatment Plant and aid in predicting the effects of development on recharge and surface water flow. The second objective was to determine if the wells in Mannheim and New Dundee should be designated as GUDI, as defined by the MOE. The majority of the background information within this section was obtained from this study, which provided an overall view of the Alder Creek groundwater system using all historic data and records available up to 2003, as well as an additional field program (CH2MHILL, S. S. Papadopulos & Associates, 2003). One year before, CH2M HILL produced a GUDI study of the Mannheim East, West, and peaking well fields. Conducted in conjunction with the Alder Creek Watershed Study, this GUDI study was completed by MOE recommendation in order to ensure well water sources were being treated and regulated to verify safe drinking water quality (CH2MHILL, 2002). These studies were very useful in providing background information regarding the local surficial geology, outlining key watershed features, and providing an understanding of water quality concerns in the area.

The GRCA is also concerned with the Alder Creek Watershed. Of particular interest to this study is a 2000 Phase 1 Discussion Paper focusing on overall watershed processes and the development of a water management plan. This includes a detailed watershed characterization, land use impact assessment, consideration for future development, and potential and ongoing water quality of the surface water and groundwater.

The Alder Creek Watershed, and on a larger scale the Grand River Watershed, have been of interest for researchers from the University of Waterloo for some time. Whether from a management perspective, via a developed understanding of the chemical constituents within the watershed, or through the development of numerical models, like Marcelo Sousa's work titled "Using Numerical Models for Managing Water Quality in Municipal Supply Wells," the Alder Creek and Grand River watersheds have been well chronicled. Sousa's study into the capture zone estimate of the Alder Creek Watershed through the use of different modelling software was very insightful in understand the regional groundwater flow field in the area. Reynold Chow also characterized the Alder Creek Watershed utilizing a variety of modelling programs in an effort to model groundwater contributions area to creek baseflow (Chow, 2012; Sousa, 2013).

2.2.8 Previous Study of Municipal Well K22A

Well K22A experienced elevated turbidity levels after prolonged pumping, forcing it to go unused despite several prior rehabilitation efforts. In 2012, Stantec Consulting Ltd. (Stantec) was retained by the Region to investigate this issue at K22A. The objectives of their study were to review historical water quality data at K22A, complete well upgrades, conduct testing before and after said upgrades, and run a pump test on K22A to assess water quality over time. Ultimately, the goal was to provide recommendations regarding K22A's functionality.

Stantec performed a well assessment, pumping K22A to waste for 30 days, with detailed water quality monitoring in an attempt to determine the cause of the turbidity spike. A hypothesis was posed. Under anaerobic conditions, iron and manganese are stable as Fe(2) and Mn(2) oxides which are soluble under neutral pH conditions. The data indicate that anaerobic water in the lower portion of the aquifer mixes with aerobic, shallow water under pumping conditions. As the upper and lower water mixes, dissolved oxygen concentrations change which cause iron and manganese to precipitate out of solution. It is this precipitate that is thought to increase turbidity. This causes a corresponding decrease in groundwater concentrations of iron and manganese, which was observed. As a result of this hypothesis, operational alternatives were posed: turbidity could be treated on site; the water could be blended and treated at the Mannheim Water Treatment Plant; or the well could simply be used as a peaking well for a reduced time period. Alternatively, it was suggested that a shallow replacement well be installed, with low dissolved iron and manganese concentrations and reduced aerobic and anaerobic water mixing thus eliminating the source of the elevated turbidity (Stantec Consulting Ltd., 2013). An alternative that was selected by the Region was to install a new shallow well (WT-TW2-13), which is the subject of the pumping test studied within this thesis. For the duration of this report, the test well will be referred to as TW2-13. Section 3.3.1 outlines its well construction and hydrostratigraphic setting.

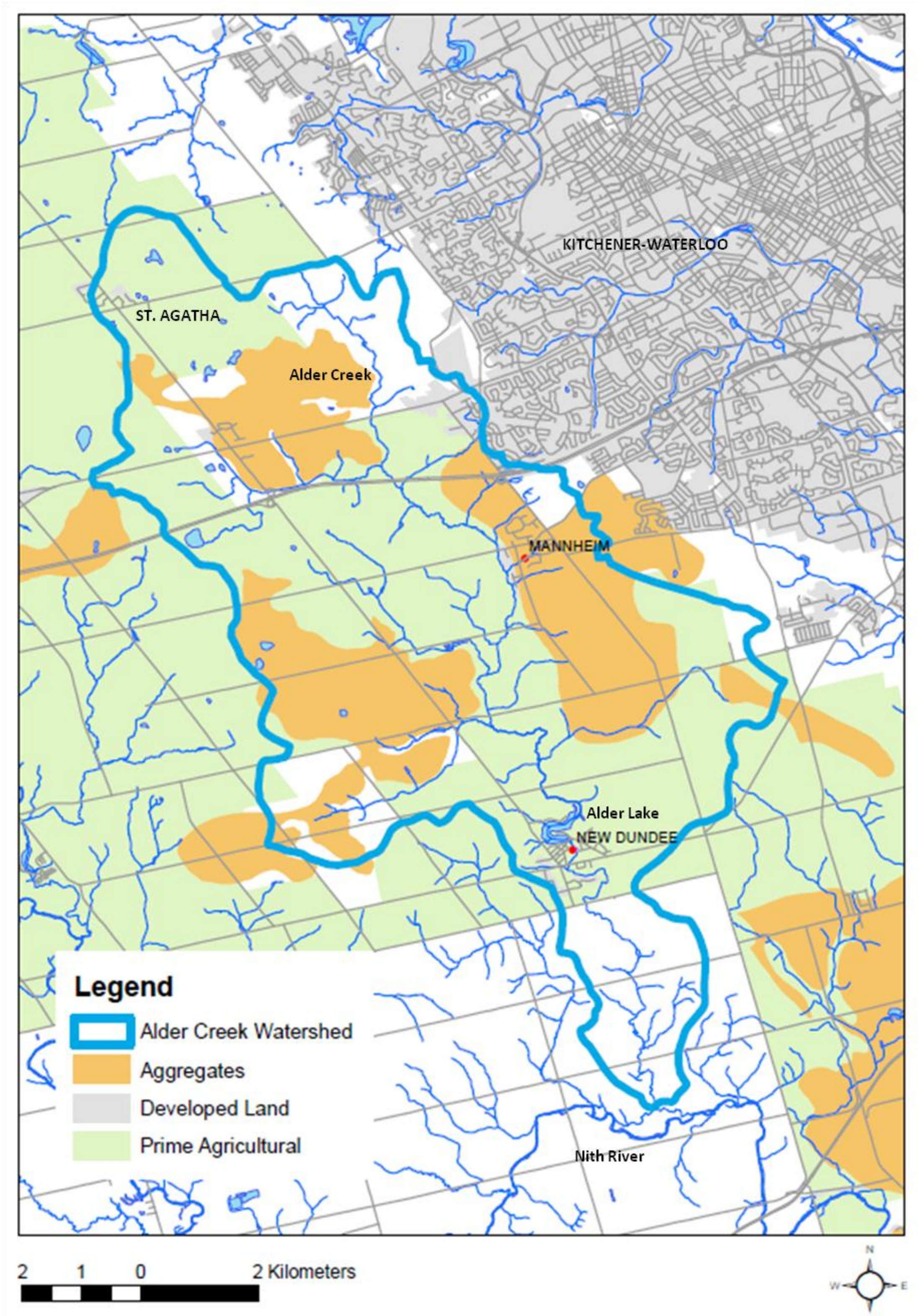


Figure 1. Map for the Alder Creek Watershed including land use and settlement locations.

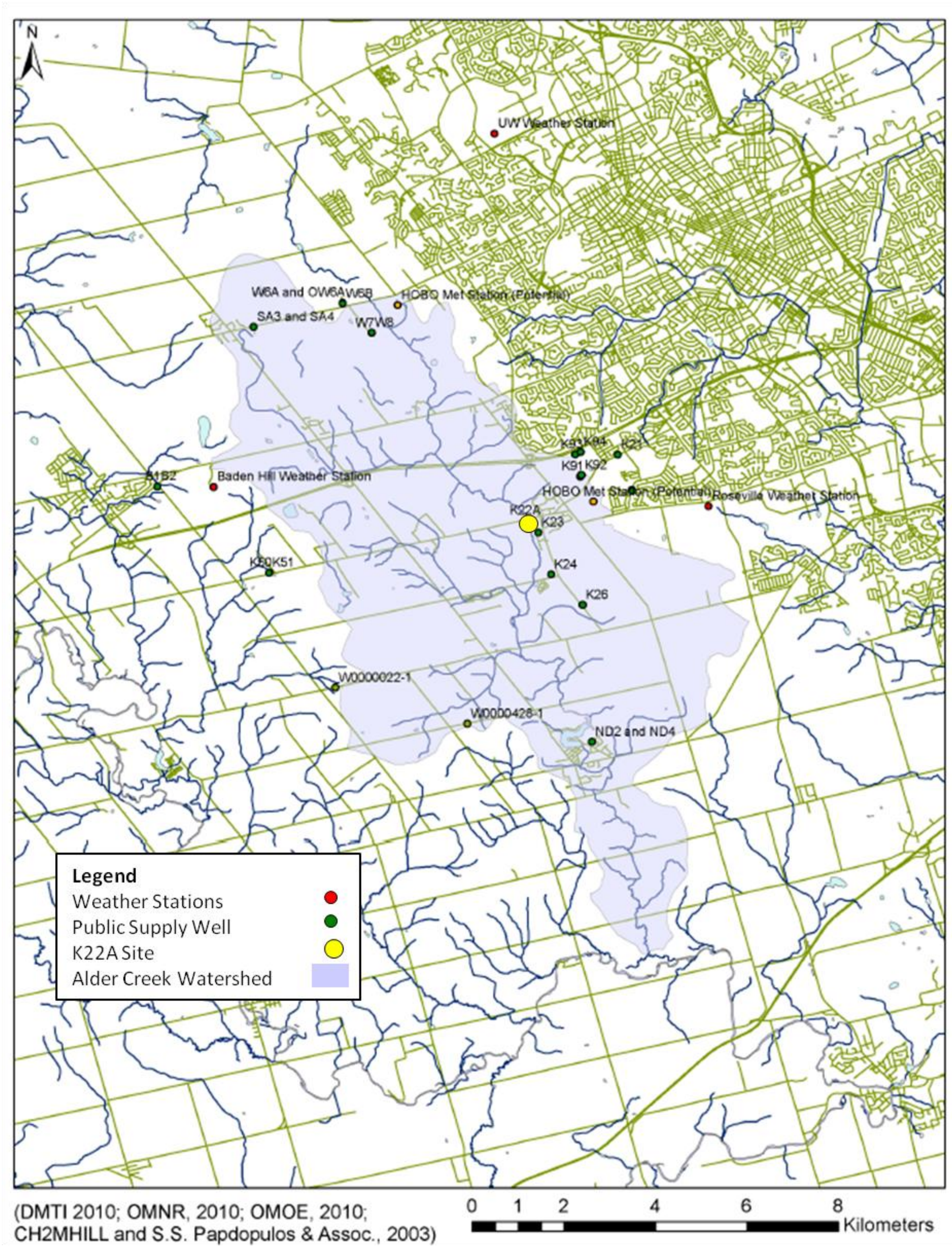


Figure 2. Public supply well and local weather station locations within the Alder Creek Watershed (CH2MHILL, S. S. Papadopulos & Associates, 2003).

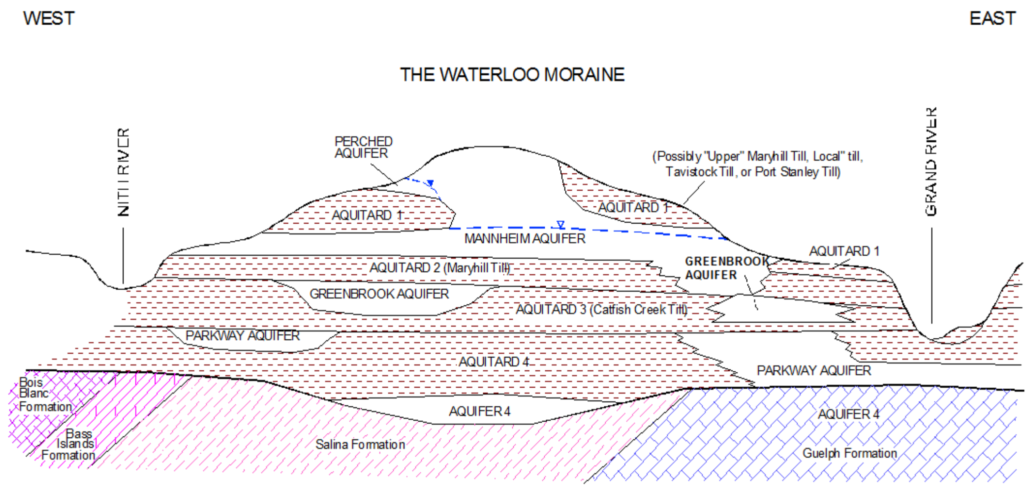


Figure 3. Waterloo Moraine Cross-Section, showing interbedded aquifer and aquitards (Merry, Martin, & Middleton, 1998).

Table 1. Mean annual flow requirements for the Grand River Watershed (Grand River Conservation Authority, 2005).

Situation	Minimum Monthly Flow (%)
If $Q_{MM} < 40\ \%\ Q_{MA}$	Use Q_{MM}
If $Q_{MM} > 40\ \%\ Q_{MA}$ & $40\ \%\ Q_{MM} < 40\ \%\ Q_{MA}$	Use $40\ \%\ Q_{MA}$
If $40\ \%Q_{MM} > 40\ \%\ Q_{MA}$	Use $40\ \%\ Q_{MM}$
Q_{MM} – mean monthly flow, Q_{MA} – mean annual flow	

Table 2. Hydraulic Conductivity Slug Test Results for the Mannheim West Well Field (Stantec Consulting Ltd., 2013).

	Estimate of Hydraulic Conductivity (m/s)					
Well	**WT-MW-OW3A-09**	**WT-MW-OW1A-11**	**WT-MW-OW1B-11**	**WT-MW-OW2-11**	**WT-MW-OW3-11**	**WT-MW-OW3B-11**
Method	**Bouwer-Rice**	**Springer-Gelhar**	**Springer-Gelhar**	**Bouwer-Rice**	**Springer-Gelhar**	**Bouwer-Rice**
Test 1	9E-05	3E-04	9E-04	7E-04	6E-04	2E-04
Test 2	7E-05	-	9E-04	5E-04	6E-04	4E-04
Test 3	8E-05	-	4E-04	8E-04	8E-04	3E-04
Test 4	7E-05	-	7E-04	6E-04	5E-04	4E-04
Test 5	7E-05	-	-	-	8E-04	3E-03
Test 6	-	-	-	-	7E-04	-
Geometric Mean	**8E-05**	**3E-04**	**7E-04**	**6E-04**	**7E-04**	**5E-04**

Chapter 3 – Methodology

3.1 Introduction

The Alder Creek Watershed field work began in autumn 2012 and ended in mid-autumn of 2013, for the purposes of this study. Initial field work was mainly site reconnaissance, obtaining land access permissions and reviewing work plans with the Region. Over the spring and summer of 2013, biweekly monitoring of water quality, stream flow gauging, and creek bed temperature profiling was undertaken. In July of 2013, drilling at the K22A pumping test location commenced during which monitoring wells were installed and the subsurface stratigraphy was mapped from drill logs. Automatic recording instruments and data loggers were installed in mid-August 2013. A 60-day pumping test began on August 19, 2013 and completed on October 17, 2013. On-going monitoring and sampling took place over this time. Shortly after the test, allowing for over a week of recovery, the data collected throughout the test were downloaded and much of the equipment was removed. Stream flow gauging continued throughout the fall of 2013. The methodology surrounding the instrumentation, monitoring and sampling, along with data analyses protocols are explained within the following subsections.

3.2 Alder Creek Watershed-wide Monitoring

3.2.1 Meteorological Stations

Weather Station 4, one of four stations recently installed within the Alder Creek Watershed as part of the Southern Ontario Water Consortium (SOWC), was installed at the K22A site location on June 12, 2013. It utilized Sutron data loggers, with data being downloadable by Xterm and AutoPoll software. The station's set of instrumentation included sensors and gauges to measure air temperature, relative humidity, precipitation, wind speed and direction, and incoming solar radiation. The data from the weather station at K22A, which was the primary source of meteorological data used for the current study, are located in Appendix B.

Data from the UW Weather Station were downloaded and used for verification of the Station 4 data. In all cases except for the precipitation gauges, the instruments used for Weather Stations 4 has a higher accuracy than the UW Weather Station, due to the now outdated equipment of the UW Station. The accuracy of the rain gauges is related to the type of instrumentation. SOWC's Weather Stations 1 to 4 use a tipping bucket style gauge which "tips" when the rainfall reaches a the required tipping volume, counting the number of "tips" over a given time period (Sutron, 2007). This has inherent error within its methodology, measuring rainfall events only to the nearest tipping volume registered. Alternatively, the UW Weather Station uses a Geonor style gauge which utilizes a continuous mass scale to measure cumulative precipitation. A precipitation reading is calculated by subtracting the amount of rainfall over a time interval, occasionally registering a negative measurement due to evaporative effects. Negative values were corrected to zero, under the assumption that no precipitation fell during those time intervals.

3.3 K22A Monitoring Wells

3.3.1 Pumping Well

Due to water quality concerns related to the Region's K22A public supply well, described earlier as being related to the mixing of shallow and deeper mineralized groundwater, a new, shallower supply well was proposed as an alternate supply that would potentially avoid this mixing problem (Stantec Consulting Ltd., 2013). TW2-13, was installed on February 15, 2013 by Gerrits Well Drilling using a truck mounted air rotary drill (Figure 4). This well is the subject of the 60-day pumping test conducted as part of the current study. The Region contracted Stantec to perform the pumping test for a hydrogeologic assessment. Throughout the duration of the pumping test, UW and Stantec shared responsibilities at the site in terms of equipment installations and monitoring, water quality sample collection, and manual water level measurements. Where Stantec played a significant role, mention is made as to the work they conducted.

TW2-13 has a 203 mm outer diameter stainless steel telescopic screen, with a No. 20 slot size from 15.4 m to 14.0 m below ground surface (mbgs), a transition from a No. 20 to a No. 15 slot size from 14.0 m to 13.4 m below ground surface, and a No. 15 slot size from 13.4 m to 11.0 mbgs, with a total screen length of 4.4 m. The surrounding material was able to cave in around the screen, followed by infilling of silica sand from 11.0 m to 10.4 mbgs and bentonite chips from 10.4 m to 7.3 mbgs. Neat cement was then used to seal the 203 mm outer diameter steel casing to the ground surface. The borehole diameter was 350 mm (Appendix C). The stratigraphy in the area was dominated by medium sand containing trace gravel, with a silty sand layer between 6.1 mbgs and 7.6 mbgs. Figure 4 shows the location of TW2-13 in relation to the other features at the K22A site.

3.3.2 Existing Monitoring Wells

The K22A site had six functioning monitoring wells available for observation during this study, installed between June 8 and June14, 2011. As with the pumping well, all of the existing monitoring wells were installed by Gerrits Well Drilling using a truck mount air rotary drill. They are located in pairs with a shallow and deep well, allowing observation between the upper and lower aquifer segments of interest. The 2-inch diameter wells are located throughout the site in close proximity to the pumping well and are shown in Figure 4. The first pair, OW3B-09 and OW2-11, is situated 6.5 m north of the pumping well, with respective bottom of screen depths 22.56 m and 12.19 mbgs. The next pair, OW1A-11 and OW1B-11, is situated in the south west corner of the property, with 27.43 m and 15.24 mbgs bottom of screen depths. The third pair is identified as OW3A-09 and OW3-11, in the south east corner of the K22A property, with bottom of screen depths 27.43 m and 15.24 mbgs (Figure 4). The deep wells are positioned roughly 22 m to 27 mbgs, whereas the shallow wells are between 12 m to 15 mbgs. All of the wells have PVC screens with a No. 10 slot size. Wells OW3B-09 and 3A-09 have 3.05 m long screen surrounded by No. 3 filter pack silica sand, with all other existing monitoring wells having screens 1.53 m in length surrounded by No. 2 silica sand filter packs. All of the boreholes for these wells had a 155 mm diameter, in-filled with bentonite grout or chips around 51 mm diameter PVC risers to ground surface. These well construction logs are provided in Appendix D, which includes location coordinates and screen depths.

3.3.3 Drilling

Drilling at the K22A site commenced on July 2, 2013 and was completed on July 12, 2013, using a 7822 Geoprobe drill rig. The contractors, Aardvark Drilling Limited used a hollow-stem auger to drill five boreholes and installed six monitoring wells for the purpose of this study (Figure 4). The soil cores were collected with a 2.5 foot-long split-spoon sampler, with one spoon extracted every five feet. This intermittent sampling was deemed appropriate given the uniformity of the subsurface material. Additional spilt-spoons were collected, until the water table was pin-pointed or in the event that a change in stratigraphy was encountered to provide a more detailed record of the subsurface. The wet sands and silts allowed the retrieval of full split-spoon samples. The samples were photographed and logged on site according to the Unified Soil Classification System (American Society for Testing Materials, 2006)

Additional grain size analyses were not deemed necessary at this location given the numerous in-depth studies previously conducted (CH2MHILL, S. S. Papadopulos & Associates, 2003; CH2MHILL, 2004; Grand River Conservation Authority, 2000; Stantec Consulting Ltd., 2013). The hydrogeology of the site has been categorized in detail in this pervious work, as explained in Section 2.2. Estimates of hydraulic conductivity of the various stratigraphic units have been derived from these previous studies and are listed in Table 2 and derived from detailed analysis of pumping test data, explained below. Because there was such extensive hydraulic testing at the site previously, and so much data was going to be available through the long-term pumping test analysis, any additional tests appeared very redundant. Appendix E includes the logged information for these boreholes and resulting constructed wells. The monitoring wells installed are explained specifically in the subsequent sections.

3.3.4 Multi-level Monitoring Wells

Four Solinst Continuous Multichannel Tubing (CMT) wells, CMT1, CMT2A, CMT2B, and CMT3, were installed by Aardvark Drilling Limited in July of 2013. The CMT construction utilized 7-Channel tubing to create seven depth-discrete zones within a single tube. The materials were transported to and assembled on site. The 43 mm diameter 7-Channel tubing has clearly numbered ports, one corresponding to the shallowest port and seven corresponding to the deepest port, allowing for the screens to be located easily. A space was cut at the appropriate depth in a given port, the bottom of the opening was securely sealed using a mechanical plug, and a centralizer was used to seal the screen mesh into place over the hole. The centralizer allows for a

112 mm screen length. Ports one to six are trapezoidal pie shapes with a 10 mm diameter and port seven is hexagonal with a diameter of 9.5 mm (Solinst Canada Ltd., 2012).

The CMT well construction resulted in the seven screened ports being installed at event increments from slightly below the water table to the base of the monitoring well. For example, CMT1 was drilled to a depth of 10.5 mbgs and ports 1 to 7 were installed at 4.06 mbgs, 5.09 mbgs, 6.10 mbgs, 7.12 mbgs, 8.16 mbgs, 9.15 mbgs and 10.12 mbgs with roughly a one meter spacing between each port. The water table was encountered at 3.66 mbgs at this location. These multilevel well ports use the notation CMT1-5, representing CMT well 1, port 5, for example. The CMT tubing was lowered into the hollow-stem augers to the bottom of the hole and then the augers were removed from around the well. The sand formation, comparable throughout the site, was assumed to collapse uniformly around the wells below the water table. Above the saturated zone, the annulus was filled with the auger cuttings, followed by a bentonite plug near the ground surface.

CMT2A and 2B wells each have a 7-Channel tube reaching the surface, with a total of 14 ports contained within the same drilled hole with a depth of 20.42 mbgs. This high resolution was used in order to provide detailed subsurface observations from the water table to the depth of the original K22A well screen. The deeper CMT2B tube was inserted into the drilled hole, with its seven ports ranging from 19.89 mbgs to 13.35 mbgs. Augers were removed to a depth of 12.12 mbgs, at which point the CMT2A tube was lowered into place and the remaining augers were removed. CMT2A-7 had a corresponding depth of 12.12 m, with CMT2A-1 located 5.61 mbgs. Appendix E provides detailed construction and location information for these wells.

The CMT wells were positioned around the pumping well. CMT1 was located between TW2-13 and Alder Creek, CMT2A and 2B was placed between the original K22A pumping well and TW2-13, and CMT3 was placed direct north of TW2-13, 15 m upstream. The orientation of these wells allows for detailed geochemical, hydraulic, and temperature monitoring in both space and time (Figure 4).

3.3.5 Additional Monitoring Wells

Two additional monitoring wells were installed on the west side of Alder Creek by Aardvark Drilling Limited in July 2013. These 2-inch diameter monitoring wells were designed to monitor hydraulic effects observed on the other side of the creek during the course of the pumping test (Figure 4). Titled UWMW A and UW MW B, these wells were drilled to depths of 18.29 mbgs and 12.80 mbgs, respectively. In both cases, a plastic screen was 3.05 m in length, with a No. 10 slot size. As with the CMTs, the annular material was allowed to collapse around the screen and casing. Some additional sand was required, followed by a bentonite seal from 3.5 mbgs to 0.46 mbgs, and 0.46 m of concrete to the surface for UW MWA and B. Construction details for these two wells are provided in Appendix E.

From roughly east to west, CMT2A, CMT2B, TW2-13, CMT1, Alder Creek, UW MWB, and UW MWA form a straight line that will act as a comprehensive cross-section for this study (Figure 4). Stantec surveyed the locations of these new wells in September of 2013, allowing for the positioning in figures and the conversion from mbgs to masl utilized for data analyses (Appendix F).

3.4 Pumping Test Summary

In order to assess the hydraulic and geochemical characteristics of the newly installed TW2-13 well, an extended pumping test was conducted on well TW2-13. A Permit to Take Water was issued to the Region by the Ontario Ministry of the Environment on May 7, 2013 with an expiry date of December 31, 2013. This initial permit stipulated a maximum withdrawal rate of 1200 L per minute, to a maximum 1 728 000 L withdrawn per day. The permit allowed for a maximum of 45 days of pumping. (Appendix G).

Gerrits Well Drilling managed the test, installing a Goulds Model 300L25pump. This six-stage submersible pump is 15 cm in diameter and 2.9 m long, weighing 24 kg. The pump was positioned 1.5 m from the bottom of the well, approximately a third of the way up the screen. The motor used to power the pump was a 25 horsepower, 575 V, three-phase motor manufactured by Franklin Electric. Above the well, a flow meter and totalizer were installed in line to allow for on-site monitoring of the test conditions. The flow meter showed an instantaneous reading of the extraction rate, measured in litres per second. The totalizer kept a record of the total extraction volume, provided in tenths of a cubic meter. The water left the pumping well through a large pipe. A spillway was constructed at the south end of the K22A property to release the extracted water from the piping into Alder Creek, downstream from the immediate test site and without causing erosion of the creek bank. The spillway was comprised of tarps within a wooden frame, held in place by drilling sand. Throughout the test, manual readings of the flow meter and totalizer were taken by reading from the gauges visible on the side of the device and the condition of the spillway was recorded regularly (Gerrits, 2013).

The pumping test on TW2-13 commenced at 10:40 AM on August 19, 2013. Stantec calculated the maximum allowable drawdown of the pumping well as 8.82 mbgs, or 9.48 m below the top of casing, given the 0.66 m stick up. Based on the available drawdown and the hydraulic parameters of the pumping zone, the well was thought to be able to yield 15 L/s over the length of the pumping period. When the test was first started at this rate, the water level dropped dramatically, surpassing the critical drawdown level which was not sustainable. After one hour of pumping, the rate was reduced to 13 L/s. After several days of pumping, drawdown began to near the critical drawdown level once again. The decision was made to reduce the pumping rate further, to 11 L/s effective at 12:00 PM on August 21, 2013. This pumping rate was maintained for the duration of the test. The manual flow meter readings showed a relative steady pumping rate, ranging from 10.3 L/s to 11.2 L/s. All of the flow meter and totalizer readings taken throughout the test are presented in Appendix H.

On Friday, September 20, 2013, an unforeseen event occurred. The power in the K22A pump house was turned off accidentally, causing the pump to stop working and the well to recover fully. Using the totalizer readings and approximate pumping rate, the pump was estimated to have shut off at 1:05 PM on September 20, 2013. When this was discovered the following Monday, Gerrits was informed and returned to restart the pump. The system was back online at 1:45 PM on September 23, 2013. On September 23, 2013, an amendment to the Permit to Take Water was issued, allowing for the extension of the pumping test on well TW2-13, citing unforeseen complications with the pump. The specifications of the permit were updated to include 60 total days of pumping at the same maximum extraction rate of 1 728 000 L per day (Appendix I).

The extracted water was directly via pipe to the south end of the property where it emptied onto a spillway that discharged to Alder Creek. The spillway was located approximately 40 m south of the pumping well. Throughout the test, some pooling was observed on the spillway. Several of the sand bags used to weigh down the tarps split open, allowing for sand to be released onto the tarps and into the creek. The sand remaining on the spillway was oxidized and exhibited a rusted colour. Part way through the test, the spillway was extended approximately 10 m, in an effort to reduce pooling and further deter the potential from stream bank erosion. Organic growth began to appear on the tarps by early October.

The pumping test was completed on October 17, 2013 at 3:00 PM. The pump, electrical equipment, gauges, piping, and spillway were removed in stages by Gerrits Well Drilling over the next month.

3.5 Instrumentation for Pumping Test

3.5.1 Resistance Temperature Detectors

Measuring surface water and groundwater water temperatures at different depths and monitoring their changes can provide insight into groundwater-surface water interaction and groundwater dynamics as a whole where there are temperature contracts between the two water sources. At the K22A field site, temperature was measured extensively during the 60-day pumping test in both the surface and subsurface environments with the intention of using variations in temperature as an indicator of groundwater-surface water interaction. Nineteen Resistance Temperature Detectors (RTDs) were installed within the multi-level CMT wells for the duration of the pumping test. These PT100 385 RTD sensors are 100 Ohm platinum resistive devices and have 4 mm diameters, allowing them to fit in the narrow ports (MICRO SWITCH Sensing and Control, 2013). Temperature values can be obtained from resistance measurements by the Callendar Van Dusen equation, which states

$$R_T = R_0 \left(1 + AT + BT^2 - 100CT^3 + CT^4\right) \qquad (1)$$

where R_T is Resistance (V) at temperature T (°C), R_0 is Resistance (V) at 0°C, and T is Temperature (°C; MICRO SWITCH Sensing and Control, 2013). Above 0°C, the quadratic formula can be used to solve for Temperature as a function of resistance with the result

$$0 = R_0BT^2 + R_0AT + (R_0 - R_T) \qquad (2)$$

$$T_R = \frac{-R_0A + \sqrt{R_0^2A^2 - 4R_0B(R_0 - RT)}}{2R_0B} \qquad (3)$$

where A, B, and C are constants based on α and β, Callendar Van Dusen parameters. β is 0 for temperatures above 0°C and α is calculated based on the difference in resistance at 0°C and 100°C. The devices are programmed and calibrated to be able to calculate temperature independently. The 385 type for these devices refers to their alpha constant value of 0.00385, which correlated to an accuracy of ± .0001 °C. To improve the accuracy of the RTDs, 10 kOhm completion resistors were added. The sensors can measure temperatures ranging from -200 °C to 650 °C, with a resolution of approximately 0.4 °C (MICRO SWITCH Sensing and Control, 2013).

All 19 of the RTDs were installed on August 16, 2013. CMT1, adjacent to Alder Creek, had RTDs installed in all seven of its ports. CMT2A, 2B, and 3 had RTDs installed in ports one, three, five, and seven. Table 3 outlines the data loggers, RTD identification numbers, and associated ports used throughout the pumping test. The 8 cm long sensors were located at the bottom of the screened ports in order to capture temperature changes at specific elevations. The Campbell Scientific (CS) 1000 and Hoskin's Sutron XLITE 9210 Datalogger were used to record temperature data every five minutes, each powered by a deep cycle marine battery. Both of these data logger models can operate in extreme temperature environments and have the capacity to transmit their data via telemetry. The CS 1000 cooperates with Loggernet software and the Sutron 9210 operates with Xterm software (Campbell Scientific Inc., 2004; Sutron, 2007). The data loggers and their batteries were stored in large ply-wood boxes designed and constructed by Paul Johnston. The batteries were charged weekly to maintain the 12 V necessary to function. There were several instances during the test when battery levels dropped prior to being charged, causing some data to be missed.

The RTDs were left in place for ten days following the completion of the test, in order to capture the full spectrum of recovery after the test. The data loggers were downloaded and instrumentation was removed on October 28, 2013 (Appendix J).

3.5.2 Drive Point Piezometers

Shallow drive point piezometers were installed to track transient changes in groundwater levels beneath the stream close to where pumping was conducted. On August 14, 2013, Stantec installed two drive points via coring and with the use of a fence post driver. Identified as WT-K22A-DP1-13 (DP1-13) and WT-K22A-DP2-13 (DP2-13), these drive points consist of 42 cm long, 19 mm in diameter stainless steel screens connected to 25 mm diameter steel casing, which extends above the surface water. DP1-13 was positioned 8.60 m west of the pumping well, in-line with the cross-section formed by CMT2A, CMT2B, CMT1, and the monitoring wells on the far side of the creek. DP2-13 was located within Alder Creek, 9.14 m north of the pumping well. DP1-13 was screened from 0.98 mbgs to 0.56 mbgs, with DP2-13 slightly deeper into the stream bed from 1.42 mbgs to 1.00 mbgs. Appendix K presents the logs for these drive points.

During the test, Stantec had pressure transducers installed to measure surface water and groundwater level fluctuation. Solinst Edge 3001 Leveloggers were used and recorded water pressure and temperature information at 15 minute intervals. Barometrically corrected data was provided by Angela Ducharme of Stantec (Ducharme, 2013). The level sensor has an accuracy of 0.1 % of its full reading with a 0.2 cm resolution. The temperature sensor has accuracy and resolution of +/- 0.1 °C and 0.1 °C, respectively (Solinst Canada Ltd., 2011).

3.5.3 Pressure Transducers

A variety of pressure transducers were used to collect water level data in the various wells throughout the K22A site prior to, during, and following the extended pumping test. The existing Region monitoring wells used Insitu Inc. TROLL loggers. Both vented and non-vented loggers were used; vented loggers do not required barometric pressure connections, however non-vented loggers do. Table 4 summarizes which loggers were used in which well, the model number of the logger, its type and data range specified, and the dates in which they were installed and removed. Depth and temperature data were recorded in all of the Region's monitoring wells at five minute intervals and are presented in Appendix L (Hutton, 2014)

The pumping well was instrumented with a Solinst Edge 3001 Levelogger, just like the drive points. Once again, temperature and water pressure information was recorded and corrected by Angela Ducharme, this time having data taken at five minute intervals. Appendix M includes this information.

UW MWA and UWMW B wells on the west side of Alder Creek were fitted with unvented Solinst 3001 LTC Levelogger Juniors and an accompanying barometric pressure logger. These loggers also have the capacity to measure temperature and electrical conductivity. Due to problems upon installation, only the logger in UWMW B was also able to record conductivity. The LTC logger has the same accuracy and resolution for its temperature and level sensor as the Edge logger, specified above. The conductivity sensor has a 2 %, 20 μS/cm, accuracy and 1 μS resolution (Appendix N).

The CMT well ports are so small that standard pressure transducers will not fit in them, therefore smaller ones were needed. Two CMT ports, CMT2A-4 and CMT2B-4, were equipped with Submersible Resistive Transmitters (SRPs) designed to measure hydraulic pressure within narrow tubes. These two ports were selected because they offered a direct comparison of water levels from different elevations; additionally, they were not already equipped with RTDs so there was space for them to be installed within the ports. These PMC MTM 3213 SPRs are 0.9 cm in diameter, allowing for them to fit within the narrow CMT ports. The sensor, fully isolated and protected by a stainless-steel casing, has an accuracy of +/- 0.1 % of its reading. The detectable pressure range can be specified as either from 0 to 15 psi or from 0 to 500 psi (Process Measurement and Controls Inc., 2013). For this test, this range was scaled for a 30 m variation in water column. These vented instruments do not required correction for barometric pressure variability. All of the hydraulic data from these devices are contained in Appendix O.

As mentioned above, water levels measured in non-vented loggers must be correct in order to account for the pressure contributions from the atmosphere. Water level logger data is downloaded in conjunction with a barometric pressure logger. Several of these barometric loggers were positioned around the site. Next, the data must be converted into the same units. Level loggers record data in meters and barometric pressure loggers record in kilopascals. The kilopascal data are converted into equivalent meters of water column and then used to find the depth of the water table below the ground surface, calculated via

$$D_{\text{barometric water column equivalent}} = P_{\text{barometric logger}} \times \frac{0.102\ \text{m}}{1\ \text{kPa}} \tag{4}$$

$$D_{\text{logger data}} - D_{\text{barometric water column equivalent}} = D_{\text{water level above logger}} \tag{5}$$

$$D_{\text{logger from top of casing}} - D_{\text{stick-up}} - D_{\text{water level above logger}} = D_{\text{water table below ground surface}} \tag{6}$$

where $D_{\text{barometric water column equivalent}}$ is the atmospheric pressure water column equivalent (m), $P_{\text{barometric logger}}$ is the atmospheric pressure measured by the barometric loggers (kPa), $D_{\text{logger data}}$ is the data recorded by the level loggers (m), $D_{\text{water level above logger}}$ is the depth of water above the level logger (m), $D_{\text{logger from top of casing}}$ is the depth of the logger from the top of the well casing (m), $D_{\text{stick-up}}$ is the length of well casing sticking above to the ground surface (m), and $D_{\text{water table below ground surface}}$ is the depth of the water table below the ground surface (m; Solinst Canada Ltd., 2013).

All of the water level data measured, from August 14, 2013 to October 28, 2013, was measured at five minute intervals. Appendix P presents all of the electrical conductivity data collected by applicable data loggers deployed throughout the test. Irregularities in these data were tied to sampling periods, when the loggers were removed for approximately half an hour at a time to purge the well and collect samples.

3.5.4 Manual Water Level Recordings

Manual water level measurements were taken throughout the pumping test in order to confirm data collected with the automatic transducer devices. These measurements were also required for the CMT wells that did not have pressure transducers constantly recording water level values. At the start and end of the test, when drawdown and recovery happened rapidly, a larger field team was assembled to take as many measurements as possible to capture the most data. Throughout the middle of the test, water levels were taken several times per week.

Several different Solinst water level tapes were used throughout the field season, allowing for measurements to either the nearest centimeter or millimeter, depending on the model. Some of the newer tapes were wider in diameter, making it difficult to pass them through the narrow CMT ports, especially when those ports were already filled with cables to RTDs and SRPs. In many cases like this, old style water level tapes that use thin wire probes were used. These tapes tended to have a poorer sensitivity and required multiple measurements in order to get a reliable and consistent reading. The water level measurements taken in wells with pressure transducers were compared to the manual measurements to verify the automatic equipment was working correctly.

3.5.5 Water Quality Sondes

Two water quality Sondes were used to continuously monitor water quality throughout the pumping test. These EXO Water Quality Sonde was used to measure Dissolved Oxygen (% saturated and mg/L), pH (standard scale and mV), Turbidity (FNU), Temperature (°C), Conductivity (μS/cm), Specific Conductivity (μS/cm), and Total Dissolved Solids (mg/L). The EXO Sonde has a built-in GPS and barometric pressure sensors as well. Accuracy and resolution information for these sensors is summarized in Table 5 (YSI Incorporated, 2012). The first Sonde was placed in a protective screened case within Alder Creek, roughly 10 m south of the pumping well. The second Sonde was positioned within a flow through cell located in the K22A pump house. The flow through cell was connected to a small pipe, diverging water extracted from pumping well into the pump house, allowing for ongoing measurements of the Sonde parameters.

The Sonde water quality data was collected at five minute intervals. The Sondes were calibrated twice a month. Due to software problems, the Sonde in the pump house stopped collecting data on September 17, 2013. The Sonde within the creek, however, collected data almost continuously from August 8, 2013 to October 22, 2013. All of the data collected by the Sondes throughout the pumping test are included in Appendix Q.

3.6 Water Quality during Pumping Test

3.6.1 Groundwater and Surface Water Sampling

Throughout the pumping test, sampling was completed by both Stantec and UW personnel. Samples collected from the pumping well were collected by Stantec, with the remaining samples from the Region and UW monitoring wells, CMTs, and Alder Creek completed by the University of Waterloo. The comprehensive sampling schedule is presented in Table 6.

The samples collected from the pumping well were taken from a tap on the side of the pipe. Five categories of samples were collected from the pumping well, including Microscopic Particle Analysis (MPA), general chemistry, Ultraviolet Transmittance, F-specific Coliphage, and a microbiological sample. Because water was continuously being pumped through the piping from the pumping well, there was no need for pumping or flushing of the system prior to sampling.

Alder Creek surface water samples were collected for MPA, general chemistry, microbiology, and F-specific Coliphage. All but MPA samples were collected by UW. To sample from the open water, a one liter plastic graduated cylinder was rinsed in and then filled with creek water. Attempts were made to fill the cylinder with moving water from the centre of the creek instead of with stagnant water near the bank. At the time each sample was collected, an EXO Sonde was used to gather a point measurement of basic water quality parameters for future comparison to the sample results and to the Sonde that was collecting continuous in situ creek measurements.

Samples collected from the Region and UW series of monitoring wells utilized Waterra tubing to purge and sample the wells by hand. The water was purged into a 30 L bucket; after each bucket was filled, a Sonde was used to measure its basic water quality parameters and the water level was recorded. Approximately three well volumes were purged before sampling commenced. In the event that the Sonde measurements had not stabilized, the well would continue to be purged until an approximate stability was reached. These wells were only sampled for general chemistry and isotopes, explained below. After collection, the samples were kept in coolers to refrigerate them before delivery to the lab and subsequent analysis.

Eight CMT ports were also routinely sampled, including CMT2A -2 and -6, CMT2B -2 and -6, CMT3 -2 and -6, and CMT1 -2 and -6. These ports were selected because they spanned almost the entire range of the multi-level well and, in most cases, were not occupied with RTD or SPR instrumentation. A Geopump Series II peristaltic pump was used to purge the wells into a bucket. As with the other monitoring wells, EXO Sonde measurements were taken intermittently and approximately three port volumes were purged prior to sampling. All of these ports were sampled for general chemistry, with additional microbiology and F-Specific Coliphage samples collected from CMT1-2 and CMT1-6 throughout the pumping test.

All of the samples collected by UW were completed in conjunction with a sampling form. The data written on those forms, including water level, Sonde measurements, purge volumes, and any additional information, is presented in Appendix R. The following sections describe the various procedures for collecting each sample type and the specific parameters yielded from those sample categories.

3.6.2 General Chemistry

General chemistry samples were collected in four separate bottles, titled Dissolved Organic Carbon (DOC), General, Metals, and Nutrients, 120 mL, 500 mL, 120 mL, and 250 mL respectively. All of the bottles were plastic. The DOC bottle contained no preservative and was only used to measure the dissolved organic carbon content of the water. The General bottle, which also did not contain a preservative, allows for the analysis of alkalinity, chloride by automated colourimetry, conductivity, hardness calculated as $CaCO_3$, nitrate and nitrite in water, pH, orthophosphate, and sulphate by automated colourimetry. The Metals bottle utilized a Nitric acid preservative and the analysis was completed using inductively coupled plasma mass spectrometry. The metals samples were passed through 0.45 μm filter before being stored in the bottle before analysis. Larger, Waterra FMT-45 In-line Groundwater Filters were used on the regular monitoring wells (Waterra, 2008). The CMT and surface water samples were collected in a syringe and then passed through smaller Whatman Disposable Syringe Filters. The filtering of the samples, both from surface water and groundwater sources, meant that the analysis would provide the dissolved metal content, not the total metal content (Contreras, 2014).

All of the general chemistry samples were submitted to Maxxam Analytics for analysis, classified under their R-Cap Comprehensive package. The parameters yielded from these analyses include Alkalinity, Ammonia, the sum of all anions and cations, chloride, dissolved organic carbon, electrical conductivity, hardness, ion balance, Langelier Index, nitrate, nitrite, orthophosphate, pH, sulfate, total dissolved solids (TDS) and UV transmittance.

The Dissolved Metals analyzed formed an extensive list, including aluminium, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, selenium, silicon, silver, sodium, strontium, thallium, titanium, uranium, vanadium, and zinc. Once again, all collected samples were kept refrigerated from the time of collection until they were analyzed. All of these Data are included in Appendix S.

3.6.3 Pathogen Sample Collection

Pathogen samples were collected by Stantec and the University of Waterloo during this study. At the request of the Region, these samples results were not released to the University of Waterloo due to their sensitive nature. Overall, frequent pathogen sampling was conducted on the pumping well water, on the surface water in Alder Creek adjacent to the well, and occasionally on CMT1 -2 and -6. The microbiology samples collected included analysis for E. coli and Total Coliform, F-Specific Coliphage, Enterococci, and MPA.

3.6.4 Turbidity

A critical water quality component of this pumping test was monitoring groundwater turbidity changes in an effort to understand its erratic levels. The initial plan for this monitoring was to use the in-line turbidity meter in the K22A pump house. A water line was run from the TW2-13 effluent hose to the pumphouse for this purpose. Upon arriving at the test site on August 19, 2013, the HACH PS1201in-line meter was not working properly. The test was started anyway and efforts were made by the Region to make the device operational as soon as possible. Despite many attempts, the in-line turbidity meter was not able to function properly at any point during the test. For a short while, the meter was displaying readings, however they were very different from those expected and what the manual turbidity meter yielded. As a result, the Region's turbidity meter was shut down halfway through the test.

The Sondes stationed in the pumphouse, the creek, and used during the sampling process also have built-in turbidity meters, however these were found to drift over time, requiring frequent calibration and cleaning. Due to this, much of the turbidity data from the Sondes was unreliable overall. As a result of these issues, a manual turbidity meter was used. Stantec's handheld meter, HACH 2100Q, was used by the Region, Stantec, and the University of Waterloo to collect almost daily turbidity readings, from September 10 to October 16, 2013. The handheld meter two-detector optical system boasts in-system calibration verification, has a range from 0 to 1000 NTU, and a resolution of 0.01 NTU. The data were compiled by Angela Ducharme from Stantec and is included as Appendix T (Ducharme, 2013).

3.6.5 Isotope Sampling and Analysis

Stable water isotopes can be very helpful as a seasonal tracer, with the abundance of lighter or heavier isotopes indicating precipitation at different times of year (Appendix U). For these reasons, surface water and groundwater samples were collected for isotope analysis throughout this field study, measuring specifically for O^{18} and H^{2}. During the pumping test, both groundwater and surface water samples were analyzed for isotopic content. Isotope samples were collected from ports 2 and 6 of CMT1, CMT2A, CMT2B, and CMT3. Six groundwater isotope sampling events took place: during the initial sampling event on August 14, 2013, 72 hours into the test, two, three, and four weeks into the test, and finally on October 17, 2013, the last day of the test.

A 60 mL sample was collected and refrigerated in the field in all instances. All of the samples were analyzed by the University of Waterloo Environmental Isotope Laboratory. They were compared to the VSMOW reference standard explained above. Those data are presented in Appendix U.

3.7 Analysis of the Pumping Test

3.7.1 Pump Test Analysis Methods

Different methods are available to calculate aquifer properties based on a series of assumptions regarding the aquifer setting and the pumping conditions. Given a series of assumptions made for the different methods, it is possible to determine hydrologic parameters under many different conditions, from homogeneous confined aquifers to more complex leaky and unconfined systems. Examples of these analysis methods include Theis and Theis Recovery, Neuman, Boulton, and Theis with Jacob Correction. These methods are explained at length in Appendix Y. In the analyses performed within this study, each of these methods were attempted with slightly different sets of assumptions to determine the best fit for the data set obtained from the 60-day pumping test. This was done to assist in defining an appropriate hydrogeologic conceptual model of the study site and also to evaluate the role of different stratigraphic layers in controlling the hydraulic connection between the upper and lower aquifer units.

3.7.2 AquiferTest

Each of these pump test analytical methods can be implemented in AquiferTest (Schlumberger Water Services, 2013). AquiferTest is sophisticated software tool for pump and slug test analysis, developed by Schlumberger Water Services. Although sophisticated, AquiferTest is also straight forward to use. A pump test can be analysed in four steps: defining the wells and aquifer setting, entering discharge data, importing water level measurements, and analysis.

In this first step, all metric units were selected and the aquifer was assigned a thickness of 40 m based on the available stratigraphic information from the site. The pumping and observation well specifications were imported, including their positions as defined with respect to the pumping well, their partially penetrating condition, screen and casing lengths and radii, borehole diameter, and the porosity or the material surrounding the screen. A porosity of 30 % was assumed for all of the wells. Step two allowed for the variable discharge conditions of the well to be entered, which was necessary given the intentional and accidental changes to the pumping rate throughout the test. Initially, the pumping rate was set at 15 L/s then changed to 13 L/s after one hour. After 49 hours, the pumping rate was once again changed to 11 L/s for the remainder of the test. This rate was interrupted 770 hours into the test due to an accidental shut off, which was remedied at the 843 hour mark. This allowed for intermittent recovery mid-way through the test. The pump test was finished after 1420 hours.

The third step of the AquiferTest analysis called for the drawdown data for the pumping well and all of the observation wells to be imported. The data sets for this stage were rather varied. All but two of the 28 CMT ports were without loggers so manual water level measurements were used, generating sparse data sets in comparison to those available from the logger data collected at five and 15 minute intervals. Continuous data allowed for more successful curve fitting. Continuous data sets from OW2-11, OW3B-09, CMT2A-4, and CMT2B-4, and the pumping well, TW2-13, were most valuable in this process.

The analysis process allows for a specific method to be selected and assumptions to be made pertaining to that method. After the iteration process to fit the data is completed, values for transmissivity and storage coefficient are determined. The site map and reporting features of AquiferTest compile these results, including data and results summary tables, the curve fitting graphs, and site maps including the calculated drawdown contours based on the analysis (Appendix AA).

3.7.3 Time of Travel

As mentioned in Section 2.1.2, establishing capture zones and time of travel estimates for potential GUDI wells is often the first step conducted in a vulnerability assessment in an effort to quantify the information available. It is a fairly straight forward from a math perspective, however it is very hard to do with any confidence because there are so many ways to do it and it is very difficult to verify your answer. Although numerical models to define capture zones are available, analytical calculations based on hydrogeological parameters can also provide estimates of these zones. For comparison purposes, three different time of travel calculation methods were conducted (Ontario Ministry of the Environment, 2001). The Fixed-Radius method can be used to calculate the radius of the capture zone, using

$$r = \sqrt{\frac{10038\ \mathrm{Q\ t}}{\mathrm{b\ n}}} \qquad (7)$$

where r is the distance from the well (m), Q is the maximum approved pumping rate of the well (L/s), t is the specified time of travel (years), b is the saturated thickness of the screened interval (m), and n is porosity (unitless; Ontario Ministry of the Environment, 2001). Porosity for these calculations is assumed to be 30 % for the all of these calculations. This method is appropriate for sand and gravel aquifers that are mostly flat-lying and does not account for a sloping potentiometric surface. Known as the cylinder method, this is a good approximation of the capture zone, however it does not account for irregularity caused by the regional groundwater flow field (Ontario Ministry of the Environment, 2001).

The Uniform Flow Field method is more flexible, considering variability in flow direction and utilizing a group of analytical expressions to better delineate the capture zone (Ontario Ministry of the Environment, 2001). The capture zone width, down-gradient, and up-gradient distances are specified as

$$\mathrm{X_L} = \frac{\mathrm{Q}}{2\,\pi\,\mathrm{K\,b}\,i} \qquad (8)$$

$$\mathrm{X} = \frac{-\mathrm{Q}}{\tan[(2\,\pi\,\mathrm{K\,b}\,i) \div (\mathrm{Q\,Y})]} \qquad (9)$$

$$\mathrm{Y_L} = \frac{\pm \mathrm{Q}}{2\,\pi \mathrm{K\,b}\,i} \qquad (10)$$

$$\mathrm{X_t} = \mathrm{K}\,i\,\frac{t}{\mathrm{n}} \qquad (11)$$

where X_L is the distance to the down-gradient null point, the estimated limit of flow, X is the distance along length of the capture zone, Y_L is the boundary width limit of the capture zone, and X_t is the up-gradient distance as a function of time, all in meters (Ontario Ministry of the Environment, 2001). Y is the width of the capture zone as a function of X (m), Q is the pumping rate of the well, K is the hydraulic conductivity, b is the saturated thickness of the screened interval, *i* is the hydraulic gradient, t in the travel time for the specified capture zone, and n is porosity (unitless). This is a two-dimensional, steady-state method. It does not account for hydrologic boundaries, such as surface water, aquifer heterogeneities, and assumes that no recharge takes place (Ontario Ministry of the Environment, 2001).

Due to the significant increase in velocity as water approaches a pumping well, it is best to determine time of travel in a piecewise fashion. The distance moving radially outward from the pumping well can be divided into increasingly larger distances. The drawdown at those respective distances can be determined from either point measurements, if available, or from interpretation of a drawdown contour map. This will allow for the calculation of the hydraulic gradient along each of the segments selected for velocity estimation. If the hydraulic conductivity is known, or can be reasonably assumed, Darcy flux can be calculated by

$$q = K\, i \qquad (12)$$

where K is the hydraulic conductivity (m/s), i is the hydraulic gradient (m/m), and q is the Darcy flux (m/s). Next, the radial groundwater velocity, v (m/s), can we calculated by

$$v = \frac{q}{n} \qquad (13)$$

Using this velocity, the time of travel for each step can be determined, where

$$t = \frac{d}{v} \qquad (14)$$

with d representing the segment length and t is the time of travel for that particular segment in meters. As explained in Section 2.1.2, the 50 day time of travel has been used in the past as a way to determine the high vulnerability zone surrounding a well and is used in this context as a comparison tool. It can be determined using the data with a time of travel extending just beyond the cumulative 50 day mark. The velocity for this last segment can then be used to determine at what distance the water will reach at 50 days:

$$d_{50\,days} = [\,(\,50\,days - \,t_n\,)v_{n+1}] + d_n \qquad (15)$$

where n is the segment before the segment that surpasses 50 days, n+1 is the segment that surpasses 50 days, t_n is the cumulative time of travel to reach segment n+1, d_n is the cumulative distance to reach segment n+1, and v_{n+1} is the velocity within segment n+1 to achieve a 50 day time of travel distance, $d_{50\ days}$ (Freeze & Cherry, 1979).

3.7.4 Aquifer Vulnerability Analysis

There are three common and simplistic methods used to calculating a vulnerability index for aquifers in Ontario. They are the Aquifer Vulnerability Index (AVI), the Intrinsic Susceptibility Index (ISI), and the Surface to Aquifer Advection Time (SAAT). AVI and ISI offer an evaluation of the protection offered by the aquifer setting based on the parameters of the subsurface. SAAT uses the AVI and ISI values along with recharge estimates to determine the time of travel. AVI calculated the hydraulic resistance, c_q, of the subsurface to groundwater flow

$$c_q = \sum_{i=1}^{j} \frac{d_i}{K_i} \qquad (16)$$

where d_i is the thickness of the geologic unit and K_i is that unit's K-factor (m/s), which is based on the material in the subsurface to allow for an estimate of the magnitude of hydraulic conductivity. The log of c_q is the vulnerability index. An AVI score of less than one indicates extreme vulnerability where a score greater than four corresponds to extremely low vulnerability.

The ISI method for calculating vulnerability is based on a factor related to the geologic material of the subsurface and its thickness calculated by

$$ISI = d_i \ x \ Kfactor \qquad (17)$$

A K-factor is the absolute value of the scientific notation exponent for the vertical hydraulic conductivity. For the gravelly to silty sands at K22A, the dimensionless K-factor is assumed to be 2. An ISI value of less than 24 indicates low vulnerability, whereas a value greater than 80 typifies high vulnerability areas. For the unconfined case, the ISI method only considers the strata over the water table to be protective.

The SAAT vulnerability method estimates a time of travel for surface contamination to reach an aquifer using the equation

$$T_{unsat} = \frac{d_{wt}\theta_m}{q_z} \qquad (18)$$

where the average annual depth (m) to the water table is d_{wt}, q_z is the yearly recharge rate (mm/year), and θ_m is the mobile moisture content value (%). T_{unsat} represents the number of years required for surface contaminants to reach the water table. On average, sand has a mobile moisture content of 10 % within the unsaturated zone (Koch, 2009).

3.8 Statistical Methods

3.8.1 Data for Statistical Comparison

Continuous and point-measurement data sets were available for comparisons with one another. Continuously measured parameters, provided via the use of data loggers, RTDs, long term Sonde deployment, and the weather stations, made for the availability of fairly continuous water level, temperature, conductivity, turbidity, precipitation, and air temperature data. The data from drive points, the weather stations, the pumping well, observation wells OW 2-11, OW 3B-09, UW MW A, and UW MWB, and all of the CMTs were compiled. Hourly averages for each of the data sets were used to allow for a comparison of all of the data available, regardless of the data collection interval for a given parameter. Specific continuous data comparisons were made for a wide variety of different data sets in order to understand potential correlations that could provide insight into the physical processes occurring during the pumping test period.

Discrete data was provided from sampling events. These data include Sonde measured parameter recorded during sampling, along with water quality results from the samples collected, including general chemistry parameter, metals, and stable water isotope content. With all 36 of these water quality-related parameters that returned information above the sample detection limit, a potential 3.72×10^{41} comparison combinations were possible. In order to narrow down the number of possible combinations, data were visually compared to determine if specific trends were apparent in the plotted data. Explained more extensively in Section 4.4, those observed trends included when parameters became increasingly similar to either the surface water or the pumping well, when the overall concentration decreased, when no trends at all were obvious, and for those parameters that caused concern for water quality. The most significance parameter comparisons were used to provide insight into the groundwater-surface water interaction processes during the course of the pumping test.

3.8.2 Statistical Functions

Two statistical analyses were performed as comparison measures for these sets of data, the correlation coefficient and covariance. The correlation coefficient is a means to quantify the linear relationship between two random variables. Equation to establish the correlation coefficient is calculated by

$$\rho_{x1.x2} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{(x_{1i}-X_1)(x_{2i}-X_2)}{\sigma_{x1}\times\sigma_{x2}}\right) \qquad (19)$$

where $\rho_{x1,x2}$ is the correlation coefficient between variables x_1 and x_2, the means of x_1 and x_2 are represented by X_1 and X_2, σ_{x1} and σ_{x2} are the standard deviations for the two data sets, and n is the number of data points in the series. The values for the correlation coefficient range from -1 to +1, with correspond to negative or positive correlations, respectively; a value of 0 indicates no correlation exists. As the absolute values of the correlation coefficient increases, the degree of correlation between the two variables also increases. A negative correlation coefficient implies that the variable one is larger than the mean of variable one and that variable two is less than the variable two mean, or vice versa. For a positive correlation coefficient to result, the comparison between the data set and its mean must be either positive or negative for both variables. Additionally, the correlation coefficient has an inverse relationship to the standard deviation. The equation has the potential to return a skewed correlation coefficient should the data sets be very large and have widely ranging data (Rong, 2011).

Applications for the correlation coefficient within environmental sciences are varied. Commonly, comparisons are conducted between two sets of data from the same parameter, such as the comparison of two years of annual conductivity data from a given well. Other applications of the correlation coefficient include the comparison of a physical parameter with a chemical one, such as looking at the relationship between water discharge and suspended sediment concentration within a creek over a given period of time. By comparing all of the continuous and point data sets collected throughout the 60-day pumping test, the potential correlation between different parameters at different locations will be quantifiable (Rong, 2011).

The second statistical function applied to the available data was calculating the covariance between two data sets. Covariance is the extent to which two random variables vary together. Defined by the equation

$$Covariance\ (x_1, x_2) = \frac{1}{n}\sum_{i=1}^{n} \{[x_{1i} - X_1][\ x_{2i} - X_2]\} \qquad (20)$$

where the two variables are x_1 and x_2, the means of x_1 and x_2 are represented by X_1 and X_2, and n is the number of data points in the series. In essence, the covariance calculation compares each value within a data series with the variables mean and then multiplies these differences together. If the covariance is positive, then the both data sets are varying in the same direction; if the covariance is negative, then the data vary in the opposite direction. Most importantly, the larger the covariance value is, the stronger the co-varying relationship between the two variables examined. Should the covariance equal zero, positive and negative variances were offset by each other and no linear relationship between the two variables exists. In other words, if the covariance is zero, then the two variables are completely independent or relate non-linearly to one another (Internet Center for Management and Business Administration, 2010).

Notably, it is difficult to compare covariances among data sets that have different scale since the number representing covariance depends on the units of the data. Large values may represent strong linear relationships in some cases, whereas they may represent weak relationships with another set of data. For this reason, covariance values must be calculated by comparing data sets with the same units and similar data ranges, matching temperatures with temperatures and concentrations with concentrations (Rong, 2011).

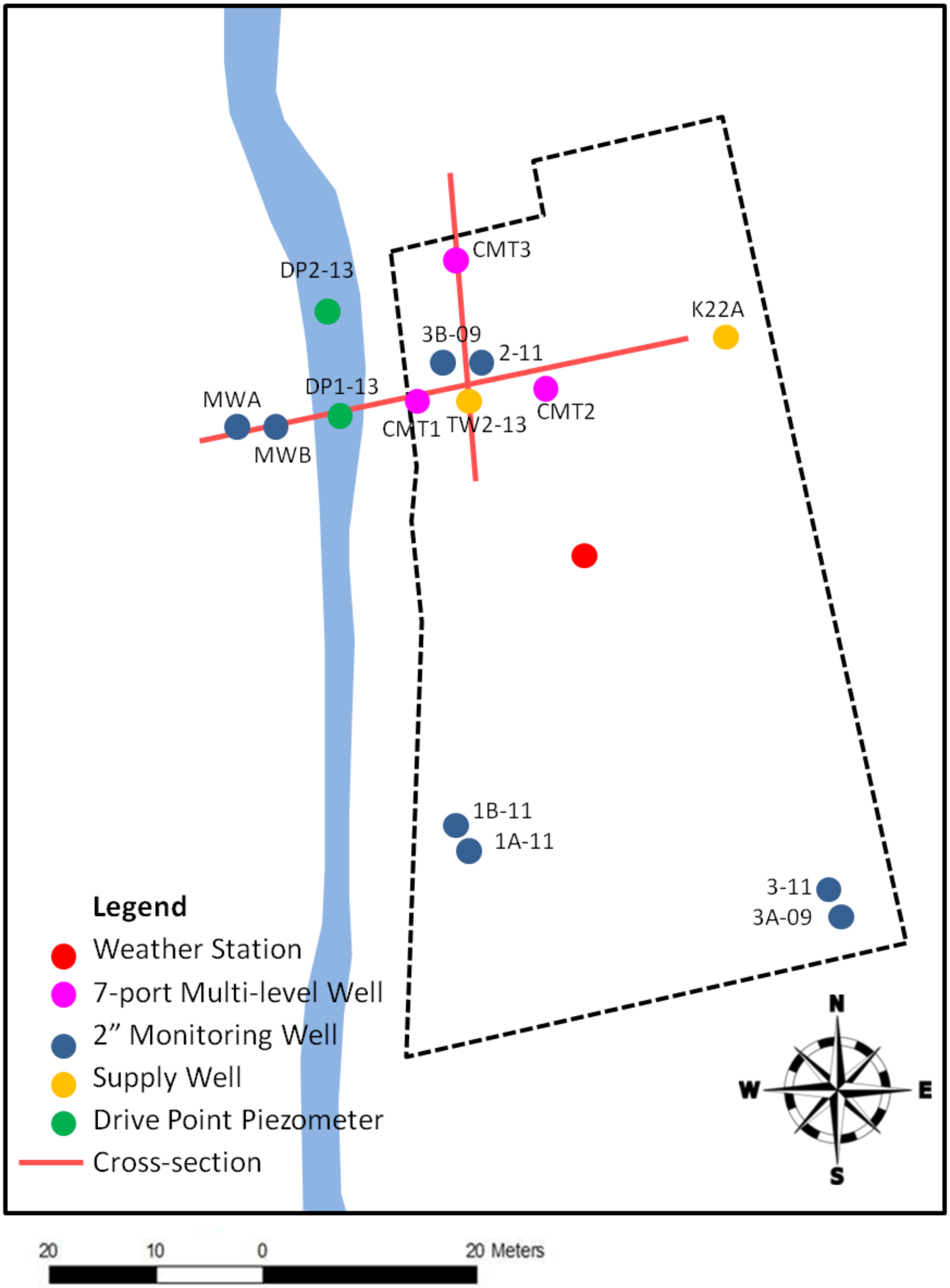


Figure 4. K22A Site Map with well locations and cross-section delineations (Regional Municipality of Waterloo, 2014).

Table 3. Location of all 19 Resistance Temperature Detectors positioned within the CMT multi-level wells.

Well	Port	Data Logger	RTD
CMT1	1	RadRelay2	9
	2		10
	3		17
	4		18
	5		19
	6	WaterLev1	6
	7		14
CMT2A	1	WaterLev5	15
	3		16
	5	WaterLev4	8
	7		5
CMT2B	1	WaterLev2	1
	3		2
	5	WaterLev3	3
	7		4
CMT3	1	RadRelay3	12
	3		13
	5	WaterLev6	11
	7		7

Table 4. Data logger model and installation periods for all Region wells on site (Hutton, 2014).

Well Id	Datalogger Model	Datalogger Type	Datalogger Range	Date Installed	Date Removed
WT-MW-OW3A-09	Rugged TROLL 100	Absolute	76m/non-vented	June 4	November 7
WT-MW-OW3B-09	Level TROLL 700	Gauged	21m/vented	December 9	July 25
	Aqua TROLL 200	Gauged	21m/vented	July 25	November 7
	Level TROLL 500	Gauged	21m/vented	November 7	Still in well
WT-MW-OW1A-11	Rugged TROLL 100	Absolute	76m/non-vented	June 4	November 7
WT-MW-OW1B-11	Rugged TROLL 200	Absolute	30m/non-vented	June 4	August 14
	Rugged TROLL 100	Absolute	30m/non-vented	August 14	November 7
WT-MW-OW2-11	Rugged TROLL 100	Absolute	30m/non-vented	June 4	July 25
	Aqua TROLL 200	Gauged	21m/vented	July 25	November 7
WT-MW-OW3-11	Rugged TROLL 100	Absolute	76m/non-vented	June 4	November 7

Table 5. EXO Sonde sensor accuracy and resolution specifications (YSI Incorporated, 2012).

Measurement	Accuracy	Resolution
Temperature (°C)	+/- 0.01 °C	0.001 °C
Dissolved Oxygen (%, mg/L)	+/- 1% or 0.1 mg/L	0.1% or 0.01 mg/L
pH (standard pH units)	+/- 0.1 standard pH units	0.01 standard pH units
Conductivity (μS/cm)	+/- 0.5 % of reading or 0.001 μS/cm	0.0001 to 0.01 μS/cm
Turbidity (FNU)	+/- 2 % of reading or 0.3 FNU	0.01 FNU

Table 6. Water Quality Sampling Schedule at K22A Site.

Sample Timing / Date		**Surface Water in Alder Creek**			
		MPA	General Chemistry R-cap Comp.	E.Coli / Total Coliform	F-specific coliphage
		-	filtered	filtered	unfiltered
Baseline	12-Aug-13 to 16-Aug-13	-	-		-
1 hour	19-Aug-13	-	UW	UW	UW
24 hours	20-Aug-13	-	UW	UW	UW
72 hours	22-Aug-13	Stantec	UW	UW	UW
7 days	26-Aug-13	-	UW	UW	UW
15 days	3-Sep-13	Stantec	UW	UW	UW
22 days	10-Sep-13	-	UW	UW	-
30 days	17/18-Sep-13	Stantec	UW	UW	UW
60 days	16/17-Oct-13	Stantec	UW	UW	UW
Total Number of Samples		**4**	**8**	**7**	**7**

Table 6. (Continued)

Sample Timing / Date		Test Well TW2-13				
		MPA	General Chemistry R-cap Comp.	UVT	E.Coli / Total Coliform	F-specific coliphage Enterococci
		-	unfiltered	unfiltered	unfiltered	unfiltered
Baseline	12-Aug-13 to 16-Aug-13	-	-	-	-	-
1 hour	19-Aug-13	-	Stantec	Stantec	Stantec	Stantec
24 hours	20-Aug-13	Stantec	Stantec	Stantec	Stantec	Stantec
72 hours	22-Aug-13	Stantec	Stantec	Stantec	Stantec	Stantec
7 days	26-Aug-13	-	Stantec	Stantec	Stantec	Stantec
15 days	3-Sep-13	Stantec	Stantec	Stantec	Stantec	Stantec
22 days	10-Sep-13	-	Stantec	Stantec	Stantec	Stantec
30 days	17/18-Sep-13	Stantec	Stantec	Stantec	Stantec	Stantec
60 days	16/17-Oct-13	Stantec	Stantec	Stantec	Stantec	Stantec
Total Number of Samples		**5**	**9**	**9**	**9**	**9**

Sample Timing / Date		Region Monitoring Wells	UW Monitoring Wells		
		6 wells General Chemistry R-cap Comp.	**10 samples** General Chemistry R-cap Comp.	**2 samples** E.Coli / Total Coliform	**2 samples** F-specific coliphage
		filtered	filtered	unfiltered	unfiltered
Baseline	12-Aug-13 to 16-Aug-13	UW	UW	UW	UW
1 hour	19-Aug-13	-	-	-	-
24 hours	20-Aug-13	-	-	-	-
72 hours	22-Aug-13	UW	UW	UW	UW
7 days	26-Aug-13	-	2 R-Cap	UW	UW
15 days	3-Sep-13	UW	UW	UW	UW
22 days	10-Sep-13	-	2 R-Cap	UW	-
30 days	17/18-Sep-13	UW	UW	UW	UW
60 days	16/17-Oct-13	-	UW	UW	UW
Total Number of Samples		**18**	**32**	**12**	**11**

Chapter 4 – Results and Discussion

4.1 Stratigraphic Cross-Section

Figure 5 presents a generalized stratigraphic cross-section of the K22A site based on the drill log information, extending from UW MWA to CMT2A and CMT2B; refer back to Figure 4 for cross-section line delineation. Overall, the stratigraphy consists mainly of medium to coarse grained sand containing trace amounts of gravel. A silt layer roughly 0.5 m to 2.0 m in thickness occurs throughout the site, spanning both sides of the creek. This layer varies in depth below ground surface between about 6.0 m to 6.7 m on the east side of the creek and 9.00 m to 9.75 m below the ground surface on the west creek bank. This layer is on average 1.5 m in thickness. Notably, CMT1 ports 1 to 3 are screened above the silt and CMT1 ports 4 to 7 are screened below the silt. CMT2A ports 1 to 3 lie above the silt layer, CMT2A-4 is screened within the silt, and the remaining CMT2A and all of CMT2B's ports are positioned below the silt layer. The screened interval of the pumping well (TW2-13) is situated completely below this lower permeability unit. The silt layer may influence subsurface groundwater movement as discussed below. Previous studies offer a great deal of insight into the hydraulic conductivities of the sand and gravel and silt units (Table 2). The new drill logs were used as a comparison to these previous studies to see if there were any notable differences in the stratigraphic records, but none were found. The sand and gravel unit has an average hydraulic conductivity of approximately 1.0 $x10^{-5}$ m/s, whereas the silt unit has a hydraulic conductivity of approximately 1.0 $x10^{-8}$ m/s (CH2MHILL, S. S. Papadopulos & Associates, 2003). These hydraulic conductivity estimates were based on grain size analysis and slug test interpretation.

Stratigraphic information can be major indicator of public supply well vulnerability. It is very important to carefully determine the geology and stratigraphy when starting to develop the hydrostratigraphic conceptual model for a site, as it can provide early insight into whether a well may be vulnerable to surface sources of contamination. In this case, the silt layer described above may or may not influence groundwater-surface water interaction close to TW2-13, which will be investigated in subsequent sections.

4.2 Water Level Data Collected During the Pumping Test

Many different groundwater level measurements were made during the course of the pumping test period at different locations in the vicinity of the pumping well (TW2-13). These included continuously logging pressure transducers in the pumping well, Region and UW wells, drive point piezometers, and SRPs in two CMT ports. In addition, a wide range of manual groundwater level measurements were made on many of the wells within the network intermittently throughout the test. The manual reading provided a more extensive tracking of transient hydraulic head throughout the study site and also served to ensure the readings collected from the automatic recording devices were accurate. There were no discrepancies found between the manual water level measurements and those collected by the pressure transducers, apart from instances where sampling was being conducted and the loggers where removed from the well while still recording data.

4.2.1 Pumping Well Water Level Information

The most dramatic water level changes observed over the course of the test were in the pumping well, TW2-13, as would be expected. Very clear pumping impacts were measured in the pumping well and these data are contained in Appendix V. At the start of the test, the static water level was roughly 333.23 masl. By five minutes into the test, the water level had decreased by almost 6 m to 327.51 masl. Twenty-four hours into the test, when the pumping rate was decreased from 15 L/s to 13 L/s and finally to 11 L/s, the water level responded by increasing by 63 cm; the water level remained relatively consistent around 328.0 masl until the pump was accidentally turned off on September 20, 2013. At the time of this temporary pump shut down, the water level in TW2-13 was 328.11 masl; five minutes and ten minutes after the pump shut off the water levels were approximately 3 m and 5 m higher, respectively. While the pump was off, the water level returned to the static level observed prior to pumping until the pump was restarted. Over the next month, the water level gradually decreased to roughly 328 masl. This water level was 3.5 m above the top of the screen. At the time of the intentional pump shut off at 3:00 pm on October 17, 2013, the water level was 328.05 masl; it increased by 5m in five minutes following the cessation of pumping. These data illustrate that the pumping well was able to maintain the reduced pumping rate of 11 L/s over the entire course of the extended pumping test and also demonstrated the rapid recovery behaviour following the stoppage in pumping. How the water level in a well responds to pumping is an indication of its aquifer setting, whether it is confined and less vulnerable or unconfined and more vulnerable. These data are compared to type curves for different aquifer settings and explained below.

Over the duration of the test, there were slight fluctuations in water levels within the pumping well. These corresponded to large precipitation events (Figure 6). Two such events are of note and provide valuable insight into how the aquifer system responds to significant recharge events. On September 20 and 21, 2013, a 64 mm cumulative precipitation event lasting 18 hours caused an increase in water level at the pumping well. Between September 21, 2013 at 1:25 pm and September 22, 2013 at 8:30 am, the water level in the pumping well increased by about 40 cm, with an approximately 24 hour time-lag from the start of the precipitation event. The pump was shut down during this period of time and the well had undergone recovery, stabilizing at pre-pumping water levels before the rainfall event was observed. The second rainfall event occurred between 2:00 am on October 6, 2013 and 7:00 pm on October 7, 2013, resulting in a total of 38 mm of precipitation. In response, the TW2-13 water level increased by 35 cm between October 7, 2013 at 6:40 am and October 8, 2013 at 6:45 am, once again approximately one day after the start of the rainfall event. Interestingly, another large precipitation event on September 1, 2013 did not appear to influence the water well level, illustrating that different responses will occur under different conditions. While the intensity of the September 1, 2013 storm was large, the total rainfall was much less than the other events because it was so short, with a total precipitation of only 12 mm, compared to over 30 mm. This demonstrates that the system is sensitive to extreme weather depending on the nature of the events, where longer, high volume and intensity precipitation events influence the pumping well. This identifies the pumping well as being responsive to extreme hydrologic events, but not all events will cause this response. The monitoring of precipitation events in the vulnerability assessment of public supply wells is valuable. Overall, these data indicate that the pumped aquifer responds relatively quickly to major precipitation events, providing additional evidence that there is a fairly direct hydraulic connection between the near surface environment and the deeper groundwater system and that the recharge process occurred rapidly. In future, vulnerability assessments could classify precipitation events based on duration, volume, and intensity and looking at the corresponding hydraulic responses observed in the groundwater from different wells in order to determine the threshold of influence. For example, an extremely vulnerable system that is hydraulically directly connected from the pumping well depth to the ground surface may respond to more minor-scale precipitation events, whereas less vulnerable, more hydraulically disconnected systems would have a high threshold for precipitation influence.

4.2.2 Observation Well Water Level Information

Data from the observation wells with continuous water level records are presented in Appendix W. This network of observation wells are spatially distributed throughout the study site as illustrated in Figure 4 and the distance between the wells and the pumping well influences both the timing and magnitude of the response during the pumping period. The responses at several key wells will be discussed below to further illustrate the response of the groundwater system to pumping. To make sense of these data, the distance to the pumping well and the observation well depth must be taken into consideration.

At the start of pumping, OW2-11, the closest well to TW2-13 with a similar screen elevation, showed the most dramatic changes in water level. In the first ten minutes of the test, the water level decreased by 79 cm; when the pump was adjusted to 13 L/s from 15 L/s an hour into the test, the water level increased by 10 cm in only five minutes (Figure 7). This well located less than one meter from the pumping well was extremely sensitive to pumping rate throughout the test. UW MWA responded to pumping experiencing a drawdown of 23 cm one hour into pumping. UW MWB, with almost the same screen depth to TW2-13 located 13 m away, responded dramatically to pumping rate, instantly decreasing by 30 cm in the first five minutes of the test. UW MWB is screened at almost the same depth as TW2-13; given the similar response to pumping between these two wells, the aquifer is shown to be continuous at depth. With responses from UW MWA and UW MWB, both on the west side of Alder Creek, it is clear that the pumping influence does not stop at the stream. This illustrates that there is lateral continuity over a large distance between wells; the influence of the pumping well clearly passed under the creek. While this is a common occurrence, often time numerical models have no flow or constant head boundary conditions at the stream, which is clearly not appropriate in this case.

The mid-test shut off period showed similarly timed responses in all of the observations wells, with changes tracking together very clearly (Figure 8). When the pump was shut off, all of the wells increased in water level, the wells responded almost instantaneously. OW2-11 once again showed the greatest change, with the water level increasing by 45 cm between 12:55 pm and 1:05 pm on September 20, 2013. In the same time span, the farther well water levels increased by roughly 10 cm. While the pump was off, water levels in all observation wells followed the same trend in water level increase observed in the pumping well. The precipitation event that caused additional recovery in the pumping well during the shut off period was also observed in the observation wells; despite the difference in depth of the different well screens, the increase was observed in all wells at around the same time. Shallower wells did observe slightly larger increases in water level, however the entire system response once again supports the conclusion that the aquifer is continuous and the silt layer does not have significant confining properties in this aquifer setting, thus making it more vulnerable.

Unsurprisingly, OW2-11 responded to the pump shut off the most, increasing in water level by 62 cm in the five minutes after the test ended. In the same time frame, the CMT2B-4, CMT2A-4, and OW3B-09 increased in water level by 39 cm, 24 cm, and 17 cm, respectively (Figure 9). The four distant wells at the south end of the site gradually increased in water level by about 10 cm in the 30 minutes following the end of the test.

Based on the manual water levels collected from CMT 1, the multilevel well located between the pumping well and the creek, the silt layer did slow the response time of the water level change to pumping, but only for a short time. Three minutes into pumping, ports 4 to 7 had an average water level decrease of 65 cm, whereas the increasingly shallow ports above the silt unit, 3, 2, and 1, had 40 cm, 15 cm, and 11 cm water level decreases, respectively. Six hours into pumping, however, this difference had decreased; ports 4 to 7 remained at around 60 cm of drawdown, however ports 3, 2, and 1 now had 43 cm, 29 cm, and 24 cm of drawdown, respectively. Similar trends were observed with the recovery data. This illustrates that the role of the silt layer is only as a delay to the vertical hydraulic response of the system and that the sand and gravel material above and below the silt, and adjacent to the creek, are hydraulically connected. Valuable insight can be obtained relative to the vulnerability of the supply well to surface sources of contamination through the interpretation of an extended pumping test where multi-level and multi-distant observation wells are present to track hydraulic response. These conclusions were possible with data collected from the start of the pumping test, with a 24-hour test being long enough in order to get all of the hydraulic data of value related to monitoring the observation well network at the start of a long test. This may not be true for all aquifer settings. While this was enough time to see a hydraulic response at the site, discussion of vulnerability regarding slower aquifer responses and the movement of groundwater tracers during the 60-day test is included in subsequent sections.

4.2.3 Drive Point Water Level Information

As explained in Section 3.5.2, there were two shallow drive point piezometers installed in Alder Creek adjacent to the K22A site for the duration of the pumping test. DP1-13, closer to the pumping well, was screened 0.98 m below the streambed; the second drive point positioned further north, DP2-13, was screened 1.42 m below the stream bed (Figure 4). They were screened in sandy silt material with a lower hydraulic conductivity than the surrounding aquifer material, based on observations of the streambed material when conducting thermal profiles in the streambed throughout the field season. Falling-head single well response tests that introduced water into the drive point piezometers responded very slowly, confirming that they sit in a lower permeability unit. DP1-13 decreased in head by 1.6 m in about 1.25 hours, with DP2-13 responding even slower, falling 0.02m over the same time. Both surface water and shallow groundwater information collected throughout the test was obtained from the transducers placed within the stream and drive point well installations.

Overall, the surface water level changed much more than the shallow groundwater level during the course of the test (Appendix X). At the start of the test, only very minute changes, less than 2 cm, in stream bed and surface water levels were captured and did not coincide with the starting of the pump. Overall, the water levels in the stream and the shallow stream bed piezometers did not demonstrate a gradual drawdown as the pumping test continued as was observed in the rest of the observation well network. During the accidental shut off, there were significant changes to the surface water and minor changes to the shallow groundwater levels; however, these were likely in response primarily to the precipitation event that occurred at the same time, not the pumping changes. Unlike in the pumping well and observation wells, no recovery in the surface water or shallow groundwater was observed in response to the unplanned pump shut down described above. Depicted in Figure 10, continuous rainfall started at 8:00 pm on September 20, 2013 and ended at 1:00 pm on September 21, 2013. The surface water levels at both drive points increased by 15 cm following an 8.4 mm rainfall event that occurred over one hour and then dropped again. The DP2-13 surface water experienced a steady increase in water level of an additional 40 cm during the precipitation event. Although DP2-13 groundwater showed no response, DP1-13 groundwater gradually increased in water level by 37 cm between noon and 11:30 pm on September 21, 2013, before returning to its equilibrium level by 11:15 am the following day. This was a 28 hour delay between the start of the larger rainfall event and the groundwater increase. A similar trend was observed during the October 7, 2013 rainfall explained earlier in this section (Figure 11). By the end of the pumping test, on October 17, 2013, there were no discernible trends in water level data in the creek or the shallow streambed piezometric levels due to pumping. Ultimately, the Alder Creek surface water elevation remained at approximately 335.4 masl, apart from increases due to precipitation events. Between the end of August and end of October, no large seasonal changes were observed in the surface water levels or temperature that would typically be occur that time of year, which was attributed to high precipitation volumes and warm temperatures in the fall. The groundwater levels measured remained at around 334.4 masl 334.5 masl for DP1-13 and DP2-13, respectively. Based on the data collected, the shallow groundwater levels and surface water levels were not affected by pumping from TW2-13. Anomalous data points that corresponded to known adjustments to loggers during sampling events were removed for the clarity of the all figures in this section.

The streambed drive point piezometers are relatively slow to respond to surface water changes, likely because they are screened in lower permeability material. The surface water at DP1-13 and DP2-13 was typically around 335.3 masl, with the shallow groundwater measured by these drive points around 90 cm lower for the duration of the test. Where DP1-13 groundwater fluctuated by 42 cm throughout the test, DP2-13 groundwater fluctuated by 6 cm; these are very minor changes, providing supporting evidence that the creek is underlain by relatively tight, low permeability sediment along this reach. CMT1-1 was screened 2 m below DP1-13 and had a static water level 1.2 m below the static water level of the DP1-13. The shallow groundwater below the creek exists 1.2 m above the groundwater table for the rest of the site and 0.9 m below the surface water in Alder Creek. This indicates the presence of a strong downward vertical gradient through the stream sediments, even under non-pumping conditions, which could indicate the potential for perched conditions beneath the stream, which could significantly influence the nature of the groundwater – surface water interaction processes. This is discussed in more detail below. Manual measurements and the presence of water in the drive point wells confirmed the transducer readings.

Previous studies of the K22A site had investigators from the Region and Stantec speculating also that the creek was perched in this area considering the large difference between the stream water level and the local water level. The drive point wells clearly illustrate that saturated conditions exist below the stream at least to the depth that the drive point piezometers were installed. In order to confirm the presence or absence of a perched condition under Alder Creek at this location, additional piezometers would need to be installed between the base of the drive point screens and the elevation of the local water table to determine if conditions of tension saturation indeed exist or if saturated conditions prevail. Both the scenario of a lower hydraulic conductivity sediment underlying the creek or the presence of perched, unsaturated conditions between the stream bed and the water table would result in relatively low infiltration rates from the surface water into the groundwater system, which would influence the potential vulnerability of a nearby supply well. Although it is not possible to positively confirm these conditions below the stream with the data from the current study, it is recommended that this be clearly established in subsequent studies associated with assessing well vulnerability.

The critical information derived from the drive point data is that Alder Creek appears to be perched approximately above the groundwater table due to the silty layer below the creek. However, the shallow groundwater measured by the drive points illustrates that there is groundwater between the surface water and regional aquifer, likely due to slow infiltration from the creek. This is investigated further below in terms of vertical gradients and the drawdown contours generated.

4.3 Pumping Test Analysis

4.3.1 Hydrogeologic Parameters

As explained in Section 3.7.1, several different methods were used to estimate the hydrogeologic parameters of the subsurface at the K22A site on the basis of the transient drawdown data collected during the pumping period from a series of observation wells. The automated AquiferTest software was used for this analysis. These methods include Theis, Recovery Theis, Neuman, Boulton, and Theis with Jacob Correction. The resulting parameter estimation, for transmissivity, hydraulic conductivity, and storage coefficient, where applicable, of each methodology are compiled in Table 7. Continuous water level data from TW2-13, OW2-11, OW3B-09, CMT2A-4, and CMT2B-4 were used to obtain these results. The benefit of this large data set was the quantity of long term data available for curve fitting. While the early stage drawdown data from the first day was valuable for curve fitting, emphasis was places on matching the longer term data with the respective models in order to determine the best fit possible. An aquifer thickness of 40 m was used for these analyses based on available stratigraphic information. These values are very similar to those from previous studies; the Mannheim GUDI study listed transmissivity as 1.9×10^{-2} m^2/s and the storage coefficient in the area ranging from 0.04 to 0.13, the same order of magnitude as the estimates obtained with AquiferTest (CH2MHILL, 2002).

The pump test analysis reports for each method, along with curve fitting details, are presented in Appendix Y. The Theis analysis provided estimates for transmissivity, hydraulic conductivity and the storage coefficient based on poorly matched curve fitting for several different wells. The mismatching of the curves with the data can be attributed to the incorrect assumptions made regarding a confined aquifer setting and consistent pumping conditions, where only early time data would be appropriate for this analysis. In unconfined aquifer settings, Theis and other confined aquifer methods only match for very early time data in a pumping test. Although the aquifer is fairly homogeneous compared to other settings, it is not confined and is not flat-lying. The silt layer does not appear to act as a confining layer. The well is also not fully penetrating and while flow was radial, the well was not pumped with a constant discharge for the entire test. That being said, the average transmissivity and hydraulic conductivity values for all of the wells analyzed were 1.2×10^{-2} m^2/s and 3.0×10^{-4} m/s, respectively. While this is a classic method that provided physically realistic values, the Theis method may not be the best to consider for this aquifer. In Figure 12, the measured drawdown for the initial starting of the test on August 19, 2013 and for the re-starting of the test on September 23, 2013 is shown relative to a typical Theis type curve and Neuman type curve. The measured drawdown deviates from the Theis curve after early time. The data more closely reflects the Neuman type curve, with its three distinct stages for early, intermediate, and late time (Schlumberger Water Services, 2013). The observation of these three distinct stages does suggest unconfined conditions; the pumping well drawdown starts to flatten out and deviate from the Theis curve, which can also be indicative of the interception of a recharge boundary. The response of the pumping test can also provide evidence of this recharge which would also be useful in understanding vulnerability. By conducting the test for a very long time, a better idea of the aquifer hydraulic response can be gained and deviations from the Theis curve can be attributed to the unconfined response and not from significant recharge from Alder Creek, which is not likely happening at this particular site. This supports the collection of data form extended pumping tests.

The Recovery Theis method revealed similar fitting problems, given the same set of assumptions applied to it. The Pumping Test Analysis Report provides average transmissivity and hydraulic conductivity values of 1.8 x10^{-2} m^2/s and 4.6 x10^{-4} m/s. For TW2-13 specifically, transmissivity was calculated as 5/0 x10^{-3} m^2/s and hydraulic conductivity as 1.3 x10^{-4} m/s. All of these values are comparable to those for Theis. The discrepancy in linear fitting and the actual data is evident and mainly attributed to the unconfined aquifer setting; the late time data was very mismatched with Recovery Theis linear fitting, starting to differ more and more as the test progressed past the one week mark.

The Neuman method is an unconfined aquifer analysis method. The Pumping Test Analysis Report for Neuman offered estimates for transmissivity, hydraulic conductivity, specific yield, and the anisotropy ratio between vertical and horizontal hydraulic conductivities. The average estimates of these parameters for all wells analyzed was 9.2 x10^{-3} m^2/s transmissivity, 2.3 x10^{-4} m/s hydraulic conductivity, 1.4x10^{-1} for the specific yield, and an anisotropy ratio of 0.35. Based on these estimates, the flow system is relatively anisotropic and the specific yield is indicative of unconfined sand. The curve fitting lines and drawdown data for each of the wells visually fit well, matching much more closely than for any other method; early, intermediate, and late time data segments align with the data during those periods of consistent pumping, matching the typical response for an unconfined aquifer system. This method provides the best overall estimation of the hydraulic parameters for the aquifer given the assumptions governing the system and adequate fitting for the data.

The Boulton Method is another unconfined aquifer analysis method available in AquiferTest, however the data curve fitting for Boulton did not match as well as for the Neuman method. The estimated transmissivity was 8.9 $x10^{-3}$ m^2/s for the aquifer, hydraulic conductivity was estimated as an average of 2.2 $x10^{-4}$ m/s for all of the wells and the specific yield was estimated as 9.9 $x10^{-1}$ for the aquifer. These specific yield values correspond to those of a coarse sand or fine gravel. Although the parameter estimations for transmissivity and hydraulic conductivity were on the same order of magnitude as for the Neuman method and made physical sense, the Boulton curve fitting was slightly off making Neuman the more favourable method.

The last method of analysis was Theis with Jacob Straight line, another unconfined aquifer assumption method. The curve fitting for this method was even more visibly mismatched than for Boulton. The estimated transmissivity and hydraulic conductivity averages for all of the wells were 1.0 $x10^{-2}$ m^2/s and 2.5 $x10^{-4}$ m/s, accordingly. The values for these parameters were the same order of magnitude as both the Boulton and Neuman methods.

Although the Neuman method had the best fitting data, all of the methods estimated the hydraulic conductivity at each of the wells within one order of magnitude. These values are also of the same order of magnitude as those of the Mannheim West Well Study, presented in Table 2. Using the values from those methods with unconfined aquifer assumption provides an average hydraulic conductivity for the site of 2.4 $x10^{-4}$ m/s. This hydraulic conductivity value matches that of clean sand and is indicative of a highly productive hydrogeologic setting (Freeze & Cherry, 1979).

Although understanding the value of hydraulic conductivity is important, the main information that can be drawn from the pumping test analyses is how the aquifer responds to pumping over a long period of time. Given that the best fit was for the Neuman method where early, intermediate, and late stage drawdown segments were observed, the aquifer appears to respond as an unconfined system. This has two implications: first, the silt unit does not significantly influence the vertical flow induced by the pumping well and second, the pumping process will likely result in a direct hydraulic impact at the water table and likely under Alder Creek. For this well, six days of pumping data were needed in order to observe the early, intermediate, and late time trends, something that would not be evident from a simple 72-hour pumping test. The value of the extended pumping test is that it contributes additional insight into the hydraulic behaviour of the aquifer system while the pumping well is operational, which enhances the understanding of the potential vulnerability of the public supply well.

4.3.2 Hydraulic Gradients

The transient vertical hydraulic head profiles in all of the multi-level wells provide critical data regarding the potential vertical movement of water between the surface and the pumping well. Figure 13, Figure 14, and Figure 15 illustrate the vertical head profiles over time for each CMT. For the sake of clarity, the mid-test shut-off period is not included. From these figures it is very evident that the water level changes as a result of pumping are observed over the entire height of the multi-level wells, both above and below the silt layer. This proves that there is a direct vertical hydraulic connection through the system, between the shallow and deep groundwater. The observed response throughout the system is an indication of the vulnerability. It was noted that some of the lines included on these plots cross over one another. This might be due to error in the manual measurements due to the obstruction of instrumentation in the narrow CMT ports or from the influence of the silt layer which might have slowed the presume pulse within the subsurface or clogged a multi-level screen. This is particularly evident for CMT2A-4.

Figure 16 and Figure 17 depict east to west and south to north cross-sections of the site, showing the water level drawdown cone as a function of the distance to the pumping well. In these figures, some of the head levels cross-over one another because wells and multi-level ports of different elevations are plotted on one graph. Time series of water level data show the consistency of the drawdown cone throughout the test, after 1 hour of pumping, straight through to 1420 hours of pumping. In this case, the mid-test shut off values between the 700 hour and 1420 hour time series are excluded for clarity and to offer a direct comparison to the end of the almost 60-day pumping test. The static series demonstrates a relatively flat-lying regional water table under non-pumping conditions. Prior to the start of pumping, the groundwater gradient at the site was relatively flat, with Alder Creek water level positioned above the water table by over 1 m.

The vertical hydraulic gradient at each of the drive points was compared to the Alder Creek surface water level data over the same time period. Additional figures for these continuous gradients are presented in Appendix Z. These gradients were calculated by finding the difference between the surface water head from the stream bed and the shallow groundwater level in the drive points below the stream bed and dividing that difference by the elevation between the drive point screens and the stream bed elevation. Fluctuation in surface water level occurs as a result of precipitation events. The surface water elevation is continually higher than the shallow groundwater elevation right beneath the creek, creating a positive gradient throughout the entire test. At the start of the test, DP1-13 groundwater appears to show a very slight increase in the vertical gradient of 2 cm that coincides with the start of pumping, however this is very minor compared to the overall variability in the gradient throughout the test.

During the mid-test shut off period, there are dramatic changes to the vertical gradients at both drive points; however, this appears to be in response to the surface water changes due to a large rainfall event which occurred over the same time period (Figure 18). Directly after the start of the precipitation event, the vertical gradient increased in the drive points due to the increased surface water level. In DP1-13, there was a subsequent decrease in vertical gradient; this may be attributed to either an influx of surface water into the subsurface or that the drive point, screened in less hydraulically conductive material, was slow to respond to the pressure change. Specifically, the vertical gradient decreased from 1.47 m/m at 3:45 pm on September 21, 2013 to 0.47 m/m at 11:45 pm on September 21, 2013. This was actually the lowest gradient recorded throughout the entire test, which may be attributed to two things, one being the pulse of surface water arriving at the shallow groundwater port and the second caused by the lack of pumping occurring during that time. Overall, DP2-13 groundwater experienced a slower, much slighter pulse in response to surface water increases than the response measured at DP1-13 (Figure 19). This might be due to the hydrostratigraphic positioning of the drive point screens beneath the stream bed. Throughout the entire test, the vertical gradients responded to surface water change, with no change as a result of pumping. However, the presence of water in the shallow groundwater drive points indicates some ongoing surface water infiltration within this segment of Alder Creek. As discussed above, the creek is likely constantly infiltrating however the infiltration rates may be influenced by the presence of unsaturated or very low conductivity materials beneath the stream.

Horizontal gradients were calculated between different locations throughout the site at different times throughout the test. These calculations are presented in Table 8 and illustrated in two sets of figures. Figure 20 and Figure 21 show the horizontal gradient between Alder Creek and other wells throughout the site, periodically throughout the test and specifically over the first 24 hours of the test. Figure 22 and Figure 23 show similar information, with the horizontal gradient between the pumping well and other observation wells throughout and at the start of the test. Throughout the test, there was a constant negative gradient between the surface water and groundwater. In response to the start of pumping, the groundwater throughout the site decreased in water level, increasing the magnitude of the gradient with the surface water. This is particularly evident for TW2-13 since this was the maximum drawdown point. During recovery, the gradient decreased in magnitude back to the pre-pumping levels. The horizontal gradients between the observation and pumping wells were positive during pumping; physically, this means that the water level was deepest at the pumping well and water would be continually flowing in that direction. The static horizontal gradient throughout the site was almost non-existent. The regional flow field below Alder Creek was flat lying and the gradients between the wells were very gentle. With the start of the pump, the gradient between the pumping well and observation wells increased, showing the induction of flow throughout the site towards TW2-13. By examining the hydraulic gradients throughout the site, it is evident that pumping invoked radial flow in all directions and that any surface water may be infiltrating to the subsurface from Alder Creek would move towards the pumping well. This groundwater system is highly connected, both vertically and horizontally, allowing for the mixing of water from both shallow and deep parts of the aquifer thus increasing the pumping well vulnerability.

4.3.3 Drawdown Contouring

The interpretation of drawdown cones are of interest when evaluating the vulnerability of public supply wells. In this section, simple model drawdown contours are compared with drawdown contours made with the actual data collected. The differences between the generated and actual drawdown contours can reveal some aquifer response characteristics in order to gain more insight into the well vulnerability from the drawdown cone analysis. Additionally, this direct comparison reinforces that simple predictive modelling drawdown cones may not match well with real conditions, so practitioners should not rely on them too heavily.

AquiferTest generates drawdown cone contour maps based on the hydraulic parameters estimated for the different analyses conducted (Appendix AA). These maps show the drawdown cone extent and magnitude in depth of drawdown for the three unconfined aquifer methods used, Neuman, Boulton, and Theis with Jacob Correction. The Neuman method generated a drawdown cone centered about the production well with radial contour lines decreasing in drawdown exponentially outward. The drawdown maximum at TW2-13 was presented in the figure as approximately 2 m and the 1 m drawdown contour extended outward from the well by roughly 30 m. The drawdown contours formulated using the Boulton method centered the drawdown cone around TW2-13, with a maximum drawdown at the well of almost 1 m, extending radially outward and evenly in all directions, and decreasing in drawdown to 30 cm of drawdown by the farthest observation wells over 40 m away from the production well. The Theis with Jacob Correction method created a similar drawdown profile to that of the Boulton method, however the maximum drawdown at the pumping well was set under 70 cm.

Each of these representations of the drawdown experienced in the pumping test is incorrect when compared to the actual dataset. Neuman method underestimated the drawdown at the pumping well and overestimated the drawdown in the surrounding observation wells. The Boulton and Theis with Jacob Correction methods approximated the drawdown at the farthest wells correctly and better approximated the drawdown at the nearest wells, however the maximum drawdown experienced at the pumping well was highly under-estimated. These calculated drawdown cones were different than the measured field data because they used artificially generated data calculated using the hydraulic parameters estimated from a particular pumping test method along with over-arching assumption about the aquifer setting. For these methods, the curve fitting was not perfect.

These theoretically generated drawdown cones differ from the actual drawdown cone generated at the field site. Surfer was used to develop drawdown contours via kriging the available data at each well at different points in time throughout the test. All of the data were used in combination, including water level measurements from wells screened at different elevations, including the multi-level manual water level measurements. Kriging is a method of linear interpolation that calculates contouring lines based on the provided data points, which in this case were the measured water levels at each of the wells, multi-level ports, and drive points at the K22A site. Surface water was included in these contour plots to show the elevated nature of the stream throughout the pumping test. Appendix AB includes drawdown contours for 1 hour, 24 hours, 72 hours, and 1420 hours into pumping and after the water table has recovered. The drawdown contours generated throughout the pumping test maintain fairly similar forms, with the deepest water level at the pumping well. The 332.5 masl contour line gradually moves farther away from the wells, extending outward to the farther wells at the south end of the site. Between 1 hour and 1420 hours into the test, the drawdown at the pumping well and the elevation of the shallow groundwater at the drive points remains at approximately 328 masl and 334.5 masl, respectively. This corresponds correctly to the drawdown cone profile show in Figure 16.

A second set of drawdown contour plots were generated and are included in Appendix AC. These plots show the response of the shallow and deep systems separately. Blue contour lines were used to depict the surface water and shallow groundwater system, which included any wells or ports screened above the silt layer. Red contour lines are used to depict the deep groundwater drawdown in wells screened below the silt layer. These sets of plots were generated under static conditions, and 1 hour, 24 hours, 72 hours, and 700 hours into the test. Under static conditions, the regional flow field is relatively flat-lying, however the drive point elevations skew the contours for the shallow groundwater system. One hour into the pumping test, the deep groundwater system had responded significantly to the drawdown at the pumping well and other surrounding wells, with the cone of depression extending to UW MWB on the west side of Alder Creek. These red, deep groundwater contours remained relatively consistent for the 24 hour, 72 hour, and 700 hour representations. The shallow groundwater system exhibited some drawdown in the area surrounding the pumping well, with CMT1 responding to the pumping quickly. At the 24 hour mark, the shallow groundwater drawdown became further emphasized, with drawdown spanning to UW MWA on the west side of Alder Creek. The surface water and shallow groundwater below Alder Creek, as measured by the drive points, are shown much higher above the rest of the shallow system.

The shallow groundwater drawdown at in the shallow CMT1 ports and UW MWA is even more evident in the 72 hour and 700 hour figures. The surface water and groundwater measured by the drive points remained above the groundwater table. The rapid response to the deep groundwater system and the eventual response in the shallow groundwater system elicited by pumping shows that the system is hydraulically connected, both vertically and radially. The shallow groundwater responded relatively quickly despite the presence of the silt layer, likely resulting in mixing of shallow and deep groundwater captured by the pumping well, increasing the well vulnerability. However, since the shallow and deep drawdown contours did not match perfectly, this may be evidence that the shallow system may also be influenced by the stream to some extent with minor infiltration occurring through the silty Alder Creek streambed.

Although the theoretical and actual drawdown cone values do no match perfectly, the hydraulic conductivity assumed in the previous section is still reasonable. However, the difference between the theoretical and actual drawdown contours emphasizes the importance of using measured values in order to understand the flow regime under pumping conditions; relying on modelled values can lead to an oversimplified understanding of the drawdown cone. When comparing the benefits of longer term pumping tests, such as this 60-day test, to shorter, 72-hour tests, the abundance of measured information from lengthier tests could be used in many ways, such as examining the change in shallow and deep groundwater responses. These also include a better understanding of climatic influences on groundwater conditions, such as recharge fluxes, or being able to better calibrate a predictive model based on observed conditions.

4.4 Water Quality Data Collected During the Pumping Test

Data from a variety of instrumentation along with water samples were combined to examine water quality changes throughout the pumping test. Data from general chemistry and metals sampling, isotope sampling, the EXO Sondes, loggers measuring turbidity, and turbidity measurements with hand-held devices were all analyzed as part of the water quality analysis. These data sets will be evaluated from the perspective of the insight they could provide in assessing the vulnerability of an operating public supply well to surface sources of contamination. Geochemical process analysis and specific contamination issues are not considered in detail within the scope of this analysis. The water quality parameters are used primarily as tracer indicators of groundwater-surface water interaction.

4.4.1 General Chemistry and Metals Information

Within this section, trends will be examined from within the water quality data and then the implications of these trends will be presented. Table 9 includes water quality information for the most relevant parameters to this site. These parameters, which show the most variation in concentration throughout the test, include anion and cation sums, chloride, dissolved organic carbon, electrical conductivity, hardness, sulfate, total dissolved solids, calcium, iron, magnesium, manganese, silicon, sodium, and strontium. All of the samples are categorized by depth and compared to the pumping well data. Shallow refers to Alder Creek surface water and wells CMT1-2, CMT2A-2, CMT3-2, and UW MWA, screened above the silt layer. Intermediate wells are screened below the silt layer and above 323 masl, the depth of the pumping well screen, and include OW2-11, OW1B-11, CMT1-6, CMT2A-6, CMT3-6 and UW MWB. Deep wells, screened below 323 masl, include OW1A-11, OW3B-09, OW3-11, OW3A-09, CMT2B-2, and CMT2B-6. These shallow, intermediate, and deep data were averaged for early time, prior to the start of the pumping test, and late time, the last day of the pumping test, prior to the pump being shut off. This comparison of early and late time data from different depths was compared directly to the samples collected at early and late time from the pumping well in order to provide insight into the groundwater mixing that occurs as the pump extracts and blends water from different sources.

Table 9 showed how water quality in the well changes over time during pumping and that there are connections between the deep and shallow groundwater. Based on the concentrations of chloride, electrical conductivity, total dissolved solids, and sodium, it is evident that shallow groundwater is being captured. Because the shallow system is likely influenced to some degree by the stream water where it infiltrates, and to surface contamination in general, this is a sign of potential vulnerability.

Overall, the early time data show water quality parameters measured from the pumping well TW2-13 as having very similar concentrations to those wells at a similar, intermediate depth. The late time data would be indicative of how groundwater movement changed over the length of the pumping test as a result of groundwater extraction. The comparison of early and late time water quality information demonstrates that mixing is occurring between these three groundwater environments. Generally, the late time data is shows lower concentrations in both the deep and shallow environment and in the pumping well as compared to the more concentrated parameters measured in the other wells at the intermediate elevation range. For this reason, it is difficult to discern if it is the shallow or deep groundwater environment that is diluting the pumping well water, merely that mixing can be observed as a result of pumping. However, there are several parameters that are indicative of separate shallow or deep groundwater contributions.

Shallow water mixing is exhibited through the dilution of calcium and hardness in the pumping well over time. These parameters are lower at the pumping well than in surrounding groundwater of similar elevation indicating capture of shallow groundwater. Deep groundwater contributions were shown via the increases in sulfate, iron, magnesium, manganese, and strontium concentrations at the pumping well which match more closely to deep groundwater quality than the shallow or intermediate environments.

All of the general chemistry and metals sample data, for each parameter that yielded data above the instrument detection limit, were plotted against time to visually represent trends that occurred over the course of the pumping test. Parameters with over 90 % of samples generating values below the detection limit were not plotted; these include orthophosphate, antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, nickel, phosphorous, selenium, silver, thallium, titanium, and vanadium. General chemistry parameters examined, illustrated in

Appendix AD, include alkalinity, ammonia, anion sum, cation sum, chloride, dissolved organic carbon, electrical conductivity, hardness, nitrate, pH, sulfate, and total dissolved solids. The metals studied, presented in Appendix AE, include aluminum, barium, boron, calcium, copper, iron, magnesium, manganese, molybdenum, potassium, silicon, sodium, strontium, uranium, and zinc. These 15 parameters were classified as either exhibiting one of four main traits: no trend in concentration over time; the pumping well concentration approached that of the shallow system; the shallow system concentrations became more similar to the pumping well; or that the range of all samples decreased over the course of the test with no clear trend otherwise (Table 10).

TDS went from spanning 400 mg/L to 1100 mg/L at the start of the test to a range of 430 mg/L to 890 mg/L by the last day of the pumping test in all samples collected. The shallow groundwater was relatively consistent throughout the test, with average TDS of 551 mg/L, clear in Figure 24. TW2-13, on the other hand, decreased from 836 mg/L to 740 mg/L in a 12 hour span at the start of the test, decreasing to 540 mg/L by October 17, 2013. Similarly, the sodium concentration in TW2-13 decreased below that of the Alder Creek surface water, from 160 mg/L to 40 mg/L during the test (Figure 25).

As mentioned above, there were several geochemical parameters that the pumping well concentrations becoming more similar to deep groundwater over time. Sulfate experienced an increasing range in concentration occurring over time (Figure 26). TW2-13 increased in sulfate from 52 mg/L to 83 mg/L by the end of the test, most closely resembling the 94 mg/L sulfate concentration of the deep groundwater. By contrast, the shallow groundwater system had an average of 53 mg/L of sulfate. While the shallow groundwater samples showed consistently low iron concentration throughout the test, the pumping well gradually increased in iron, from starting below the detection limit on August 19, 2013, to 0.15 mg/L 72 hours into pumping, steadily increasing to 0.29 mg/L by October 17, 2013 (Figure 27). This shows that the pumping well is indeed blending water from deep and shallow systems as illustrated by the consistent evidence provided by the water chemistry tracers showing the capturing of shallow groundwater.

Included in Figure 28, pH exhibited a decreasing variability in samples over the course of the test, with the initial samples showing a range in pH from 7.6 to 8.35; at the end of the test, this has decreased to 7.89 to 8.39. While pH results for the different sampling locations did have different magnitudes, many of the samples followed a similar curvature in the data. The pH values at all of the wells and the surface water trended together over the course of the test; this may be attributed to seasonal changes and supports the premise that the groundwater system is highly connected, with shallow and deep groundwater mixing occurring.

From these data, deductions can be made regarding the mixing of water due to pumping. Deep groundwater showed generally higher concentrations of sulfate, iron, manganese, silicon, and strontium. These metals are more prevalent in deeper groundwater due to weathering of metal-containing minerals and rocks deeper within the aquifer. As indicated in Table 10, iron and sulfate were the only two parameters to show a clear increase within the pumping well with no change present in the shallower wells. These iron and sulfate contributions are a result of iron sulfate present deep in the aquifer and therefore in the deeper groundwater. Their increased concentrations indicate deep groundwater is captured by the pumping well.

The shallow groundwater system is tied to the dilution of hardness and calcium concentrations at the pumping well relative to the surrounding environment. This evidence illustrates that shallow groundwater is mixing with the deeper groundwater to reach the pumping well, indicating its vulnerability.

Sodium and chloride concentrations, along with electrical conductivity, are likely attributed to road salt application for de-icing purposes in the winter. These parameters were highest in OW2-11, CMT2A-6, UW MWB, and CMT1-6, all screened at around the same elevation; however, chloride and sodium were relatively low in Alder Creek. In Figure 29, many geochemical parameters have been plotted as a function of electrical conductivity in order to deduce which ions are contributing to create electrically conductive water. Hardness, sodium, chloride, and calcium are most closely tied to electrical conductivity. Also TDS is included in this figure for comparison, which correlates strongly to electrical conductivity since it is essentially a sum of all suspended ions, molecules, and colloids, with ions being the cause for any electrical conductivity. In this case, electrical conductivity is a very good surrogate for sodium and chloride, so in instances where road salt application is of concern, electrical conductivity could be measured continuously and inexpensively to monitor salt plume movement within the subsurface.

In summary, the variation of general chemistry and metal parameters over the course of a pumping test, in both the pumping well and in surrounding observation wells screened at different elevations, indicate groundwater movement under pumping conditions: iron and sulfate show deeper groundwater being pulled up to the pumping well; shallow groundwater dilutes the hardness and calcium of the deeper system; similar changes observed in shallow and deep groundwater over the duration of the test show the connectivity of the entire system, as exhibited by the pH data.

4.4.2 Stable Water Isotope Information

The stable water isotope samples collected throughout the pumping test are presented in a series of plots in Appendix AF, including a comparison of the samples collected to the Local Meteoric Water Line (LMWL), $\delta^{18}O$ and $\delta^{2}H$ as a function of time, the isotopes plotted with respect to depth, and $\delta^{18}O$ and $\delta^{2}H$ in relation to temperature and precipitation data. All of the samples plotted fall along the LMWL, with only slightly heavier values for $\delta^{18}O$ and $\delta^{2}H$. When the $\delta^{18}O$ and $\delta^{2}H$ data from samples collected over the course of the test were plotted, limited differences in the per mill values for stable water isotopes were observed for the groundwater or surface water. Alder Creek isotope results fluctuated during the test, with a range of -9.64 to -10.36 ‰ $\delta^{18}O$ and -64.13 to -68.72 ‰ $\delta^{2}H$. A similar variability was observed in the groundwater samples collected, with minimum and maximum values for $\delta^{18}O$ of -9.37 ‰ and -11.24 ‰ and for $\delta^{2}H$ of -61.81 ‰ and -75.62 ‰. While the Alder Creek samples fluctuated more, the CMT1-2 samples showed a dampened response to the surface water changes, slowly increasing and decreasing throughout the test in accordance to the changes in surface water. CMT1-6 data shows a delayed change in isotopic composition compared to CMT1-2. This shows that surface water and groundwater fluctuations tracked together over time, perhaps supporting the idea that there is some surface water infiltration that is influencing the shallow groundwater system.

When plotted as a function of depth, there were no clear trends evident due to pumping. In an attempt to unearth a clearer trend in the isotope data, the surface water samples were compared to the precipitation record from throughout the pumping test. Samples collected on August 26, 2013, showed Alder Creek $\delta^{18}O$ and $\delta^{2}H$ isotopic levels of -10.31 ‰ and -69.79 ‰, respectively. On September 1, 2013, an 11.8 mm rainfall event occurred. By the next sampling event, on September 3, 2013, the surface water had become significantly lighter, with -9.68 ‰ δ^{18}O and -65.20 ‰ δ^{2}H. This could be explained by the precipitation being relatively light compared to the surface water, which would have been heavier, having undergone evaporation and the resulting depletion of lighter isotopes prior to the rainfall event. When the isotope data was compared to air temperature data, this evaporation trend appears to be somewhat true. δ^{18}O and δ^{2}H content correlates to temperature in all sampling events, apart from September 16, 2013 which happened to did follow a 6.4 mm precipitation event on September 11, 2013. Assuming that evaporation increases with temperature, and the surface water would become heavier with evaporation due to the removal of lighter isotopes, a correlation is apparent. Overall, there was limited significance to the isotope data collected in connection to the pumping test and the potential to function as a vulnerability indicator.

4.4.3 Electrical Conductivity Information

In contrast to the isotope data, the conductivity data gathered throughout the test is indicative of trends. Two data sets were available: point measurements of conductivity using the Sonde during sampling of groundwater and surface water and continuous logger data from OW2-11, OW3B-09, and UW MWB and Sonde data from TW2-13. The data collected during sampling, presented in Figure 30, show all of the samples converging to a more similar conductivity over time, a trend also evident in the general chemistry samples. Overall, the surface water samples and groundwater samples show a decrease in conductivity throughout the pumping test, with the exception of several erratic measurements observed in CMT3-2, CMT1-6, CMT2A-6, and OW2-11. This change across the site may be attributed to seasonal changes and the dilution of ions from the surface, such as sodium and chloride that might be introduced in the winter as road salt.

The continuous electrical conductivity data from the four wells mentioned above are included in Appendix AG. The deepest monitoring well, OW3B-09, maintained an electrical conductivity of around 860 μs/cm, thus illustrating that deeper groundwater was not influenced by shallower pumping from TW2-13. Alternatively, OW2-11 and UW MWB, screened at about the same elevation as the pumping well, were much more variable, obviously impacted by the influences of pumping. OW2-11 increasing rather gradually with the start of pumping until September 7, 2013, at which point the electrical conductivity decreased irregularly to until the end of the test in October. This trend may be attributed to seasonality and the movement of any salt plumes within the subsurface. During the mid-test shut off, more complex changes to the conductivity took place, as illustrated in Figure 31. At 1:30 pm on September 20, 2013, 30 minutes after the pump shut off, the conductivity in OW2-11 decreased from 1225 μs/cm to 1020 μs/cm by 1:40 pm on September 21, 2013. The conductivity then proceeded to increase to 1465 μs/cm by September 22, 2013 at 2:00 am. The conductivity then gradually decreased until noon on September 23, 2013, when the pump was restarted; with the starting of the pump, the conductivity jumped from 1090 μs/cm to 1270 μs/cm almost instantaneously. The increase in conductivity while the pump was off may have been the result of the rainfall event that occurred between September 20, 2013 at 8:00 pm and September 21, 2013, at 2:00 pm. This 64 mm cumulative precipitation event may have been the cause of a one day delay in conductivity increase seen in OW2-11. When the entire series of data from OW2-11 is compared to the precipitation record during the test, there seems to be a correlation between large precipitation events and conductivity increases which take place roughly one day later. OW2-11 showed such large changes in electrical conductivity compared to OW3B-09 possibly because OW2-11 was shallower and lay in the wake of the drawdown cone, compared to the deeper OW3B-09 that did not register the same magnitude of geochemical changes. Also, the shallower well's response to precipitation indicates the strong connection between the ground surface and the underlying groundwater composition, once again enforcing the idea that the aquifer is vulnerable to surface activities.

The Sonde information from the pumping well, TW2-13, showed a general decrease in conductivity over the first month of the test. Although there were some spikes in the data, the conductivity decreased fairly regularly from 1300 μs/cm at the start of the test to approximately 1030 μs/cm by August 21, 2013 at 2:00 pm. The electrical conductivity continued to decrease, but more slowly, to 700 μs/cm on the last day that there was data available from the Sonde, on September 17, 2013.

4.4.4 Turbidity Information

The Sondes used for continuous monitoring of the pumping well water and in Alder Creek experienced drifting in their data. The magnitudes of the readings collected by the Sonde sensors were much too high to make physical sense. Although calibrated throughout the test, the Sondes may have required more frequent calibration and sensor cleaning in order to obtain accurate information over a longer period of time.

There was very limited turbidity data available from the test due to the error with the in-line turbidity meter on site in the pump house. Thus, despite the poor reliability of the turbidity data, Sonde data was used in an attempt to extract turbidity information since this is a large parameter of concern for water treatment requirements. The Sonde had measured continuous turbidity data, in NTU, from the creek and pumping well, with additional point measurements collected from Alder Creek and the groundwater sampling locations during each sampling event throughout the test. Additionally, a handheld device was used to measure instantaneous turbidity levels from TW2-13. All turbidity figures are presented in Appendix AH. Neglecting UW MWA data, since that well was screened in silt, the sampling data has an initial range of 500 NTU. By the end of the test, this range had decreased to 170 NTU. Throughout the test, all of the sampling locations showed significant decreases in turbidity, with OW3B-09 and UW MWA as the exceptions.

The handheld device used to measure the turbidity at TW2-13 was very erratic and seemingly random. When compared to precipitation events, air temperature, UV Transmittance, iron, and manganese concentrations, no trend became evident. The handheld device was used by several different operators over the course of the test. The subtle differences in procedure used by each operator may have been the cause of the turbidity data variability instead of an external factor. The turbidity data from the Sonde measuring the pumping well effluent was much too high, with values around 25 NTU for the first month of the test, very different from the anticipated and measured values using the handheld device, as well as the general chemistry record from pervious well studies. The surface water Sonde data was much more reasonable even though the parameter magnitude was wrong (Figure 32). The turbidity values were generally below 27 NTU throughout the test, however over the course of the test the turbidity spikes became increasingly high. The larger spikes in turbidity within the surface water, such as those observed on September 1, 12, and 21, 2013, and October 4 and 4, 2013, happened to coincide with the large precipitation events. The turbidity might be attributed to runoff carrying sediment into Alder Creek.

4.4.5 Dissolved Oxygen Information

DO information obtained from the continuous Sonde data from Alder Creek and the pumping well and discrete Sonde data from sampling events at all monitoring wells were examined (Appendix AI). While the magnitude of the continuous Sonde data is considered inaccurate due to several instances when DO exceeded the saturation limit for oxygen for the temperature conditions, it can still be deduced that DO in Alder Creek experienced diurnal fluxes which generally peaked around 10:00 am, which is attributed to typical day and night temperature fluxes for southern Ontario. When compared with both temperature and precipitation, there was no clear correlation. In reality, seasonal temperature changes would influence DO concentrations, with water expected to become increasingly anaerobic moving into the fall due to the reduced temperatures and subsequently a reduced capacity for the water to hold oxygen. The Sonde measuring the pumping well water experienced two spikes in DO of approximately 2 mg/L, during the installation process on August 19, 2013, and again several days later on August 21, 2013. Both of these irregularities might be attributed to inspection of the flow-through cell to ensure that the probes were submerged. Otherwise, the entire month of data recorded over the first half of the pumping test was rather smooth. There appeared to be a subtle increase in DO concentrations over the test, initially resting at around 0.16 mg/L on August 20, 2013, increasing to 0.33 mg/L by September 4, 2013, where it remained for the duration of data collection on September 17, 2013. This could potentially support Stantec's hypothesis that more oxygenated, shallow groundwater was pulled downwards, mixing with the anaerobic deep groundwater.

The discrete DO measurements recorded during sampling periods were also compared to the precipitation and air temperature data available, with no clear correlation. However, when DO concentrations at each sampling location were plotted as a function of depth, a pattern became pronounced; overall, the DO concentration decreased with depth (Figure 33). Additionally, several of the sampling locations experienced trends that may be indicative of groundwater movement, with the larger variations in DO occurring in those wells closer to Alder Creek. CMT1-2, the sampling location nearest to the creek, experienced increased in DO over the course of the test which may be due to infiltrating surface water, evidence which supports the idea of some infiltration from the creek to the shallow groundwater system (Figure 33). CMT2A-2, the second shallowest port sampled, also increased dramatically in DO concentration over the test, from 2.9 mg/L to 6.2 mg/L. CMT2A-6 and CMT2B-2 decreased in DO concentration, from 2.5 mg/L to below 1.8 mg/L; CMT2B-6 increased in DO concentration, from 1.4 mg/L to 1.9 mg/L, becoming more similar with its adjacent ports, a possible result of anaerobic and anaerobic water mixing. No distinguishable trends emerged for CMT3 ports, the four monitoring wells at the south end of the property, the monitoring wells on the other side of the creek, and CMT1-6. This may be attributed to two things: first, wells were outside of the significant drawdown zone; second, the wells within the zone of influence showing no trend have screen elevations very similar to the pumping well, so no consistent DO change may be a result of lateral flow in those areas. The DO concentration of OW3B-09 remained relatively consistent throughout the test, which shows that 3 m below the pumping elevation, groundwater mixing was not occurring, something that makes physical sense. Ultimately, the only significance that can be drawn from this data is that CMT1-2 may have experienced elevated DO levels as a result of shallow groundwater or surface water infiltration, evidence which supports higher vulnerability conditions in the area.

4.5 Temperature Data Collected During the Pumping Test

Water temperature data were collected throughout the test using the RTDs within the CMTs, the Sondes in the creek and pumphouse, and loggers in the drive points, Region and UW wells, and the pumping well. Air temperature was also measured by the weather stations positioned throughout the watershed.

4.5.1 RTD Temperature Information

All RTD figures are shown in Appendix AJ; the RTD data is presented separately for each CMT for clarity. Three specific times of interest were given their own 24 hour plots: at the start of the test on August 18, 2013, when the test re-started on September 23, 2013, and the start of the recovery period on October 17, 2013. Several insightful observations were deduced from these graphs. Prior to the start of the test, CMT1 ports 1 to 3 contained warmer water, ranging from 13 to 15 °C, than the deeper ports with water 8 °C. This difference happens to coincide with the positioning of the silt layer; while the silt layer does not significantly slow flow, it might provide some buffering between deeper, colder groundwater and shallower, warmer groundwater. CMT2A shows a similar trend, with the more shallow port at 11.6 °C and the deeper ports monitored, all below the silt layer, ranging from 7 to 9.5 °C. Overall, a trend for deeper multi-level ports to have lower temperature was observed, with CMT1-3, CMT2A -5 and -7, and CMT2B -5 and -7 as the exceptions.

Shown in Figure 34, at the start of the test, CMT1-1 experienced a gradual 1 °C decrease in temperature before gradually reaching its static temperature again. CMT1-2 warmed by approximately 0.2 °C with the starting of the pump test. CMT1-3 observed a 1.4 °C temperature increase over seven hours once the pumping commenced. Ports 4, 5, 6, and 7 all experienced warming following the start of pumping, with CMT1-4 experiencing the smallest, most gradual increase and CMT1-7 undergoing a sharper, 1.5 °C increase over only three hours. The majority of the RTDs in the CMT2A, CMT2B, and CMT3 wells experienced little, if any, change. This increase in temperature in the deeper CMT1 ports supports the idea shallow and deep groundwater mixing, providing additional evidence that the well is in a vulnerable aquifer setting.

When the pump test was restarted again after the accidental shut off, CMT1 ports 1, 2, 3, and 4 did not undergo a significant temperature change (Figure 35). CMT1 ports 5, 6, and 7 all underwent a temperature increase of at least 1°C over two hours, a more rapid change than with the initial start of the test. The difference in temperature between ports 1 to 3, at 14 to 16 °C, and 4 to 7, at 9 to 11 °C, still existed however it was less dramatic than prior to the test starting in August.

When the pump was shut off and the water table was allowed to recover, interesting trends in temperature were identified (Figure 36). Once again, the difference between temperatures in ports 1 to 3 and ports 4 to 7 became smaller, with only a 3 °C difference between the two sets of data. When the pump was shut off, CMT1 ports 4 to 7 all decreased in temperature rather sharply, with an average decrease of 1.2 °C over two hours. CMT1-7 experienced the most dramatic temperature decrease with a 1.6 °C change in that time. This was attributed to cooler, deep groundwater rising within the ports to the elevation of the silt layer. So while the silt layer does not confine the aquifer and restrict flow across it, it does appear to create a temperature gradient across it, above which the shallow groundwater temperature is warmer. Some speculation can be made from these temperature data regarding the influences of minor infiltration from Alder Creek influencing the shallow system, making the pumping well vulnerable to the surface; these data can also provide insight regarding stratigraphic influences on groundwater properties.

It should be noted that due to the high sensitivity of the sensors, hourly averages were used to smooth the data and reduce noise in order to discern trends. Additionally, there were several instances of dramatic temperature changes over an hour long period which caused large spikes in the data. This coincided with sampling events, when the RTDs were left in place and pumping with the peristaltic pump changes conditions about the probe.

4.5.2 Data Logger Temperature Information

The level loggers in the Region wells, pump test well, UW wells, and drive points all contained temperature sensors. For each of these equipment sets, temperature-time plots were generated for the entire data series, the start of the pump test, the restarting of the pump test, and the recovery period (Appendix AK). The following observations were made.

The drive points monitored temperature in shallow groundwater and surface water. Surface water temperatures near the drive points DP1-13 and DP2-13 were rather erratic throughout the entire test, experiencing diurnal temperature fluxes. Overall, the surface temperature responded to air temperature changes, decreasing from midnight and 7:00 am, before increasing again (Figure 37). A similar correlation between air temperature and surface water temperature was also observed on September 23, 2013 (Figure 38). The surface water experienced temperature changes more gradually as a function of higher specific heat capacity in relation to air. From these data, no pumping test influences on surface water temperature were apparent.

The drive points measuring groundwater temperature measured more subtle temperature changes in response to air temperature, likely because they were screened within low permeability material below the streambed. DP 1-13 data, closest to the pumping well, showed groundwater responding to air temperature change however it was delayed compared to the faster surface water temperature fluctuation. Generally, the shallow groundwater temperature trend follows the overall trend in surface water changes, in response to air temperature changes with the seasons. This indicates that the area immediately below the Alder Creek streambed is somewhat connected to the surface water, perhaps as it slowly infiltrates into the subsurface. Hourly averages were used to more clearly to depict these trends. No correlation between surface water temperature and precipitation events was found, since the temperature of rainfall is also controlled by air temperature.

Alternatively, the pump test well data shows a significant temperature change in response to pumping. As shown in Figure 39 to Figure 42, the general decrease in temperature with pumping and increase in temperature with recovery is evident. With the starting of the pump, the temperature in TW2-13 decreased from 9.1 °C to 8.3 °C in twenty-five minutes. For the first day of the pumping test, the TW2-13 temperature data was somewhat irregular due to the changing pump rate and any sampling that might have taken place prior to starting the pump. The results of pumping and recovery are much clearer from the September 20 to September 23, 2013 when the pump was shut off and restarted. When the pump turned off at approximately 1:00 pm on September 20, 2013, the temperature in TW2-13 gradually increased from 9.3 °C to 12.1 °C over 14 hours. The temperature remained at 12.1 °C until the pump was restarted at 12:30 pm on September 23, 2013; the temperature responded by rapidly decreasing to 9.3 °C in only 90 minutes. A similar increase in temperature was observed when the pump was intentionally shut off on October 17, 2013. Overall, the temperature in the TW2-13 was very quick to respond to pumping, decreasing with pumping and increasing with recovery. This indicates that deeper, colder water was captured by the pumping well in addition to the downward movement of the warmer, shallow groundwater system. This supports the shallow and deep groundwater blending idea evidenced by the water quality information. It should be noted that pumping well data examined on its own may be misleading with respect to how the system is actually responding; all of the data needs to be considered in order to understand how the shallow groundwater system is captured as well.

The UW wells on the west side of the creek yielded interesting results. UW MWA, partially screened within the silt layer, did not experience a significant change in temperature throughout the test, stagnating at approximately 8.9 °C (Figure 43). This is likely due to the horizontal flow field this far from the pumping well where there is not much vertical groundwater movement. The UW MW B data, however, showed temperature changes in groundwater on the other side of Alder Creek due to pumping (Figure 44 and Figure 45). When the pump was started, the temperature in UW MWB increased from approximately 8.3 °C to 8.4 °C in five hours. When the pump was shut off in September, when the temperature decreased quickly from around 8.6 °C to 8.5 °C between 1:00 pm and 3:00 pm. When the pump was restarted, the temperature responded by gradually increasing from 8.5 °C to 8.6 °C over four hours. Unfortunately due to battery problems, the UW MWB logger was not operational when the pump test finished on October 17, 2013. Hourly averages were used for these data in order to reduce noise and smooth the data to look for trends. This further demonstrates that the groundwater system is connected beneath the creek, however because the temperature changes are so subtle, its difficult to state this definitively.

Ultimately, temperature is an indicator of groundwater movement. These results show that deep groundwater was drawn to the pumping well, from a depth similar to that of OW3B-09 which remains at relatively the same temperature throughout the test. This colder water resulted in the sharp temperature decreases at TW2-13 with the starting of the pump. The responses in CMT1 and UW MWB show reverse effects, with temperatures increasing during pumping and decreasing when pumping is stopped. Simply, the pumping well pulls up cold water and the temperature decreases. However, the influence of pumping in the shallow and intermediate system indicates that there is warmer shallower water moving deeper. Without measuring both parts of the system, it would be difficult to make any clear conclusions, which is an interesting and not completely intuitive.

Any air temperature data used from October 15, 2013 onwards was from Weather Station 1, located at the Mannheim Water Treatment Plant nearby. Erratic data measurements that corresponded to sampling events were removed for the clarity of the graphic representations created.

4.6 Statistical Analysis

4.6.1 Continuous Data Comparison

As explained in Section 3.8.2, correlation coefficients and covariances were calculated for continuous and discretely measured variables. The continuous data sets were compared over matching time intervals, presented in Table 11. Conditional formatting was used to emphasize areas of interest. For correlation coefficients, which vary from -1 to 1, blue hues were used to represent negative values and red hues were used to highlight positive values. For values above 0.8 and below -0.8, indicating a strong linear correlation, red and deep blue were used. Values ranging from 0.5 to 0.8 or -0.5 to -0.8 were formatted with pink and light blue, respectively, to locate moderate correlations. Finally, correlation coefficients between 0.2 to 0.5 and -0.2 to -0.5 were deemed slight and were highlighted with pale pink and pale blue, correspondingly.

The correlation coefficient data yielded one strong linear correlation between the water level and water temperature in the pumping well. This was anticipated based on the results presented in Figure 42 showing the very rapid response to temperature based on pumping conditions. Several positive, moderate linear correlations were observed between the continuous parameters. These included water level and water temperature for UW MWA, water level and conductivity for OW3B-09, and both water level and turbidity comparisons for the surface water and for TW2-13. Air temperature and water temperature for the DP1-13 and DP2-13 surface water and DP1-13 shallow groundwater also had positive, moderate correlations. The surface water and shallow groundwater responded to air temperature very distinctly, which was explained above. Moderate, negative correlations were observed between water temperature and conductivity at TW2-13 and UW MWB and between conductivity and turbidity for TW2-13. This inverse relationship between conductivity and turbidity might be explained through the hypothesis posed by Stantec in 2013. For many dissolved metal ions that contribute to conductivity, under neutral pH conditions they remain in solution. With a pH change, these metals may form precipitates, which result in increased turbidity. Therefore, as conductivity decreases and ions form solids, turbidity will increase. When compared, pH and conductivity yield a negative correlation coefficient of -0.30.

Other slight correlations were discovered for different parameter comparisons. For many wells, apart from the CMT 2B temperature data, there was a slight negative correlation between air temperature and water temperature. The temperature dynamics in the subsurface were more likely attributed to the pumping conditions and resultant groundwater movement than seasonal conditions since the well was so much deeper than the other multi-levels. Explained above, deeper groundwater seemed to flow to the well, influencing the temperature in the area of the drawdown cone. While the moderately deep wells, including CMT 1 ports 4 to 7, CMT 2A ports 1 to 5, and CMT2B-1, experienced lowered temperatures during the test due to the movement of colder deep groundwater, the deeper ports of CMT 2B, placed at or below the pumping well screen, maintained their colder temperatures.

No significant correlations were found between precipitation and water level, water temperature, conductivity, or turbidity. This may be due to the time delays observed between the start of a precipitation event and subsequent changes in these other parameters. Precipitation responses also differ based on the magnitude of a given event and the moisture conditions within the subsurface, which change seasonally. As speculated for the relationship between air and water temperature above, the fluctuation of water temperature was more strongly influenced by pumping conditions overall so even a major influx of precipitation at a different temperature would still only impact the temperature record for a short time in comparison to the 60 days of pumping.

4.6.2 Discrete Data Comparison

To reiterate from Section 3.8.1, point-measured water quality data included information collected during and as a result of sampling events, including individual Sonde measurements and sample results for general chemistry, metals, and stable water isotopes. For these comparisons, correlation coefficients were conducted as they allowed for normalized comparisons, resulting in unitless parameters. Since many of these parameters have different units, and those with the same units have very different ranges for each parameter, covariances were not appropriate for these data.

The correlation coefficients for these discrete data are included in Table 12, with the same conditional formatting explained in the section above. Several very strong positive correlations were discovered between $\delta^{18}O$ and $\delta^{2}H$, anion and cation sums, anion sum and conductivity, cation sum and conductivity, TDS and conductivity, chloride and TDS, chloride and conductivity, sodium and conductivity, sodium and chloride, and calcium and hardness. Many of these make sense logically. With a correlation of 98 %, stable water isotopes have very strong linear relationships, commonly represented with meteoric water lines. The presence of anions is overall balanced by cations in water, with a correlation coefficient of 0.99. The electrical conductivity of water is dependent on the presence of ions, where distilled water behaves as an insulator and salt water as a conductor. The resulting correlation coefficient between anion and cations with conductivity is 99 %. With salt water being such an excellent conductor, comprised of dissolved chloride and sodium, it is no surprise that when compared to conductivity, these constituents have correlation coefficients of 0.94 and 0.92, respectively. The resulting 98 % correlation between sodium and chloride is a strong indicator of the presence of road salt.

Of all of the parameters that showed the pumping well water samples becoming increasingly similar in water quality to the shallow groundwater samples, only calcium and manganese showed more than slight correlation at 63.6 %. The positive correlation coefficient between these two metals might be attributed to the subsurface mineral composition, which would result in increased water hardness. When manganese and hardness are compared, a 69 % correlation is shown.

Copper and silicon both showed a visible correlation, with all of the sources having increasingly similar concentrations over the course of the test, with silicon steadily increasing and copper steadily decreasing over the course of the pumping test. The negative correlation coefficient of -0.68 between these two metals matches the groundwater movement explained throughout this chapter. Copper, attributed to shallower groundwater quality, decreased in concentration as deeper groundwater water drawn up to the pumping well, which contained more silicon.

While the manganese and iron concentrations showed a positive, moderate correlation of 65 %, when both metals were compared to pH and DO, only slight negative correlations were evident. This was not significant enough to either prove or disprove the geochemical conditions hypothesized by Stantec to explain the turbidity problems with K22A (Stantec Consulting Ltd., 2013). Unsurprisingly, for the parameter that exhibited no clear trends, no correlations surfaced.

Overall, correlation coefficients indicated several worthwhile trends, further enforcing ideas regarding groundwater flow and helping to identify water quality relationships. Surface water and climate parameters were very similar, with strong correlations between surface water temperature and air temperature. Where air temperature is not available, reasonable climate conclusions can be drawn from surface water temperature alone. Unfortunately, there is no clear surrogate to precipitation data discovered through these comparisons.

Trends discerned from water quality can be useful when pinpointing water quality concerns and deciphering their potential causes. Where strong sodium and chloride correlations exist, road salt problems can be identified. When certain metals correspond positively, they can indicate the presence of certain minerals in the subsurface and assess their level of contribution to the quality of the water. Negative correlations can help identify water movement, where concentration increases in some parameters may correspond to concentration decreases in other parameters, showing a change in source water origin. Water quality trend analyses may be useful in recognizing water quality variability and groundwater movement, offering a simple method in the quantification of those connections. The statistical methods used above are quick ways to identify potential surrogate parameters when conducting vulnerability assessments in order to best use existing data and make decisions concerning hydrogeological and geochemical monitoring.

4.7 Vulnerability Evaluation

4.7.1 Time of Travel

Based on the basic time of travel methodology explained in Section 3.7.3, given a pumping rate of 11 L/s, the 4.4 m unsaturated zone thickness, and assumed porosity of 0.3, a series of capture zone radii were calculated for given travel times. These values are presented in Table 13. In one year of travel, water will flow from a radius of 289 m at the given pumping rate. In a 50 day time of travel, like that specified in the GUDI regulations, a radial capture zone of 21 m was calculated. Given that Alder Creek is within 11 m of TW2-13, this well could be deemed as GUDI.

Using the Uniform Flow Field method, which assumes a regional flow gradient like the one observed at the study site, with parameters as specified within this section and using the 4.1×10^{-4} m/s hydraulic gradient assumed, the down gradient null interval was calculated as 48.6 m, the boundary limit of the capture zone was calculated as 152.8 m, and the up-gradient distance as a function of time was calculated as 117.8 m for 50 days of travel (Table 14).

The final methodology for calculating the time of travel calculated the time of travel based on increasing hydraulic gradients approaching the pumping well, the stepwise method. In this case, time of travel for each radial step from the pumping well was calculated. These steps were 1 m, 4 m, 8 m, 13 m, 20 m, 30 m, 40 m, 50 m, and 60 m from the well. Corresponding travel times were calculated and are presented in Table 15. Back calculating was used to determine the radial distance for a 50 day time of travel, given steps for 40 m and 50 m yielded 42.45 day and 56.60 day times of travel, respectively. The velocity calculated was used for this estimate, which found that the 50 day time of travel distance of 48.8 m.

The three methods for calculating the 50 day time of travel under pumping conditions yielded 21.4 m, 117.8 m, and 48.8 m. Providing that the stepwise method best accounts for variable flow conditions, since groundwater velocities increase dramatically with proximity to the pumping well, the 48.8 m estimate seems most appropriate and conservative. Since Alder Creek is 11 m away from TW2-13, this would imply that the pumping well is classified as a GUDI well based on the regulations in place.

By examining the drawdown contour plots, observing the high vertical gradient across the streambed, acknowledging that the stream is losing some water to the subsurface, identifying that there is mixing between the shallow and deep groundwater systems, given that the aquifer is unconfined, and now that the time of travel from Alder Creek to the pumping well is under 50 days, the vulnerability of the TW2-13 is evident.

4.7.2 Vulnerability of the Pumping Well to Surface Water Contamination

The methods used to provide an index of aquifer vulnerability, as explained in Section 3.7.3, are AVI, ISI, and SAAT. These results are presented in Table 16. For AVI, a 30 m aquifer thickness was assumed and a K factor of $10x10^{-4}$ m/s was used to calculate a c_q value of 4.87. According to the MOE guidelines, and AVI score greater than 4 implies limited vulnerability whereas a score less than 2 implied high vulnerability; AVI classifies TW2-13 as being of limited vulnerability. The ISI method utilized a K-factor of 2 for gravelly to silt sands and an aquifer thickness of approximately 30 m. The resulting ISI was 60, corresponding to moderate vulnerability for the area. For the SAAT, given a 10 % mobile moisture content of sand and average of 400 mm of recharge annually, the number of years required for surface contaminants to reach the water table is 0.8, or around just under 300 days. While this sounds like a large amount of time, it is relatively low when considering that this is the amount of time it could take for a spill to contaminate the subsurface and tarnish a drinking water supply. AVI, ISI, and SAAT provided different results for vulnerability; limited, moderate, and moderate, respectively. Each of these methods makes large generalizations and assumptions about the behaviour of water within the subsurface and exterior factors which impact the hydrogeology at a given site, such as uniform thickness, homogeneity, static water tables, and constant recharge and moisture content.

There is a vast amount of room for improvement available when it comes to quantifying vulnerability. AVI, ISI, and SAAT do not utilize the physically measured data available from a hydrogeologic investigation such as this. An improvement to these vulnerability standards would accommodate for variable conditions, such as seasonality or extreme weather events, incorporate other indicators measured in the field, like temperature, precipitation, turbidity, conductivity, water levels in surrounding surface water bodies, or more. These factors could each be given values for different classes of groundwater and surface water interaction which, when used in combination, would offer an indication of vulnerability that would account for variable conditions in climate, water quality, and surface water proximity.

4.7.3 Ecological Impact of Pumping Well on Alder Creek Baseflow

There were no effects due to pumping observed in Alder Creek. As explained in Section 2.1.3, if pumping decreased flow to less than 40 % of its mean annual flow, the aquatic health of the stream would be harmed. Over the course of the 60-day pumping test, there were no changes to surface water levels as a result of pumping. While there may be some surface water infiltration occurring adjacent to the K22A site, this did not result in an observable surface water elevation change. Additionally, neither surface water temperature nor water quality parameters were altered in any way by pumping because the flow system was one way only: water may have infiltrated into the ground from the surface, but never vice versa. Thus, the impacts of pumping on Alder Creek were negligible and no potential harm to the ecosystem is anticipated due to the production well positioning. In a different stream segment that may be more hydraulically connected and gaining groundwater at different times of the year, the influence of pumping would be more significant, as it would likely reduce the groundwater contributions to stream baseflow that are crucial to sustain flow.

4.7.4 Climate Change Implications

Section 2.1.5 outlined the anticipated strain on water resources as a result of climate change. From increased climatic variability, temperatures, and intensity in precipitation to reduced snow pack and recharge volumes, water quality and quantity are both at risk. Based on the connection between parameters monitored at the K22A site, several predications and subsequent areas of concern are anticipated as a result of these changes. Increases in air temperature will cause a direct increase in surface water temperatures and eventually cause increases in temperature for the shallow groundwater system. Higher temperatures result in higher evaporation rates, which would take more and more water from Alder Creek. With a monthly mean flow of 0.045 m^3/s in July compared to the mean annual flow estimated at around 0.08 m^3/s, a health minimum flow for Alder Creek at K22A is 0.029 m^3/s (Table 1). This flow requirement would not be met should water elevations decrease by over 5 cm, which is possible given climate change predictions.

Precipitation volumes are expected to increase, with more high intensity rainfall events, yet longer periods are expected between rainfalls. High intensity rainfall will cause more runoff, resulting in water level spikes within surface water bodies, more erosion causing increased turbidity within surface water, and negatively influence water quality. With increased runoff volumes, more road salt will be carried into Alder Creek, spiking sodium, chloride, and electrical conductivity values in the subsurface over time. Given that TW2-13 is in close proximity to a large road and many agricultural operations, increased runoff volumes might create problems with nitrate, phosphorous, and petroleum hydrocarbons being introduced into Alder Creek. Although the surface water samples and groundwater samples show a decrease in conductivity throughout the pumping test, this phenomenon may no longer occur if more ions are recharged into the subsurface from these contamination sources over time. Variability in precipitation and increased evaporation will make the impacts of seasonality and rainout for stable isotope data interpretation more complex. Groundwater levels did fluctuate in response to precipitation events, observed clearly in TW2-13 and OW2-11. It may become more difficult to perform pump test analyses from water level data alone, as precipitation events of larger and larger magnitude will cause fluctuations to the water table elevation.

During the anticipated periods of reduced precipitation, Alder Creek will experience very low flows. Over time, reduced snow pack and lowered water tables may cause more surface water to be lost to the subsurface, decreasing the assimilative capacity and baseflow of Alder Creek. Overall, this might change how groundwater moves; the rapid response of deep groundwater pulled to TW2-13 during pumping will lessen due to the strain on the aquifer to sustain the population. With less water to draw on, the TW2-13 equilibrium drawdown cone would be lower and extend farther outwards radially. In some locations, higher vertical gradients may result in greater influxes of surface water, shortening the time of travel between surface water and a pumping well, increasing its vulnerability.

4.8 Indicator Chart

Throughout this study, many different parameters have been measured, analyzed, and compared in an effort to understand groundwater-surface water interaction at the K22A Site and assess the vulnerability of TW2-13. Those parameters that hold the most relevance in this understanding, whether as a direct indicator of groundwater movement or as a surrogate for another parameter, have been summarized in Table 17. This table was compiled as a tool to suggest which parameters should be given prioritization when conducting a well assessment under similar stratigraphic settings. In this format, a specific indicator method or analysis technique is listed alongside the required instrumentation, specific observation from within the study, its associated value as an indicator, and possible application scenarios. Ideally, this table is useful in decided what parameters should be measured in the field and help to draw conclusions from the collected data efficiently, whether identifying trends, looking for correlations, or understanding the implications of irregularities.

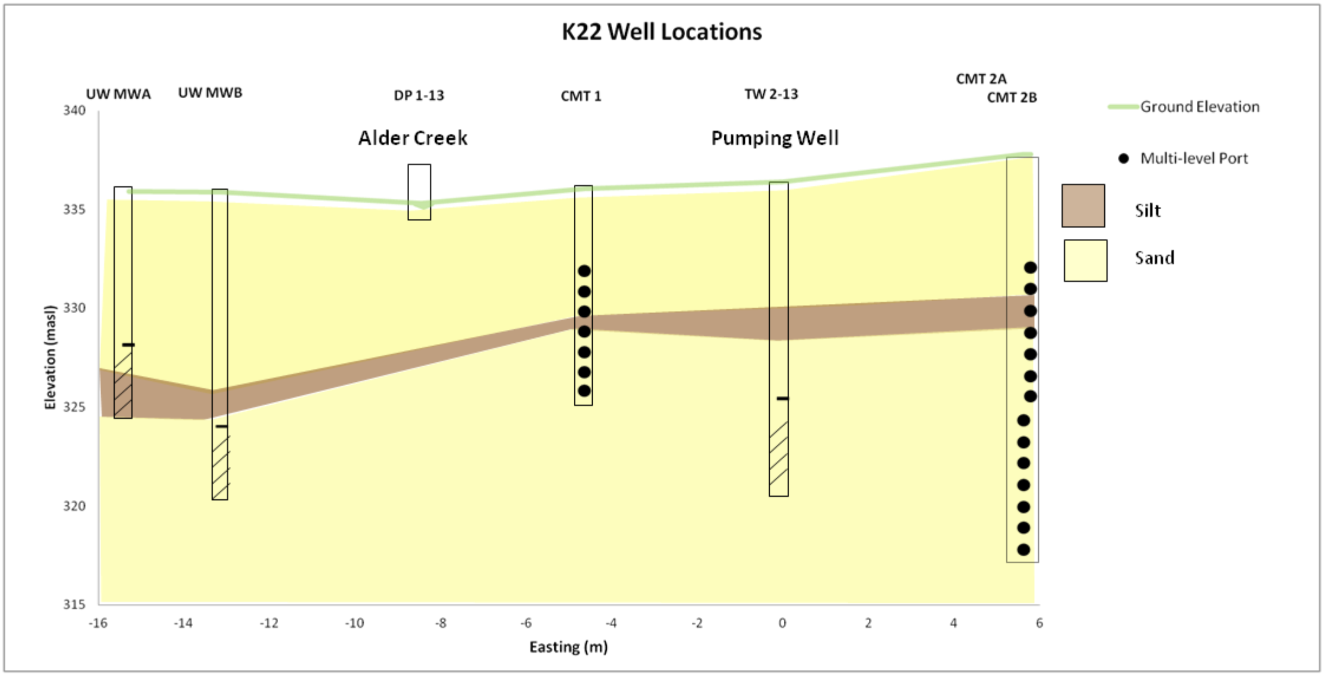


Figure 5. K22A Site Cross-section, from UW MWA to CMT2A and 2B.

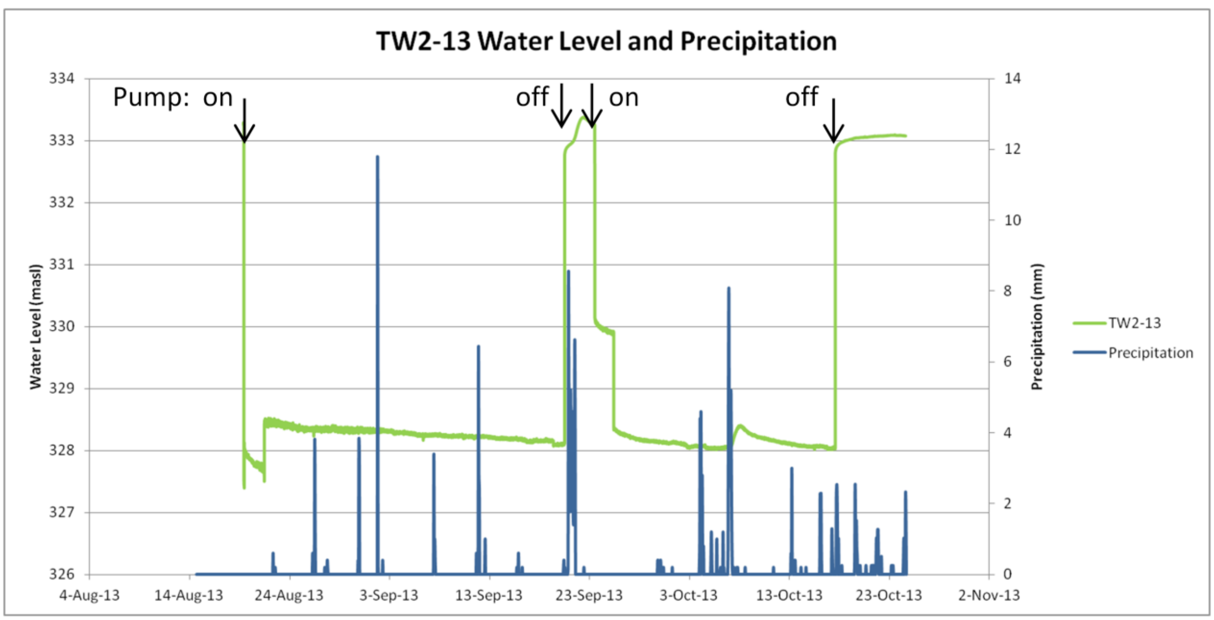


Figure 6. Continuous water level data in the pumping well, TW2-13, and precipitation data throughout the 60-day pumping test.

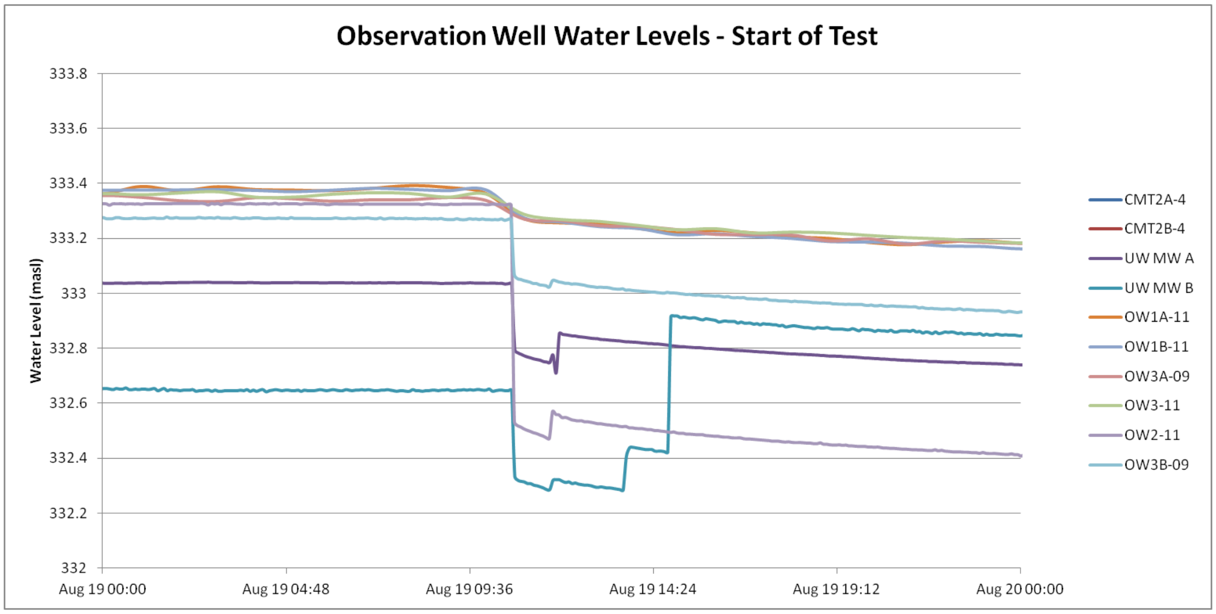


Figure 7. Continuous water level data in the observation wells, CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, at the start of the pumping test, August 19, 2013.

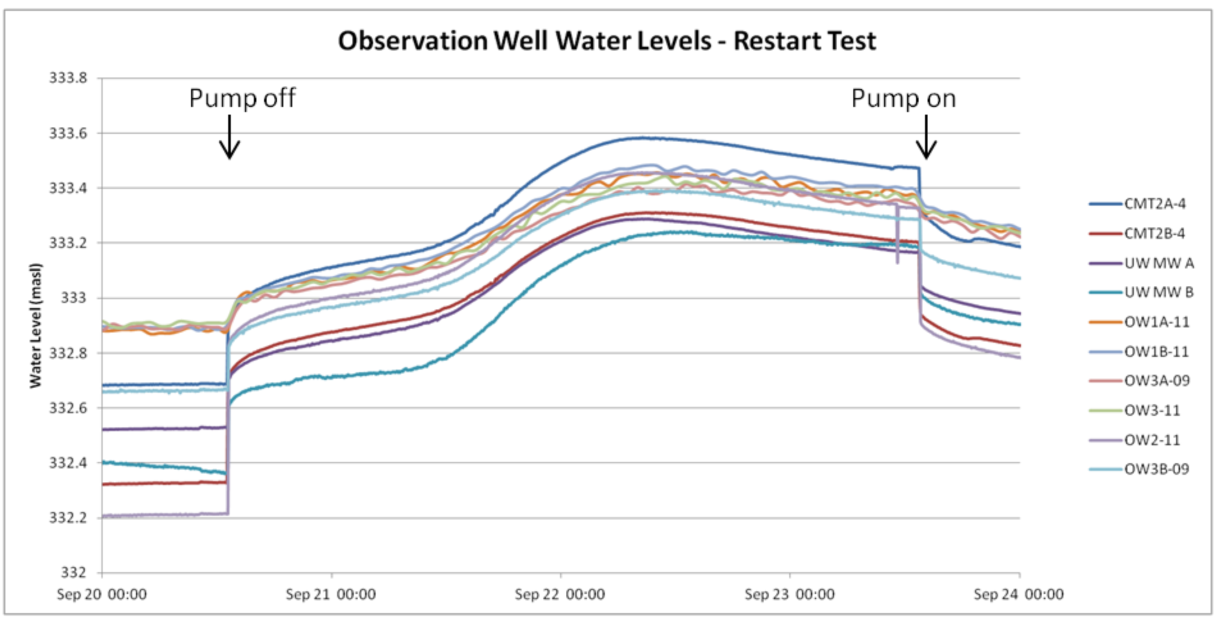


Figure 8. Continuous water level data in the observation wells, CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, during the mid-test shut off period, September 20 to September 23, 2013.

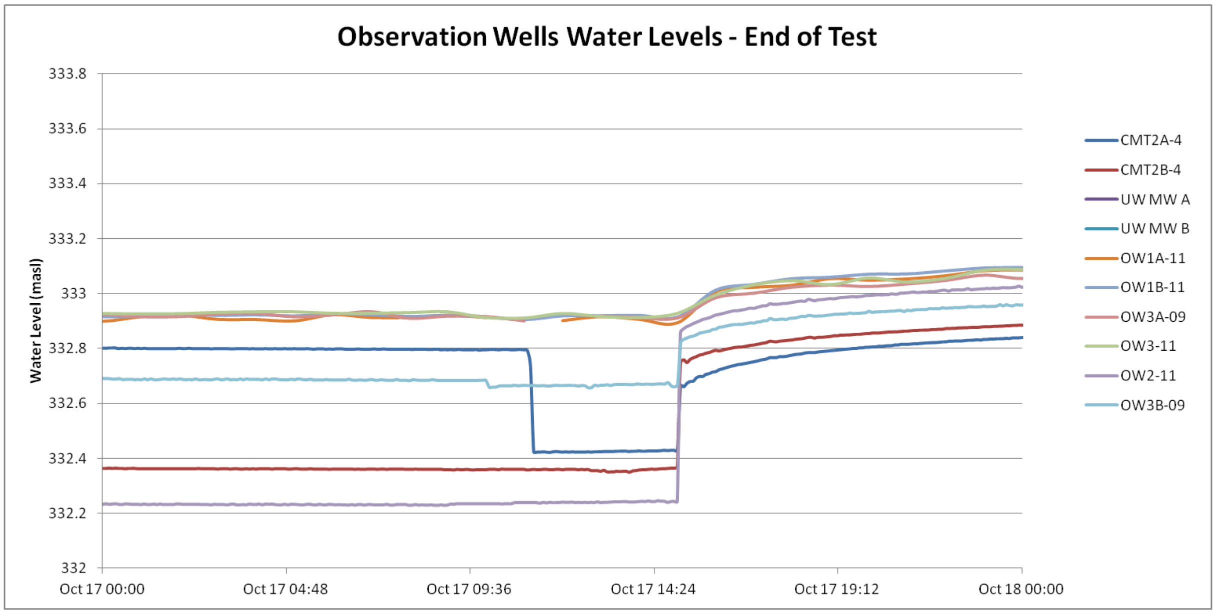


Figure 9. Continuous water level data in the observation wells, CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, at the end of the pumping test, October 17, 2013.

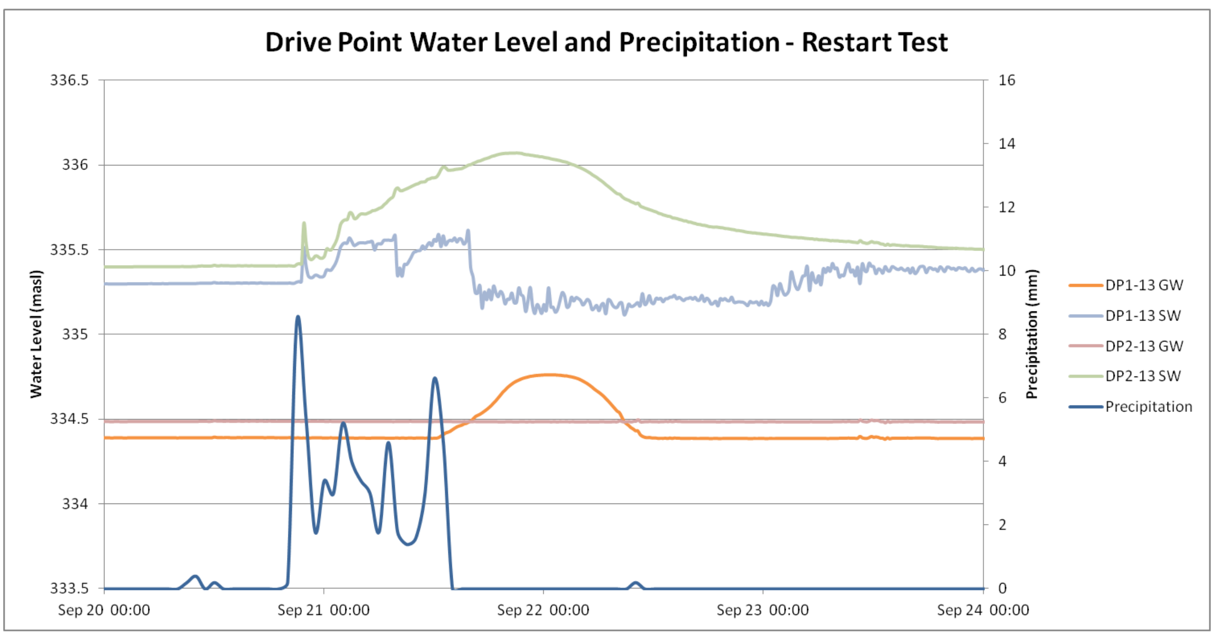


Figure 10. Continuous water level data in the shallow groundwater and surface water at the drive points, DP1-13 and DP2-13, and precipitation data during the mid-test shut off period, September 20 to September 23, 2013.

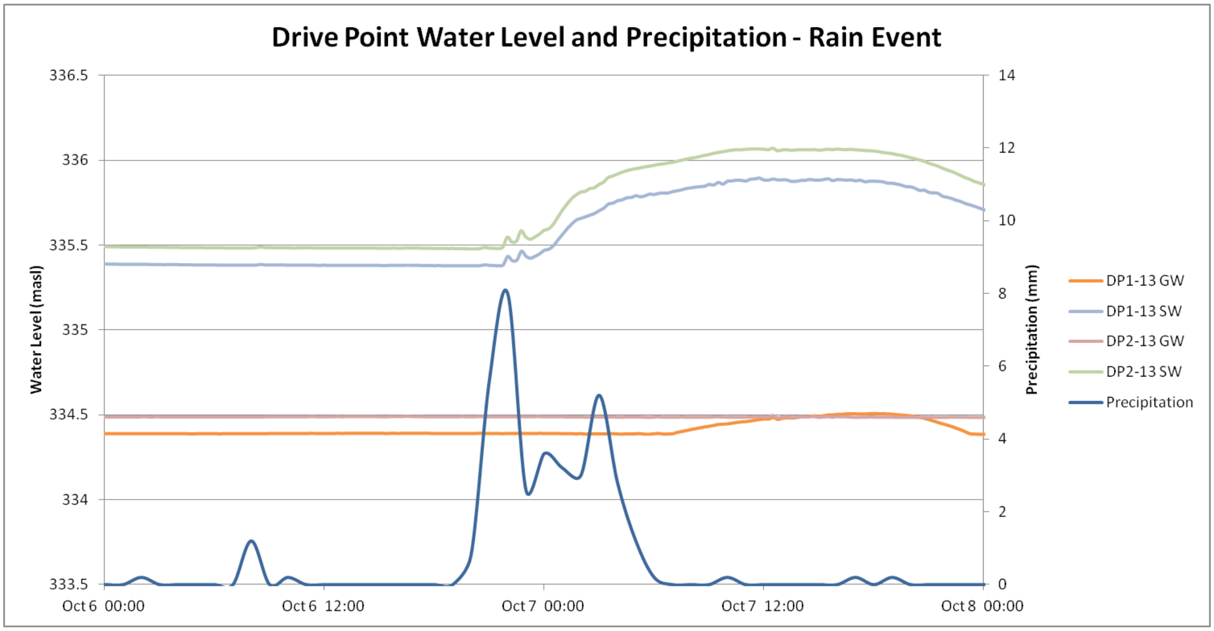
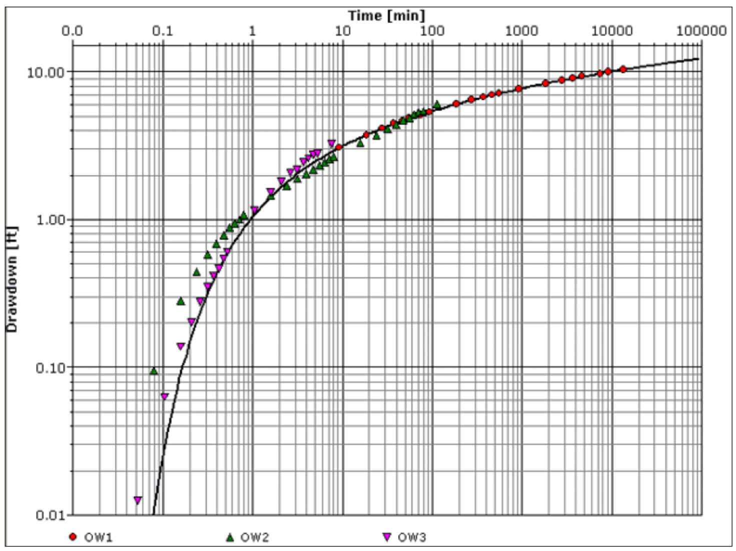
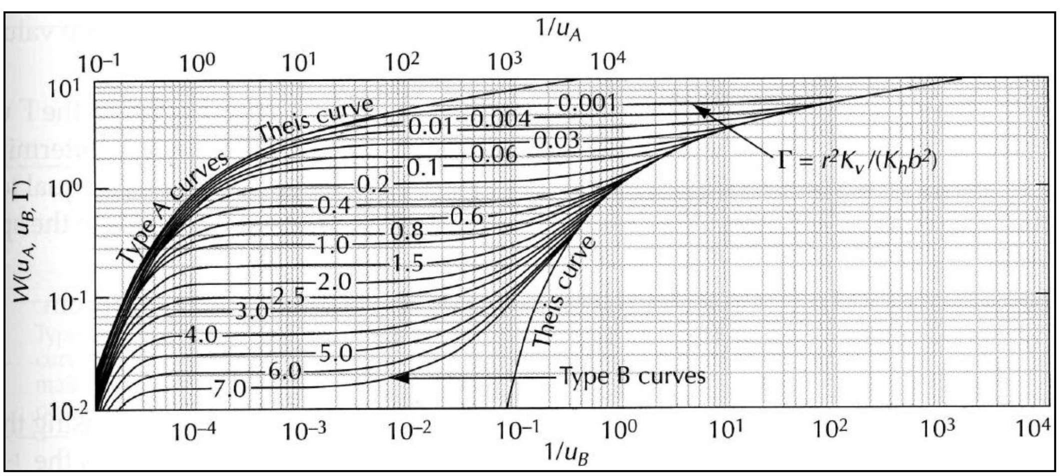


Figure 11. Continuous water level data in the shallow groundwater and surface water at the drive points, DP1-13 and DP2-13, and precipitation data during a large rainfall event on October 7, 2013.

a)



b)



c)

Figure 12. Type curve comparison to actual drawdown measurement of the pumping well; a) measured drawdown for initial and re-started pumping for TW2-13; b) Theis Type Curve example; c) Neuman Type Curve example (Schlumberger Water Services, 2013).

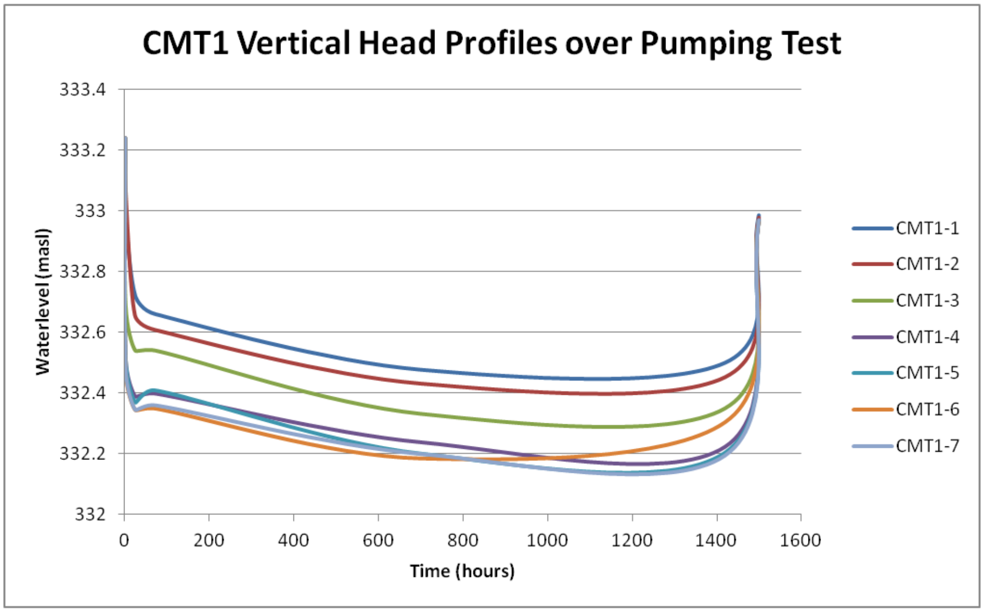


Figure 13. Vertical Head Profile over the duration of the pumping test at CMT1.

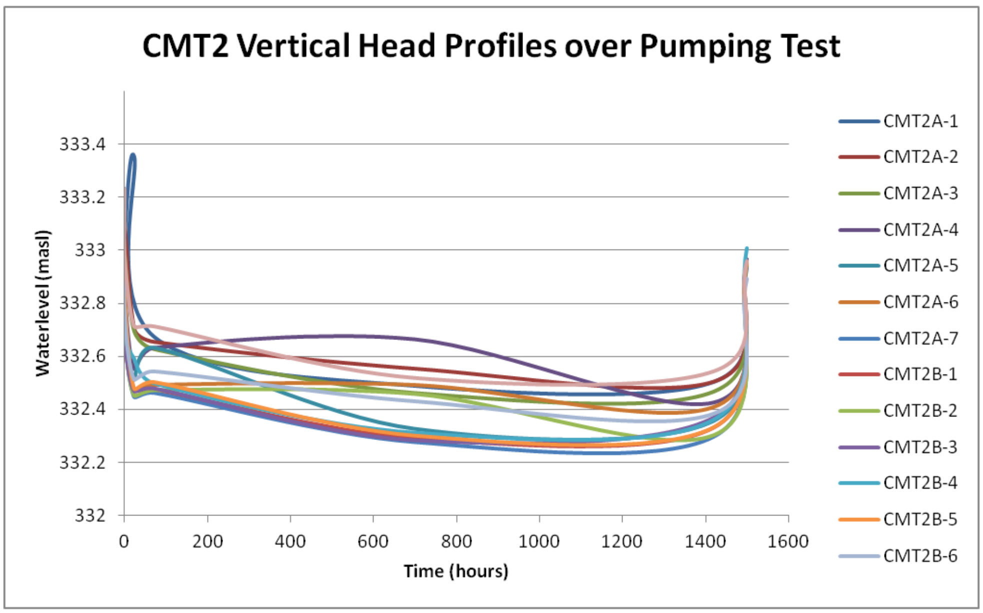


Figure 14. Vertical Head Profile over the duration of the pumping test at CMT2.

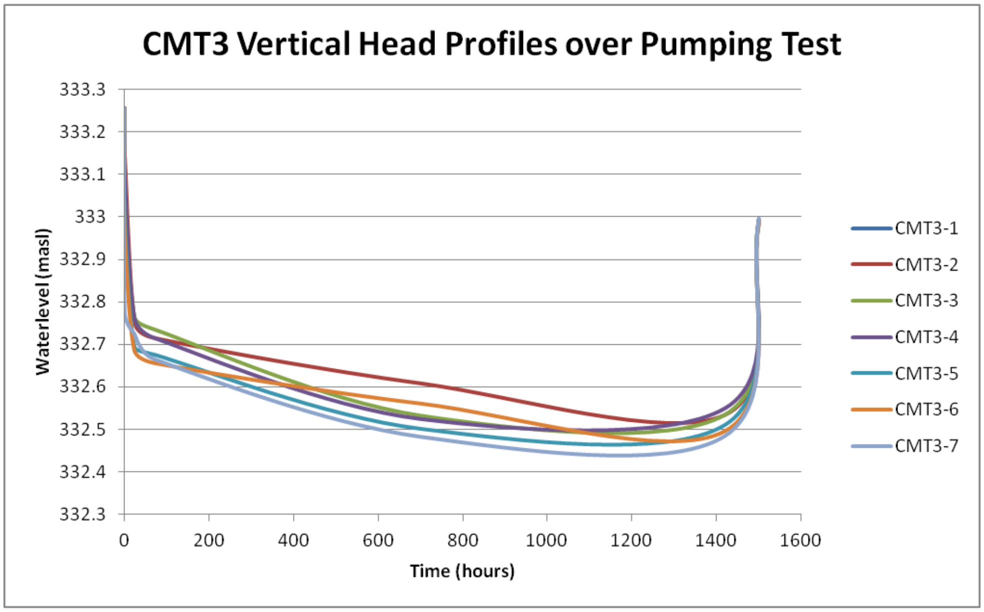


Figure 15. Vertical Head Profile over the duration of the pumping test at CMT3.

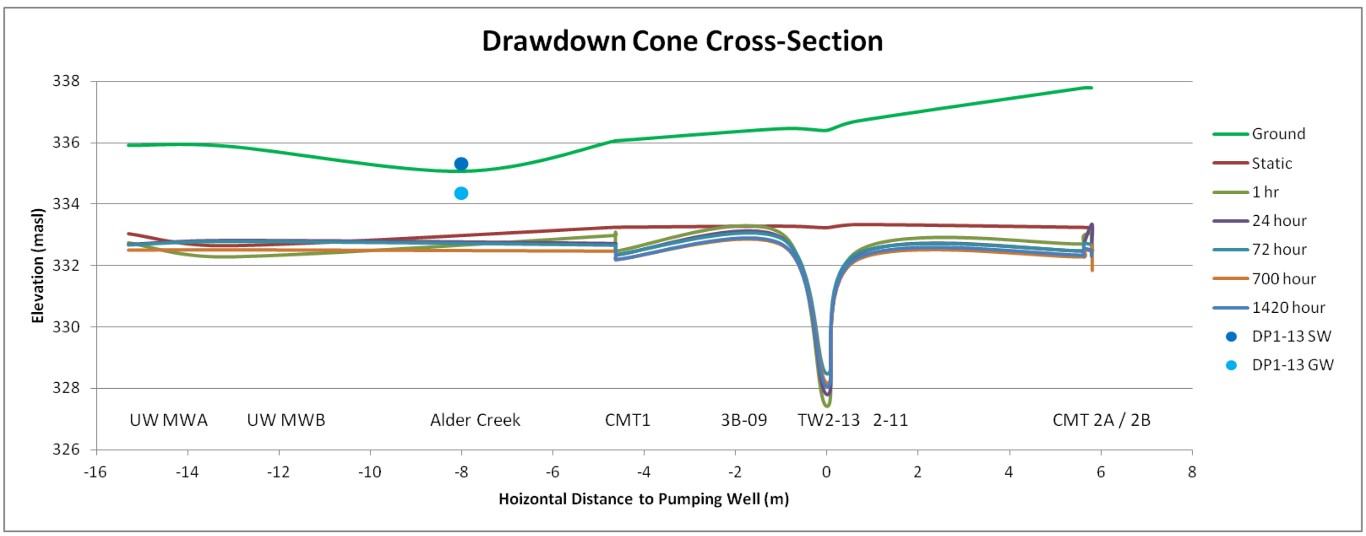


Figure 16. West to east cross-section of the K22A Site, from UW MWA to CMT 2A and CMT2B, depicting the drawdown cone under static conditions, 1 hour, 24 hours, 72 hours, 700 hours, and 1420 hours into the test. Note that wells 3B-09 and 2-11 are projected onto this cross-section line using the angled distance from the production well, causing a slight distortion of the drawdown cone shape in reference to those wells in line with the production well.

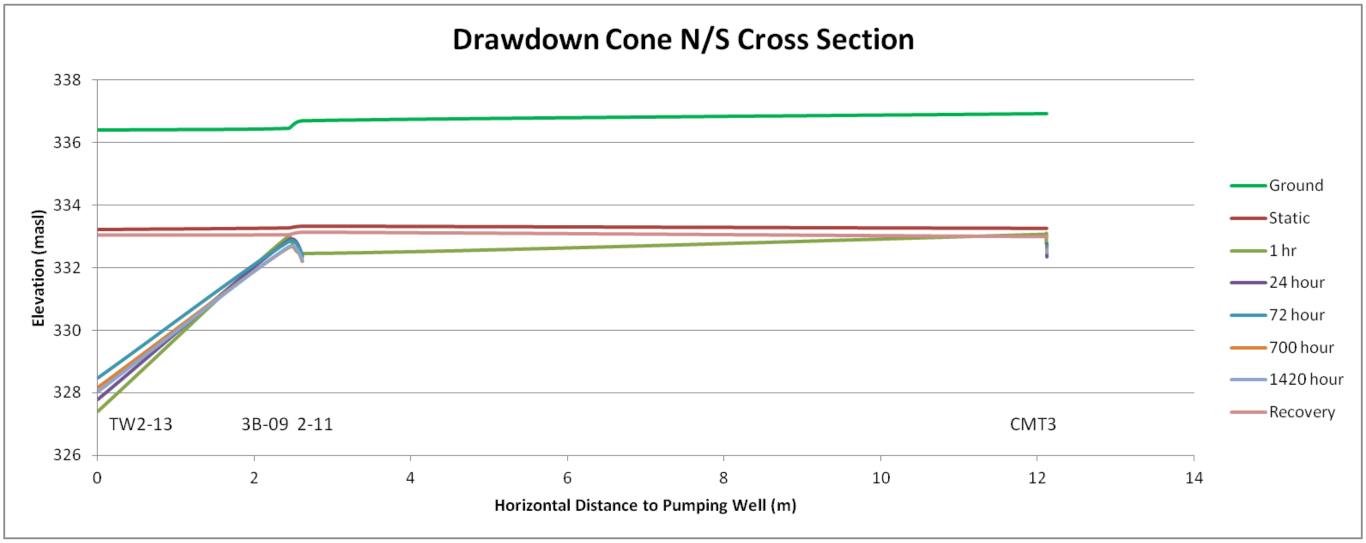


Figure 17. South to north cross-section of the K22A Site, from TW2-13 to CMT3, depicting the drawdown cone under static conditions, 1 hour, 24 hours, 72 hours, 700 hours, and 1420 hours into the test, and after recovery.

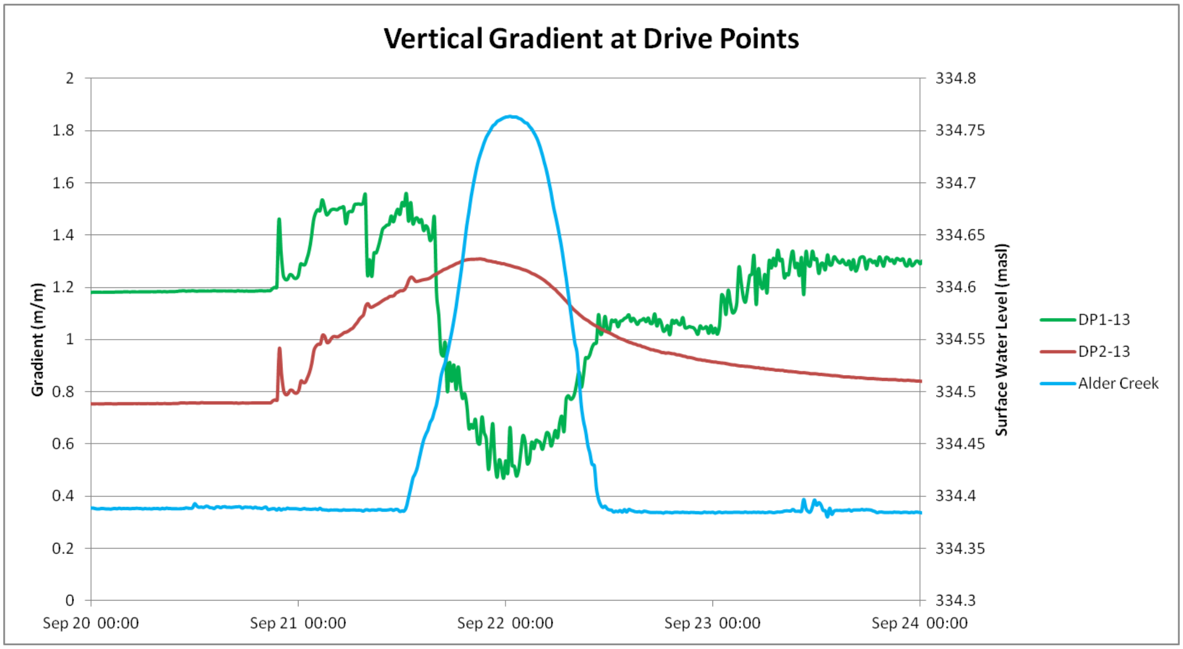


Figure 18. Vertical gradient between shallow groundwater and surface water at drive points, with surface water elevation data during the mid-test shut off period from September 20, 2013 to September 23, 2013. Note: a positive gradient indicates the surface water.

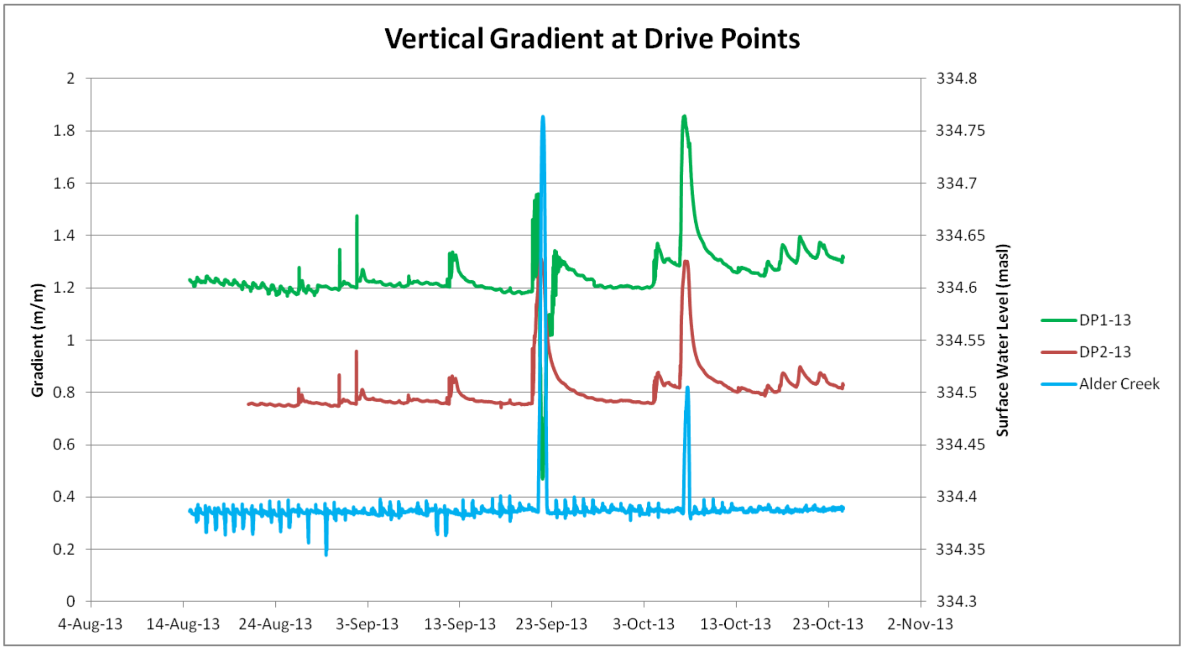


Figure 19. Vertical gradient between shallow groundwater and surface water at drive points, with surface water elevation data over the duration of the 60-day pumping test. Note: a positive gradient indicates the surface water elevation is higher than groundwater.

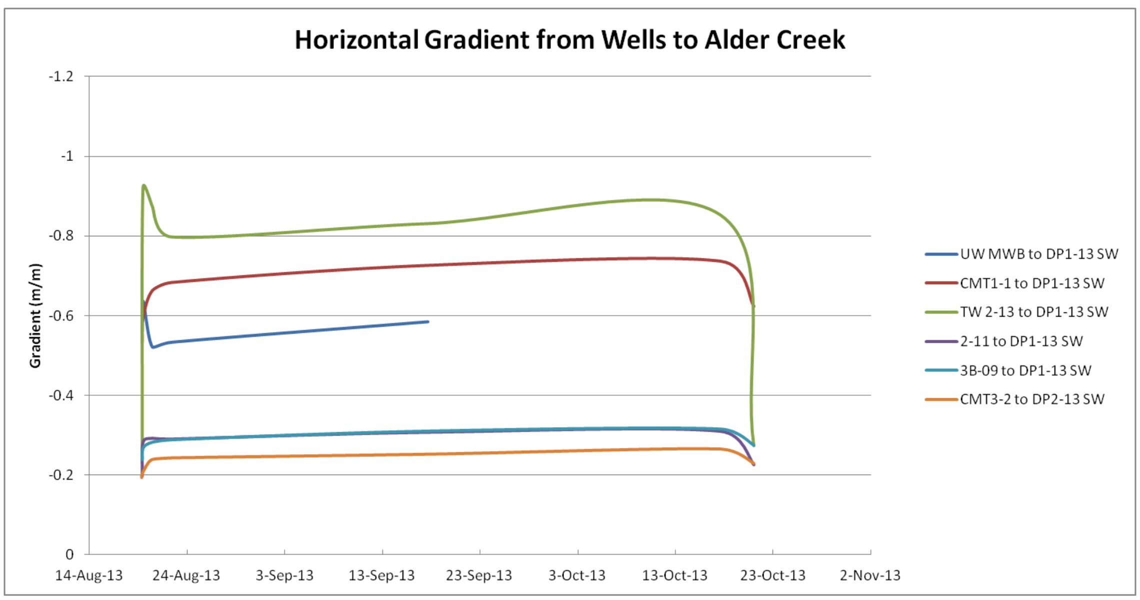


Figure 20. Horizontal gradient between Alder Creek surface water and other wells, including UW MWB, CMT1-1, TW2-13, OW2-11, OW3B-09, and CMT3-2, prior to pumping, 1 hour, 24 hours, 72 hours, 700 hours, and 1420 hours into the test, and after recovery, where a negative gradient indicates preferential flow away from Alder Creek.

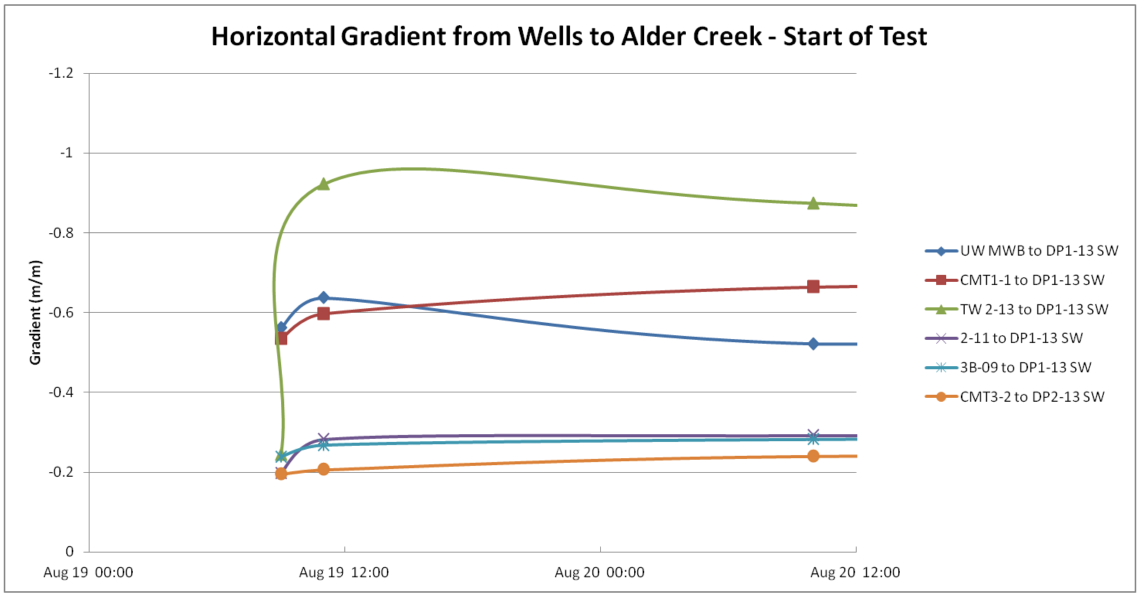


Figure 21. Horizontal gradient between Alder Creek surface water and other wells, including UW MWB, CMT1-1, TW2-13, OW2-11, OW3B-09, and CMT3-2, with values from prior to pumping, 1 hour, and 24 hours into the pumping test, where a negative gradient indicates preferential flow away from Alder Creek.

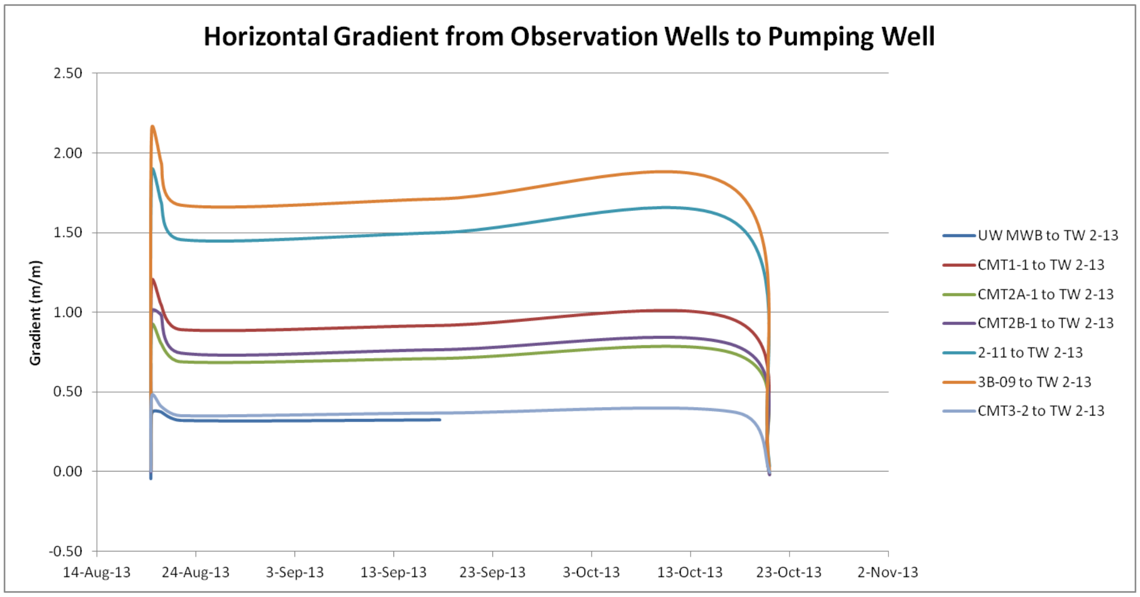


Figure 22. Horizontal gradient between the pumping well, TW2-13, and other wells, including UW MWB, CMT1-1, CMT2A-1, CMT2B-1, OW2-11, OW3B-09, and CMT3-2, prior to pumping, 1 hour, 24 hours, 72 hours, 700 hours, and 1420 hours into the test, and after recovery, where a positive gradient indicates preferential flow toward the pumping well.

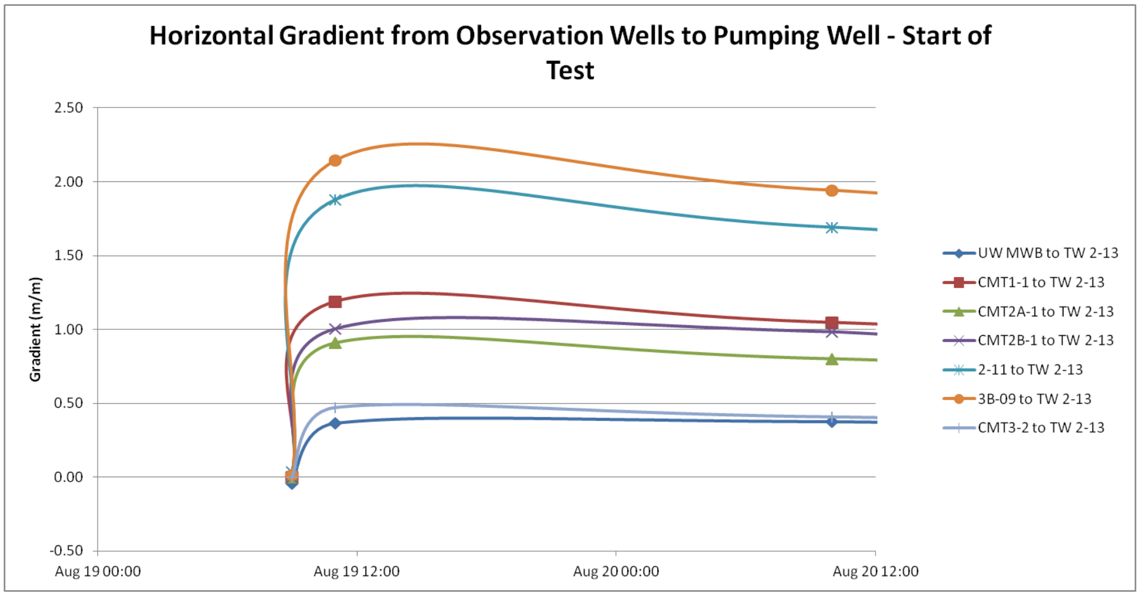


Figure 23. Horizontal gradient between the pumping well, TW2-13, and other wells, including UW MWB, CMT1-1, CMT2A-1, CMT2B-1, OW2-11, OW3B-09, and CMT3-2, with values from prior to pumping, 1 hour, and 24 hours into the pumping test, where a positive gradient indicates preferential flow toward the pumping well.

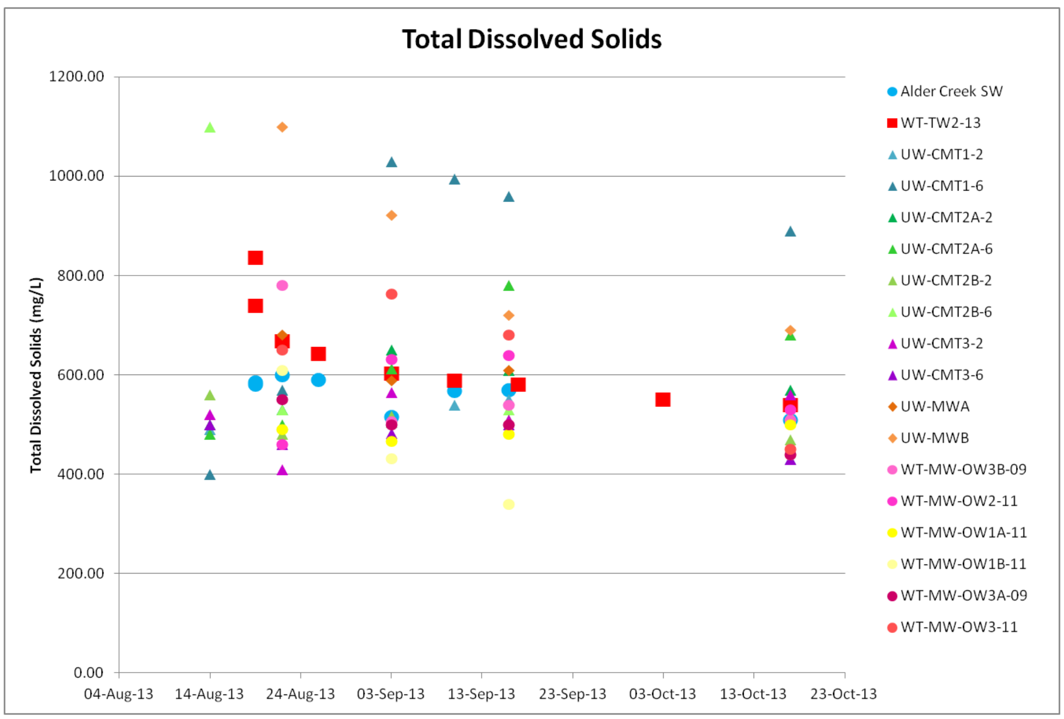


Figure 24. Total Dissolved Solids in ground and surface water samples collected during the pumping test.

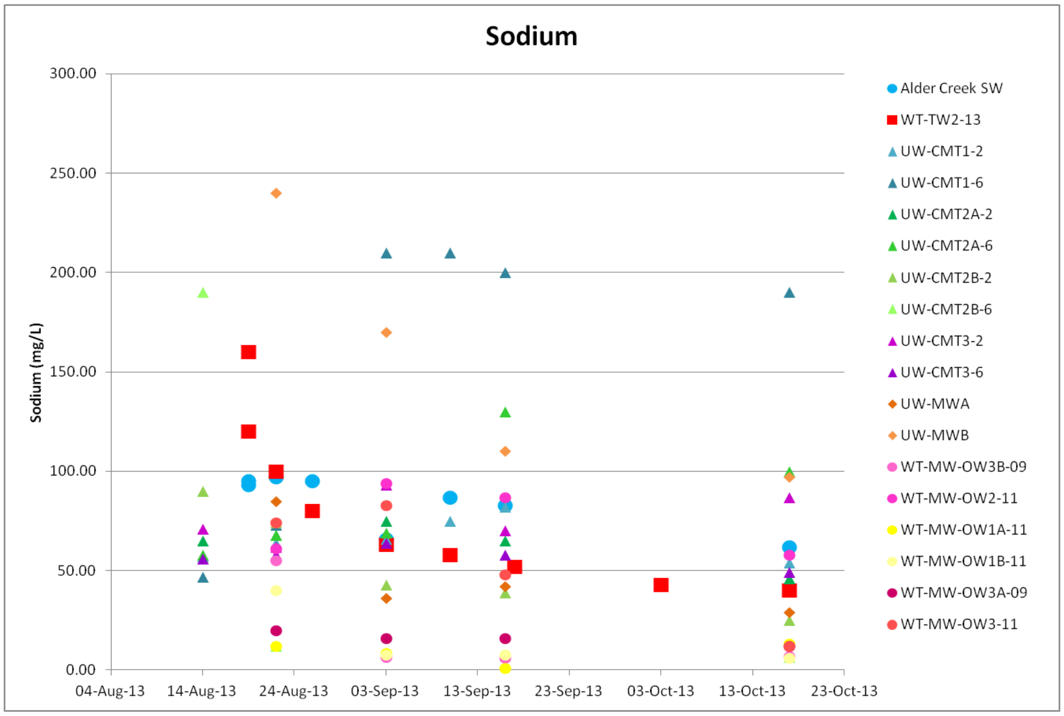


Figure 25. Sodium in ground and surface water samples collected during the pumping test.

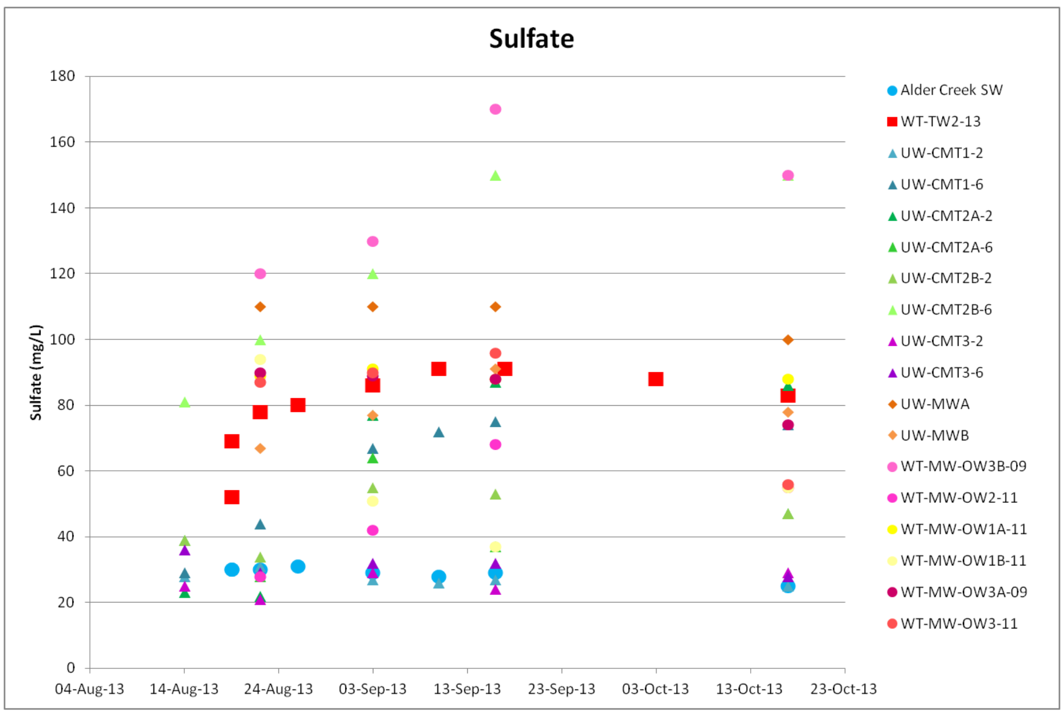


Figure 26. Sulfate in ground and surface water samples collected during the pumping test.

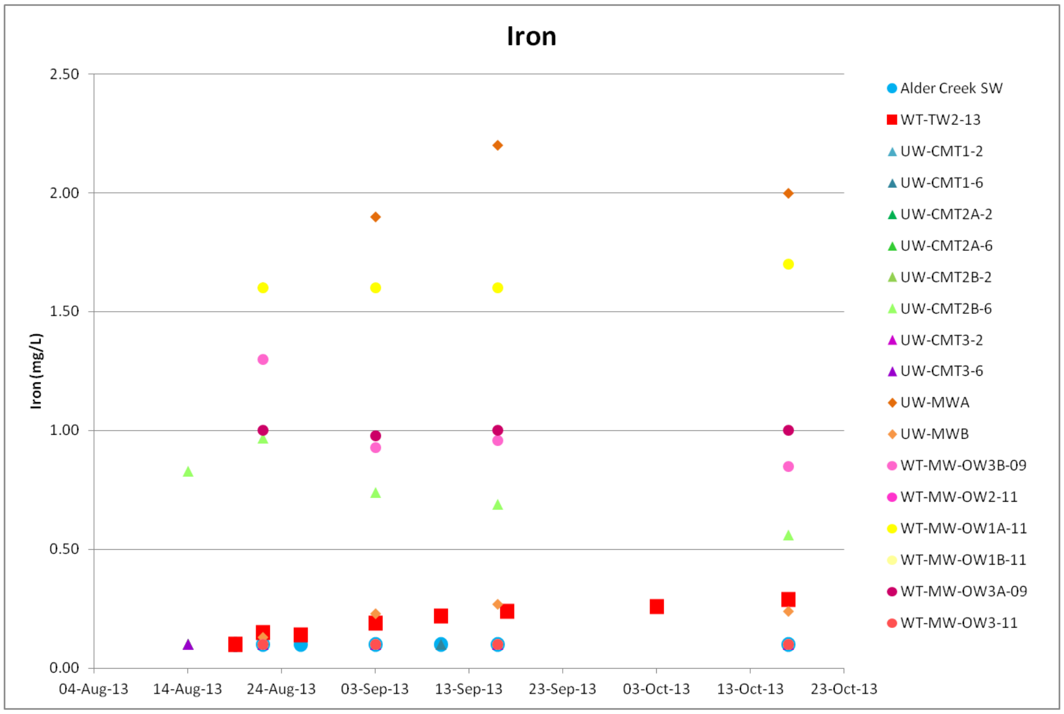


Figure 27. Iron in ground and surface water samples collected during the pumping test.

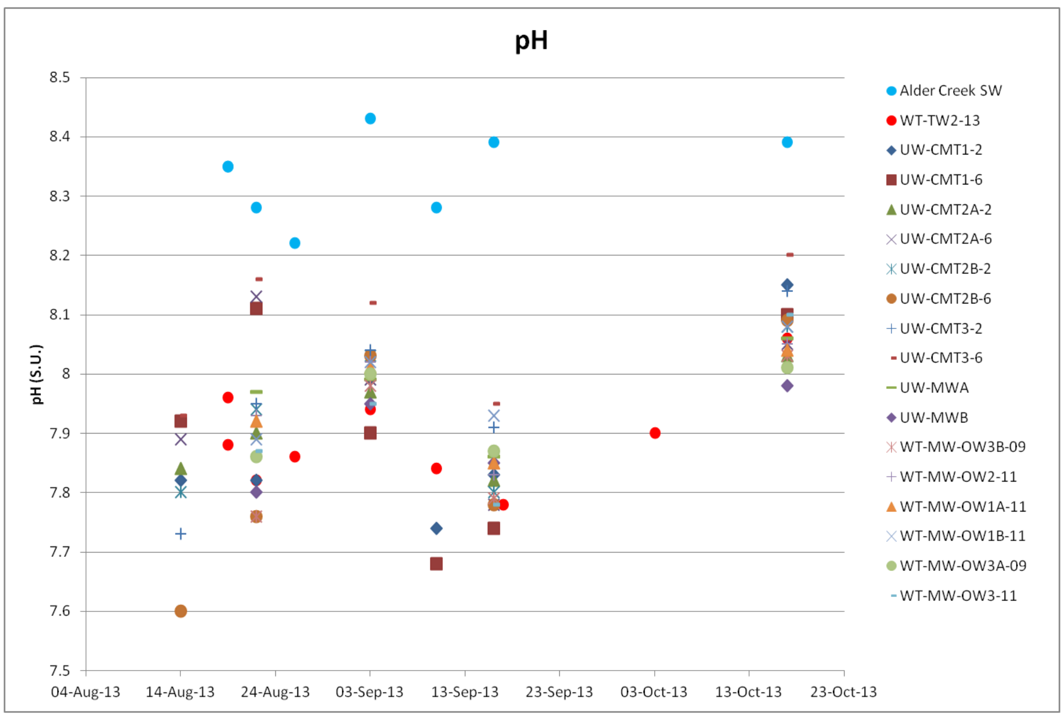


Figure 28. pH in ground and surface water samples collected during the pumping test.

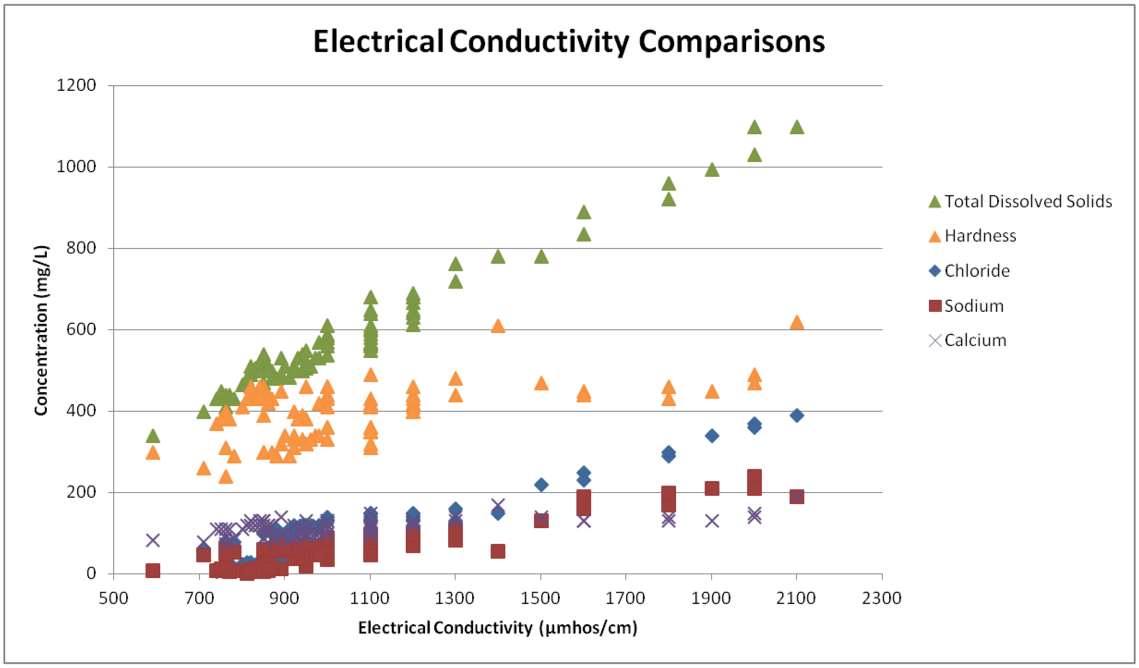


Figure 29. Total dissolved solids, hardness (as CaCO3), chloride, sodium, and calcium plotted as a function of electrical conductivity as a comparison tool.

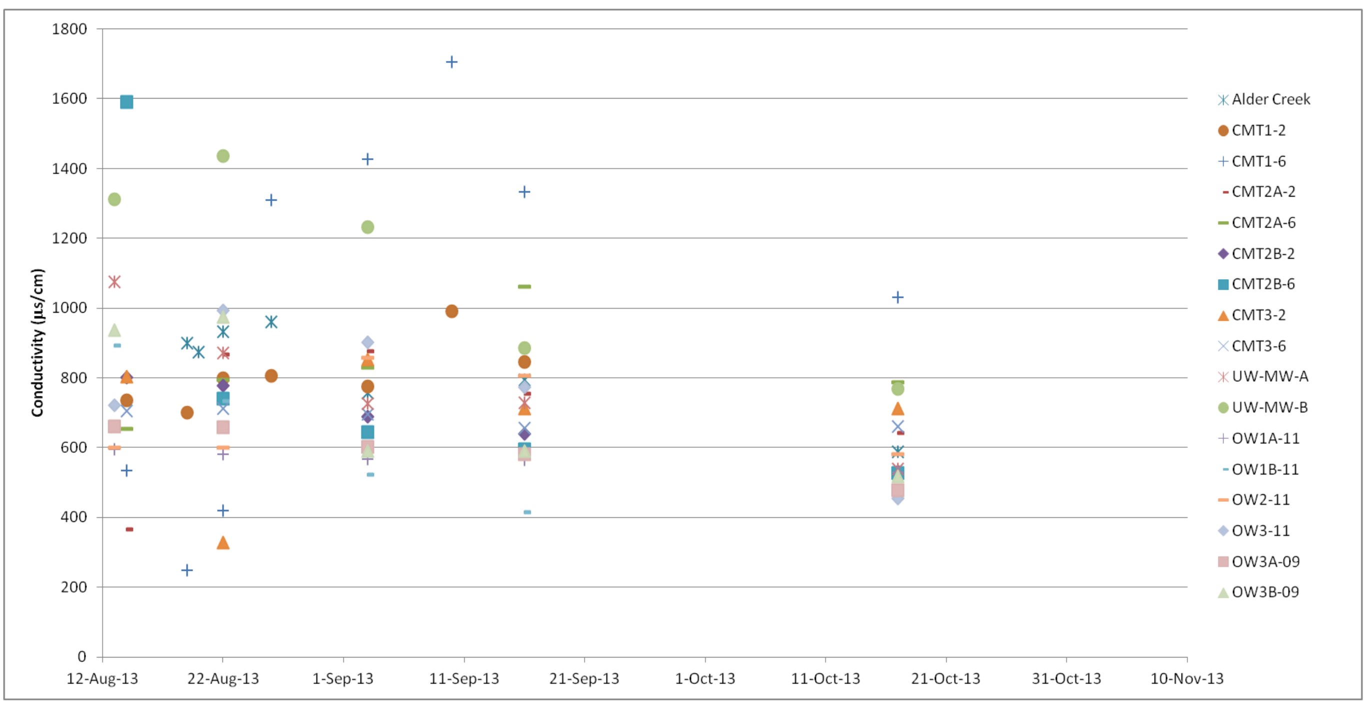


Figure 30. Conductivity measurements taken with the Sonde during sampling events.

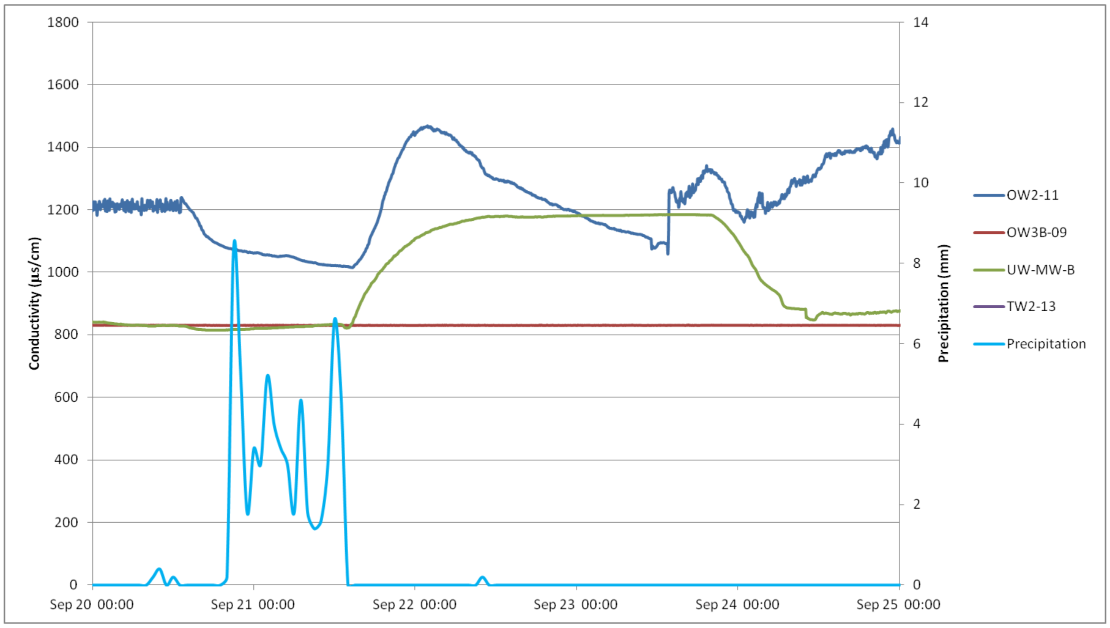


Figure 31. Continuous conductivity in wells OW2-11, OW3B-09, UW MWB, and TW2-13 and precipitation data during the mid-test shut off period, September 20 to September 23, 2013.

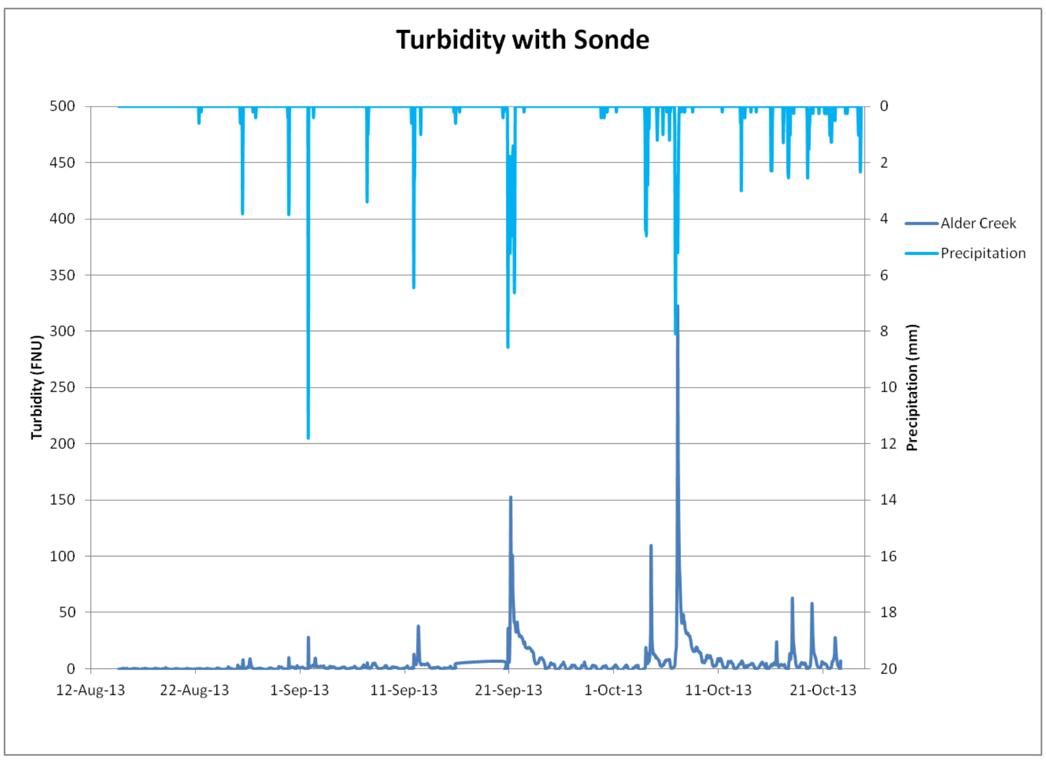


Figure 32. Continuous turbidity measurements from the Sonde in Alder Creek compared to precipitation events.

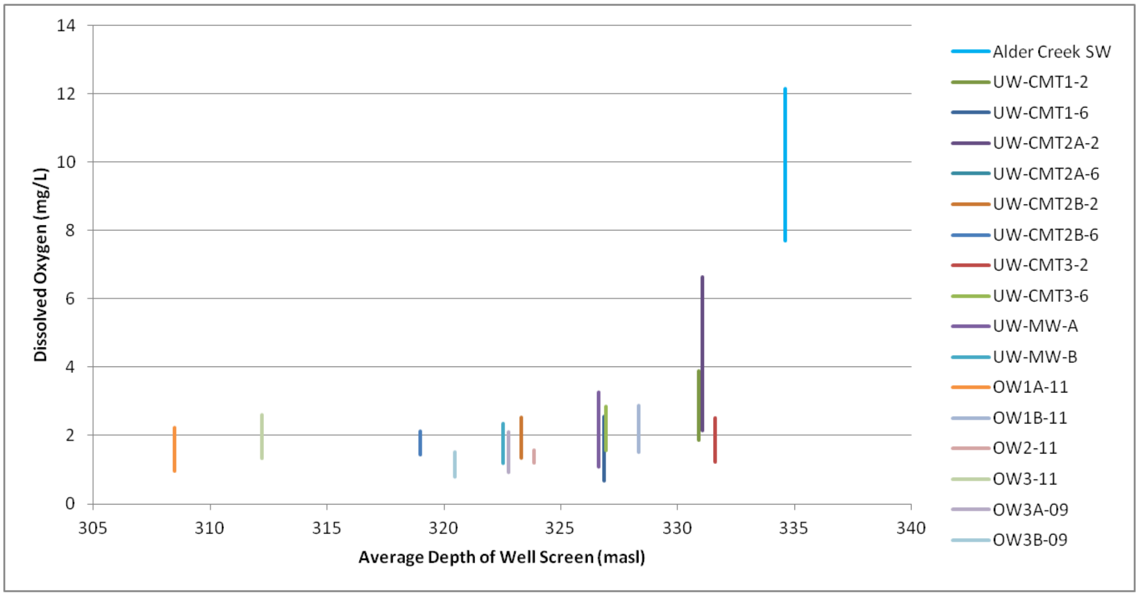


Figure 33. Dissolved oxygen concentrations collected using the Sonde, where each line represents the range of dissolved oxygen measured at a given location over the course of the test, plotted as a function of sample depth.

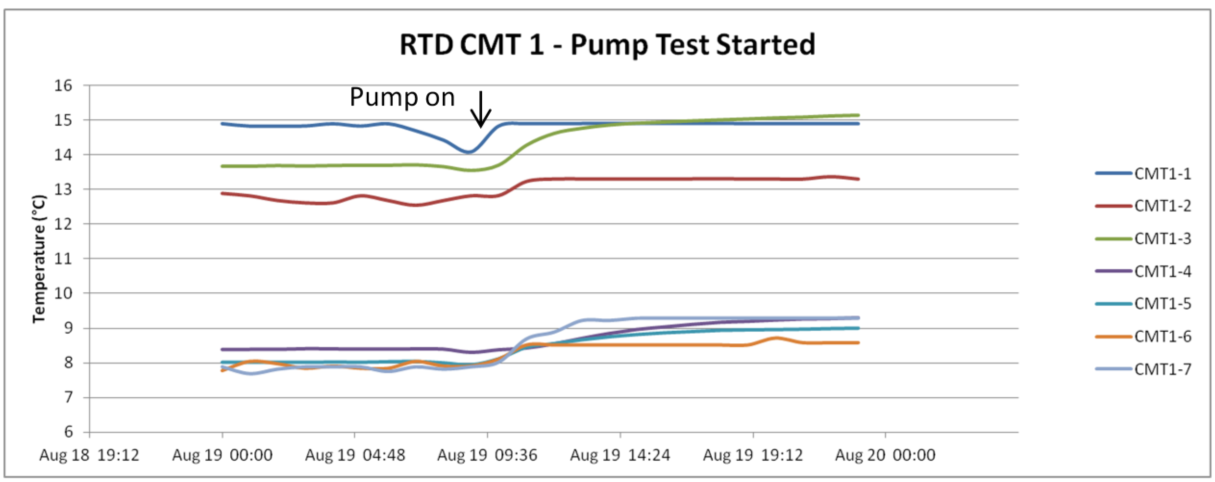


Figure 34. CMT1 temperature data for the start of the pumping test, on August 19, 2013.

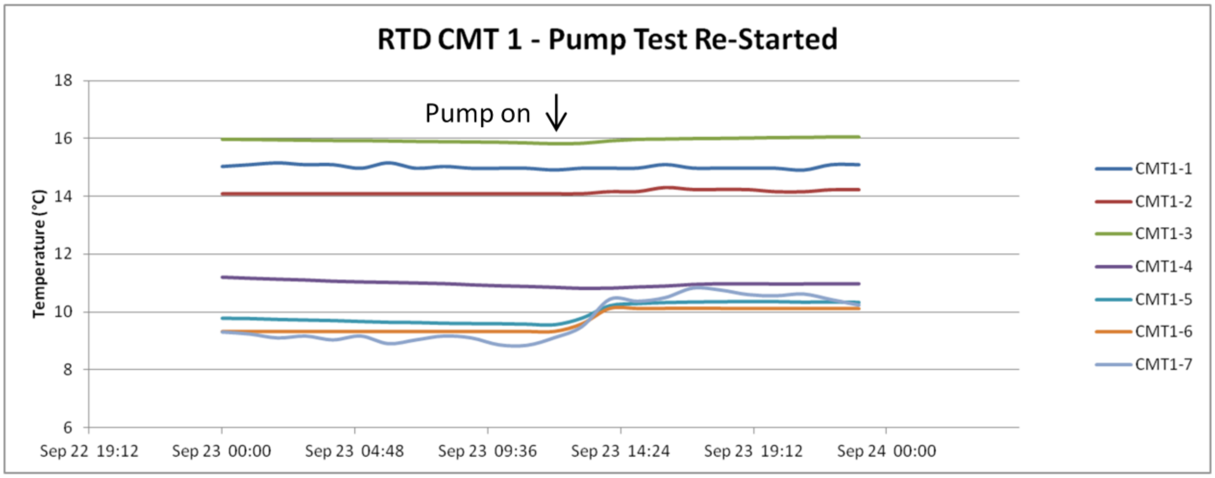


Figure 35. CMT1 temperature data for restarting of the pumping test, on September 23, 2013.

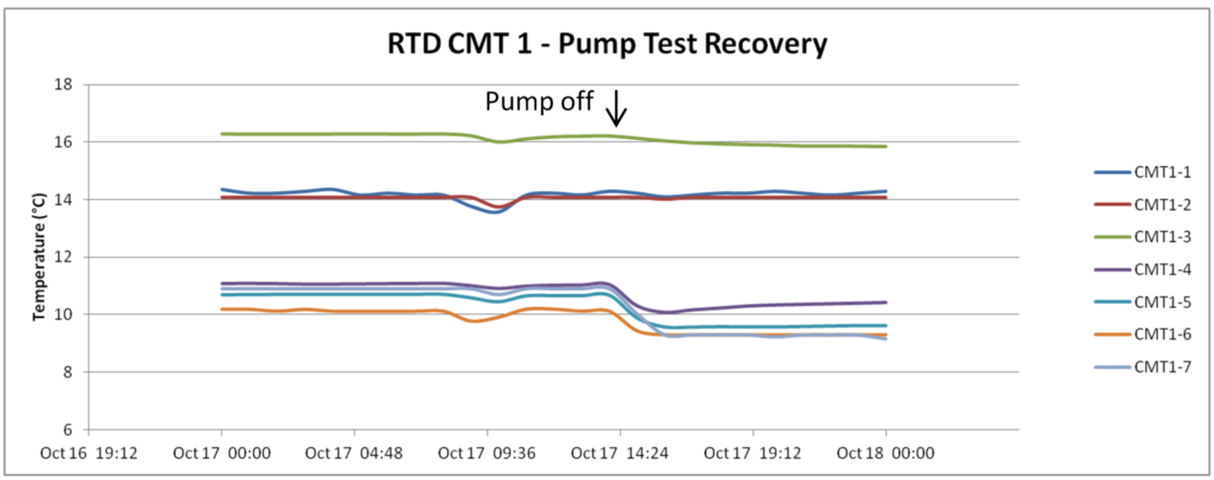


Figure 36. CMT1 temperature data for the end of the pumping test, on October 17, 2013.

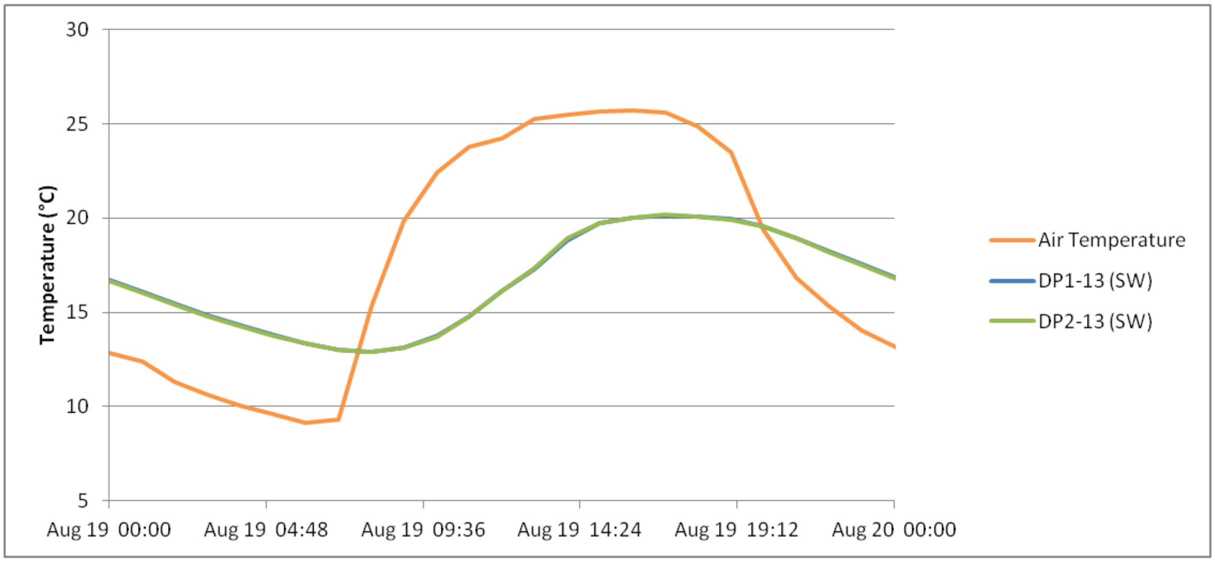


Figure 37. Drive point surface water and air temperature data for the start of the pumping test, on August 19, 2013.

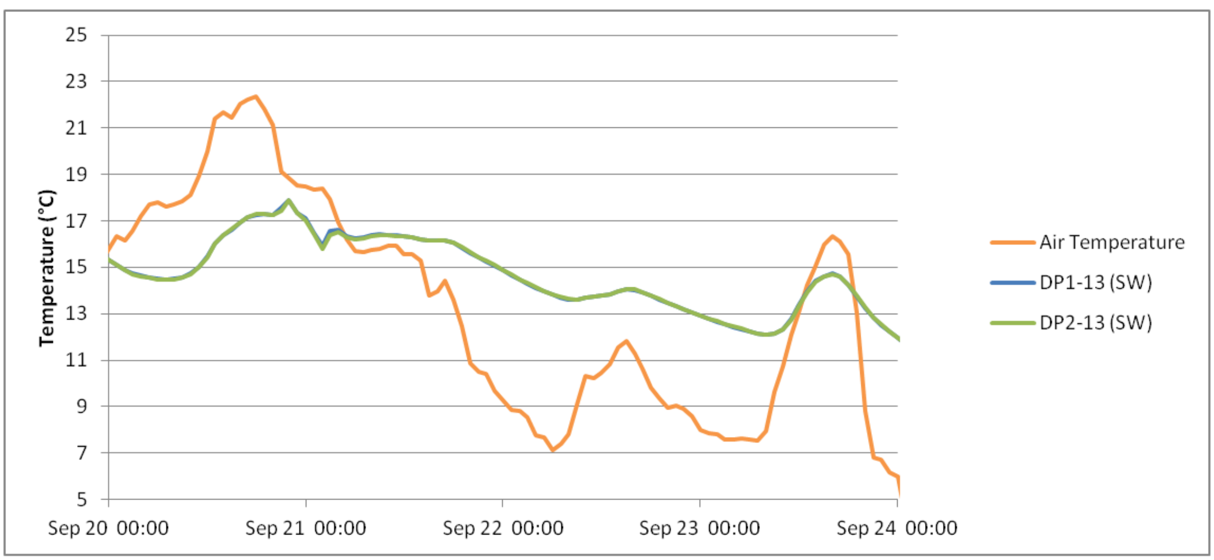


Figure 38. Drive point surface water and air temperature data for mid-test shut off period, from September 20 to 23, 2013.

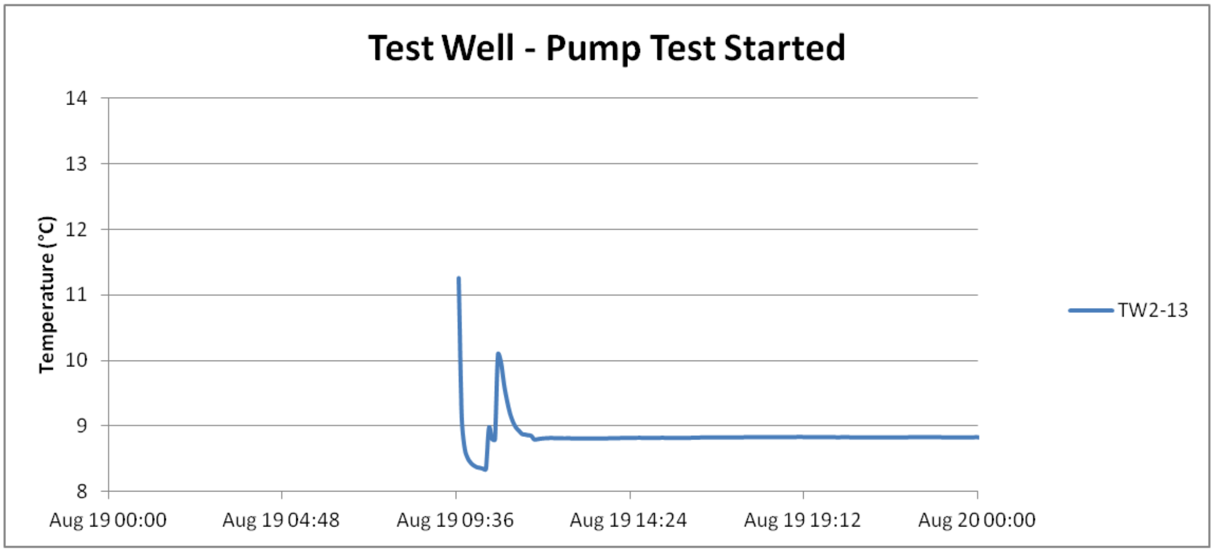


Figure 39. Pumping well TW2-13 temperature data at start of the pumping test, on August 19, 2013.

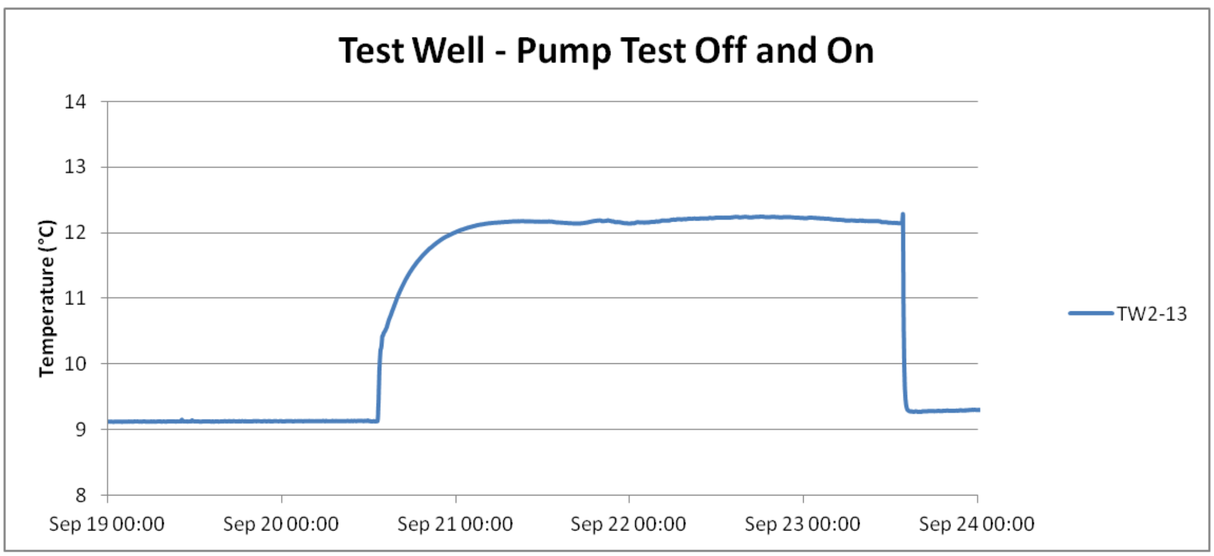


Figure 40. Pumping well TW2-13 temperature data over the mid-test shut off period, from September 20 to 23, 2013.

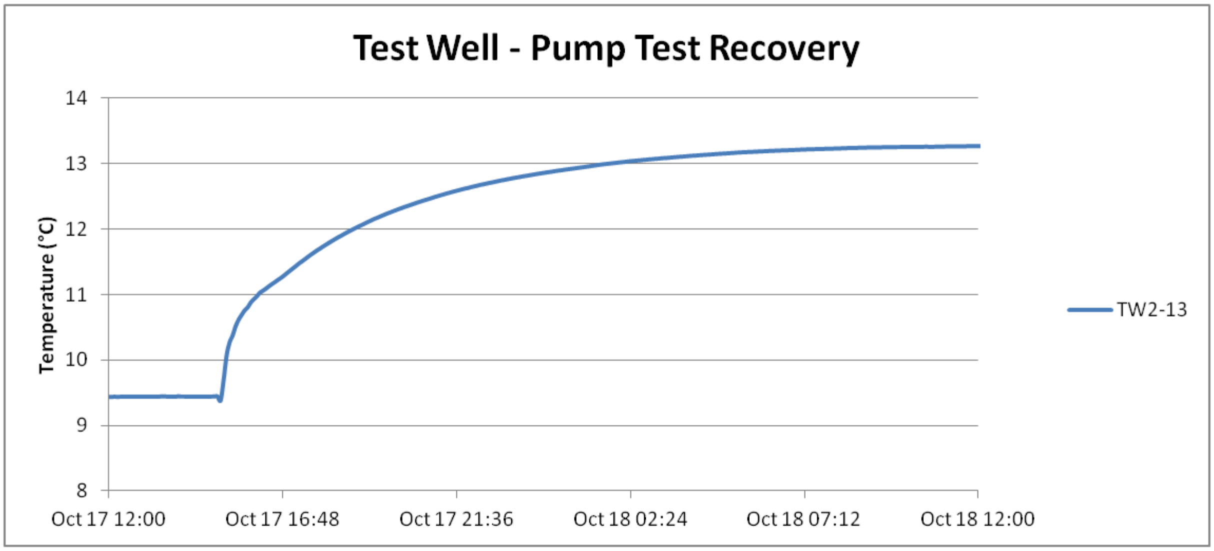


Figure 41. Pumping well TW2-13 temperature data at the end of the pumping test, on October 17, 2013.

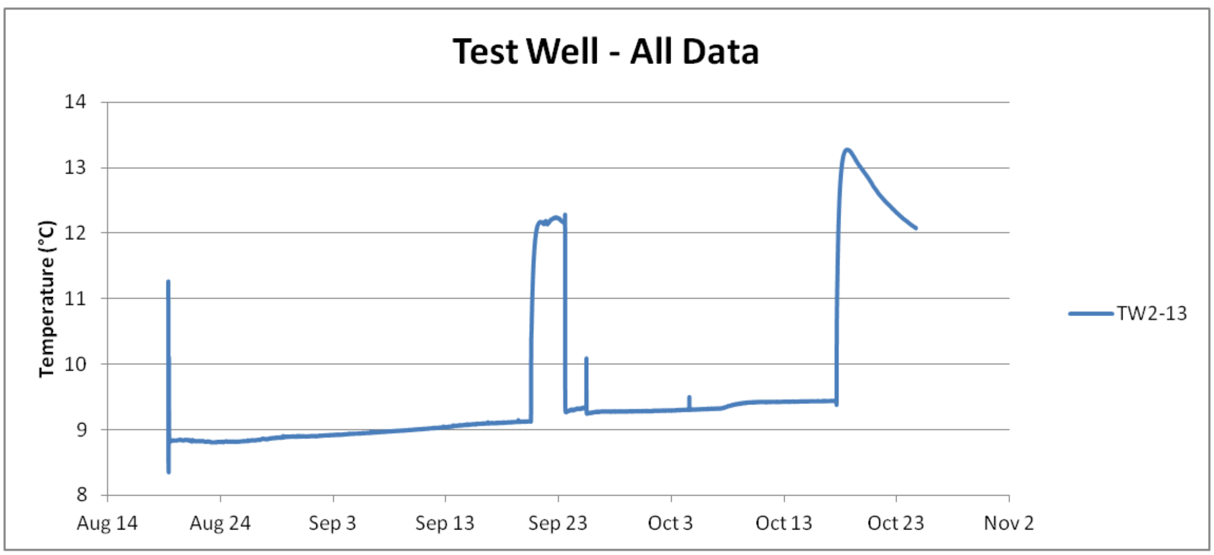


Figure 42. Pumping well TW2-13 temperature data over the duration of the pumping test.

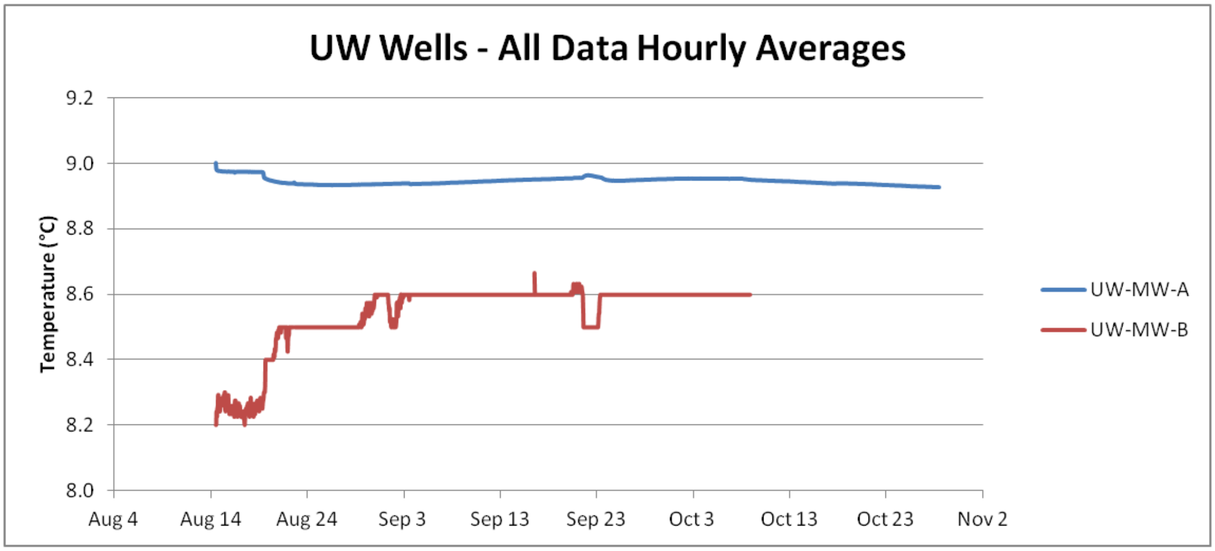


Figure 43. Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, over the duration of the pumping test.

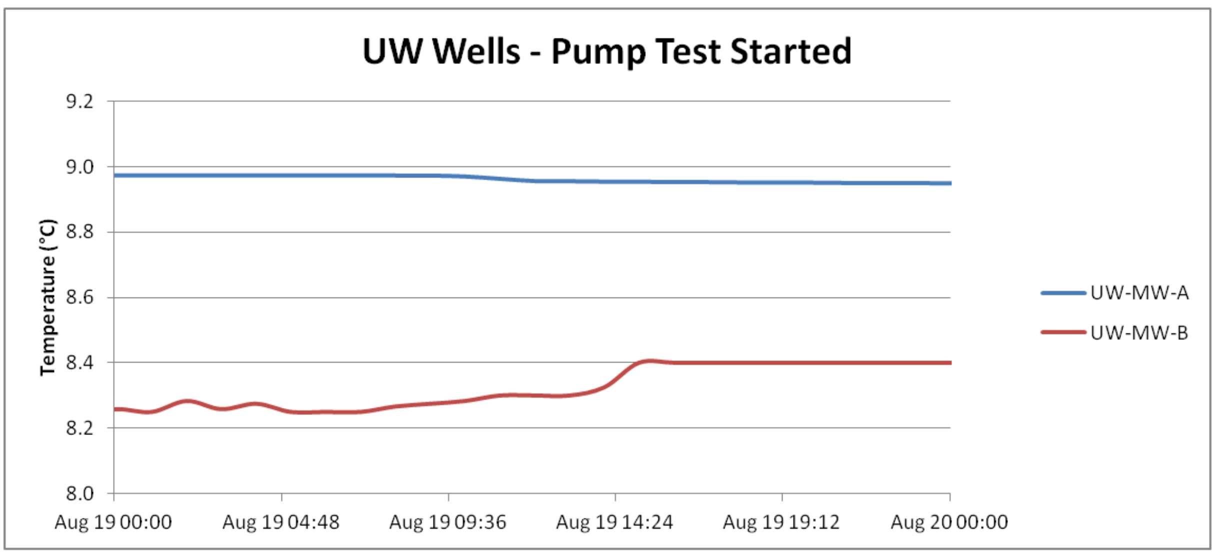


Figure 44. Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, at start of the pumping test, on August 19, 2013.

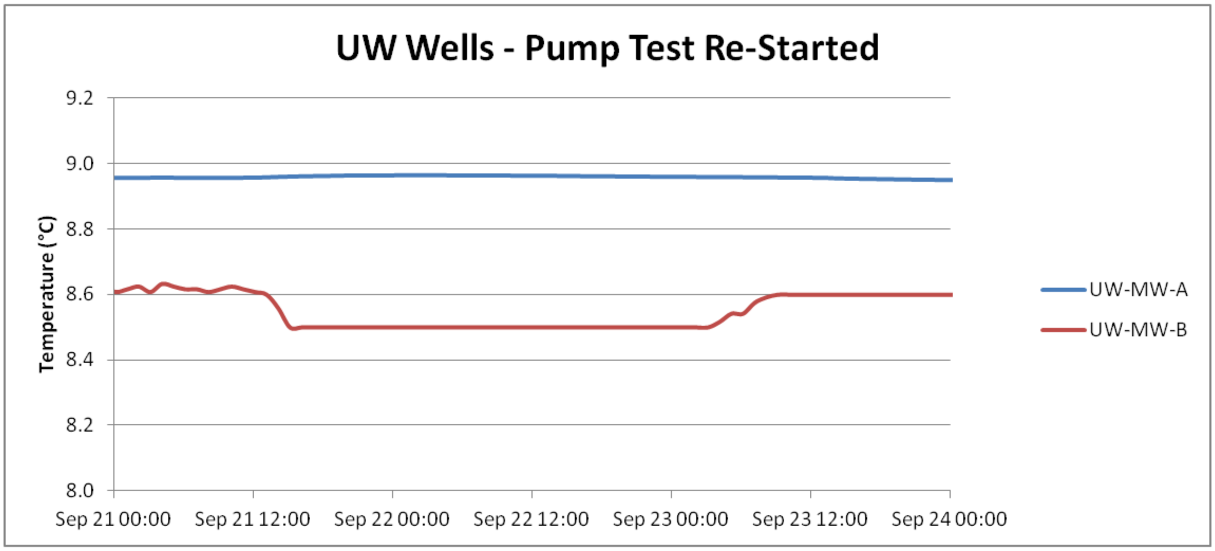


Figure 45. Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, over the mid-test shut off period, from September 20 to 23, 2013.

Table 7. Hydrogeologic parameter estimation Pumping Test Analysis Report generated in AquiferTest for Recovery Theis, Theis, Neuman, Boulton, and Theis with Jacob Correction methods.

Method	Wells	Hydrogeologic Parameters			Average		
		Transmissivity (m^2/s)	**Hydraulic Conductivity (m/s)**	**Storage Coefficient (-)**	**T (m^2/s)**	**K (m/s)**	**S (-)**
Recovery Theis	TW2-13	4.99E-03	1.25E-04	-			
	2-11	2.48E-02	6.20E-04	-			
	3B-09	2.90E-02	7.24E-04	-			
	CMT2A-4	1.55E-02	3.87E-04	-			
	CMT2B-4	1.74E-02	4.35E-04	-	1.83E-02	4.58E-04	-
Theis	TW2-13	1.45E-03	3.63E-05	5.73E-01			
	2-11	2.51E-02	6.27E-04	1.00E-07			
	3B-09	1.21E-02	3.02E-04	8.76E-02			
	CMT2A-4	1.97E-02	4.93E-04	1.70E-02			
	CMT2B-4	1.00E-03	2.50E-05	1.00E-04	1.19E-02	2.97E-04	1.36E-01
Neuman	TW2-13	1.69E-02	4.22E-04	2.99E-07			
	2-11	1.68E-02	4.20E-04	2.02E-01			
	3B-09	1.03E-02	2.57E-04	5.00E-01			
	CMT2A-4	1.00E-03	2.50E-05	1.00E-04			
	CMT2B-4	1.00E-03	2.50E-05	1.00E-04	9.20E-03	2.30E-04	1.40E-01
Boulton	TW2-13	1.17E-02	2.93E-04	9.90E-01			
	2-11	2.10E-02	5.25E-04	4.31E-03			
	3B-09	1.07E-02	2.67E-04	7.61E-01			
	CMT2A-4	1.61E-02	4.03E-04	2.33E-02			
	CMT2B-4	1.00E-03	2.50E-05	1.00E-04	1.21E-02	3.03E-04	3.56E-01
Theis with Jacob Correction	TW2-13	2.05E-02	5.12E-04	1.12E-01			
	2-11	8.91E-03	2.23E-04	1.00E-07			
	3B-09	1.67E-02	4.16E-04	3.51E-01			
	CMT2A-4	1.00E-03	2.50E-05	1.00E-04			
	CMT2B-4	2.20E-02	5.50E-04	1.00E-04	1.38E-02	3.45E-04	9.26E-02
				Overall Average	1.31E-02	3.26E-04	1.81E-01

Table 8. Horizontal gradient between surface water, pumping well, and observation wells data points over the test duration, where positive gradient values indicate that the Second Location water level is higher than the First Location water level.

		Gradient (-)						
First Location	**Second Location**	**Static**	**1 hr**	**24 hour**	**72 hour**	**700 hour**	**1420 hour**	**1500 hour**
UW MWB	DP1-13 SW	-0.56	-0.64	-0.52	-0.53	-0.58	-	-
CMT1-1	DP1-13 SW	-0.53	-0.60	-0.66	-0.68	-0.73	-0.74	-0.62
TW 2-13	DP1-13 SW	-0.24	-0.92	-0.87	-0.80	-0.83	-0.85	-0.27
2-11	DP1-13 SW	-0.20	-0.28	-0.29	-0.29	-0.31	-0.31	-0.23
3B-09	DP1-13 SW	-0.24	-0.27	-0.28	-0.29	-0.31	-0.32	-0.27
CMT3-2	DP2-13 SW	-0.19	-0.21	-0.24	-0.24	-0.25	-0.27	-0.23
UW MWB	TW 2-13	-0.04	0.37	0.38	0.32	0.33	-	-
CMT1-1	TW 2-13	0.00	1.19	1.05	0.89	0.92	0.95	-0.01
CMT2A-1	TW 2-13	0.00	0.91	0.80	0.69	0.71	0.74	-0.02
CMT2B-1	TW 2-13	0.00	1.00	0.98	0.74	0.77	0.79	-0.02
2-11	TW 2-13	0.04	1.88	1.69	1.46	1.50	1.56	0.03
3B-09	TW 2-13	0.02	2.15	1.94	1.67	1.71	1.77	0.00
CMT3-2	TW 2-13	0.00	0.47	0.41	0.35	0.37	0.37	-0.01

Table 9. Mean shallow, intermediate, and deep groundwater quality at early time, prior to the pumping test, and at late time, the last day of the test prior to the stopping of the pump.

Early time

	Anion Sum	Cation Sum	Chloride	Dissolved Organic Carbon	Electrical Conductivity	Hardness (as CaCO3)	Sulfate	Total Dissolved Solids	Calcium	Iron	Magnesium	Manganese	Silicon	Sodium	Strontium
	meq/L	meq/L	mg/L	mg/L	µmhos/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Shallow	10.2	10.3	122.0	2.9	1016.0	352.0	43.2	554.0	102.8	0.40	22.4	0.02	4.5	74.2	0.25
Inter-mediate	10.6	10.9	133.2	2.5	1058.3	356.7	48.8	591.7	105.3	0.11	23.2	0.06	3.9	83.7	0.24
Deep	12.6	12.8	147.2	1.7	1245.0	476.7	84.3	688.3	137.3	0.82	33.5	0.14	5.6	73.5	0.39
TW2-13	14.6	15.9	250.0	2.2	1600.0	450.0	52.0	836.0	130.0	0.10	27.0	0.10	4.8	160.0	0.29

Late Time

	Anion Sum	Cation Sum	Chloride	Dissolved Organic Carbon	Electrical Conductivity	Hardness (as CaCO3)	Sulfate	Total Dissolved Solids	Calcium	Iron	Magnesium	Manganese	Silicon	Sodium	Strontium
	meq/L	meq/L	mg/L	mg/L	µmhos/cm	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Shallow	9.3	9.8	83.6	3.1	904.0	366.0	53.0	516.0	103.0	0.48	24.6	0.02	5.1	55.6	0.25
Inter-mediate	10.8	11.7	114.5	2.3	1076.7	400.0	56.2	610.0	116.8	0.12	25.3	0.05	4.6	83.4	0.26
Deep	8.6	9.0	28.3	1.6	813.3	420.0	94.2	481.7	120.0	0.72	30.8	0.11	5.7	12.6	0.35
TW2-13	9.9	9.7	69.0	1.7	940.0	390.0	83.0	540.0	110.0	0.29	27.0	0.07	5.2	40.0	0.33
	Mixing	Mixing	Mixing	Mixing	Mixing	Diluted by shallow	Mixing/ deep	Mixing	Diluted by shallow	Mixing/ deep	Mixing/ deep	Mixing/deep	Mixing	Mixing	Mixing/ deep

Shallow: surface water and wells CMT1-2, CMT2A-2, CMT3-2, and UW MWA screened above the silt layer

Intermediate: wells OW2-11, OW1B-11, CMT1-6, CMT2A-6, CMT3-6 and UW MWB, screened below the silt layer and above 323 masl

Deep: wells OW1A-11, OW3B-09, OW3-11, OW3A-09, CMT2B-2, and CMT2B-6, screened below 323 masl

Table 10. Summary of Trends observed from General Chemistry and Metals Sampling

Water Quality Concentrations Converge over the Pumping Test	**Water Quality Concentrations Decrease over the Pumping Test**	**Water Quality Concentrations in the Pumping Well Increase over the Pumping Test**	**No Trend**
Alkalinity	Ammonia	Sulfate	Dissolved Organic Carbon
Anion Sum	Chloride	Iron	Nitrate
Cation Sum	Electrical Conductivity		Aluminum
Hardness	Total Dissolved Solids		Barium
Calcium	Copper		Boron
Magnesium	Molybdenum		Manganese
Potassium	Sodium		Strontium
Silicon			Uranium
			Zinc

Table 11. Correlation coefficient and covariance calculations for continuous data measured during the 60-day pumping test, with matching time intervals.

Correlation Coefficient	**Waterlevel and Temperature**	**Waterlevel and Conductivity**	**Waterlevel and Turbidity**	**Temperature and Conductivity**	**Temperature and Turbidity**	**Conductivity and Turbidity**
DP1-13 GW	-0.01					
DP1-13 SW	-0.25		0.55		-0.06	
DP2-13 GW	-0.33					
DP2-13 SW	-0.19					
Climate Data						
TW2-13	0.94	-0.42	0.57	-0.63	0.34	-0.76
2-11	0.13	-0.35		-0.22		
3B-09	-0.01	0.51		0.31		
UW MWA	0.65					
UW MWB	-0.37	0.47		-0.74		
CMT1-1						
CMT1-2						
CMT1-3						
CMT1-4						
CMT1-5						
CMT1-6						
CMT1-7						
CMT2A-1						
CMT2A-3						
CMT2A-4						
CMT2A-5						
CMT2A-7						
CMT2B-1						
CMT2B-3						
CMT2B-4						
CMT2B-5						
CMT2B-7						
CMT3-1						
CMT3-3						
CMT3-5						
CMT3-7						

Table 11. (Continued)

Correlation Coefficient	Air and Water Temperature	Precipitation and Waterlevel	Precipitation and Temperature	Precipitation and Conductivity	Precipitation and Turbidity
DP1-13 GW	0.50	-0.01			
DP1-13 SW	0.67	0.19			
DP2-13 GW	0.46	0.03			
DP2-13 SW	0.67	0.19			
Climate Data			0.04		
TW2-13	-0.34	0.17	0.16	-0.03	0.06
2-11	-0.40	0.06	0.09	-0.04	
3B-09	0.42	0.01	-0.06	-0.06	
UW MWA	-0.25	0.02	0.04		
UW MWB	-0.13	-0.02	0.09	-0.10	
CMT1-1	0.29		0.02		
CMT1-2	-0.01		0.03		
CMT1-3	-0.14		0.01		
CMT1-4	-0.42		-0.02		
CMT1-5	-0.32		-0.05		
CMT1-6	-0.24		-0.05		
CMT1-7	-0.05		-0.06		
CMT2A-1	-0.30		-0.01		
CMT2A-3	-0.39		0.04		
CMT2A-4		0.09			
CMT2A-5	-0.51		0.08		
CMT2A-7	-0.49		0.08		
CMT2B-1	-0.44		0.07		
CMT2B-3	0.23		0.01		
CMT2B-4		0.09			
CMT2B-5	0.40		-0.05		
CMT2B-7	0.35		-0.05		
CMT3-1	-0.10		-0.11		
CMT3-3	-0.22		-0.11		
CMT3-5	-0.08		-0.08		
CMT3-7	-0.10		0.01		

Table 11. (Continued)

Covariance	Air and Water Temperature
DP1-13 GW	9.01
DP1-13 SW	15.70
DP2-13 GW	6.73
DP2-13 SW	15.61
Climate Data	
TW2-13	-2.39
2-11	-1.07
3B-09	0.46
UW MWA	-0.02
UW MWB	-15.45
CMT1-1	1.02
CMT1-2	-0.05
CMT1-3	-0.54
CMT1-4	-2.05
CMT1-5	-1.43
CMT1-6	-0.91
CMT1-7	-0.27
CMT2A-1	-1.85
CMT2A-3	-2.36
CMT2A-4	
CMT2A-5	-5.60
CMT2A-7	-4.27
CMT2B-1	-2.24
CMT2B-3	0.59
CMT2B-4	
CMT2B-5	1.03
CMT2B-7	0.86
CMT3-1	-0.54
CMT3-3	-1.90
CMT3-5	-0.43
CMT3-7	-0.16

Table 12. Correlation coefficients for point-measured water quality data collected during sampling events throughout the pumping test.

Comparisons	Correlation Coefficient
Turbidity and DO	-0.089
DO and $\delta^{18}O$	0.216
$\delta^{18}O$ and $\delta^{2}H$	0.979
DO and pH	0.565
Anion and Cation	0.989
Anion and Conductivity	0.988
Cation and Conductivity	0.983
DO and DOC	0.536
TDS and Conductivity	0.983
TDS and DOC	-0.038
Chloride and DO	0.067
Chloride and DOC	0.261
Chloride and TDS	0.887
Chloride and Conductivity	0.942
Conductivity and Sodium	0.915
DO and Mg	-0.267
DO and Fe	-0.251
Ba and Ca	0.308
Ba and Mn	0.259
Ba and K	0.001
Ba and Na	0.062
Ba and U	0.112
Ba and Zinc	0.001
Ca and Mn	0.636
Ca and K	-0.140
Ca and Na	0.304
Ca and U	0.402
Ca and Zn	-0.140
Mn and K	-0.277
Mn and Na	-0.076
Mn and U	0.358
Mn and Zn	-0.277
K and Na	0.406
K and U	0.488
K and Zn	0.454
Na and U	0.341
Na and Zn	0.161
U and Zn	0.005
Cu and Si	-0.680

Table 12. (Continued)

Comparisons	Correlation Coefficient
Al and Bo	0.174
Al and Fe	-0.075
Al and St	-0.143
Bo and Fe	-0.069
Bo and St	0.068
Fe and St	0.781
Mg and Mo	-0.513
Na and Chloride	0.975
Mg and Fe	0.649
Mn and pH	-0.271
Fe and pH	-0.135
Mn and DO	-0.267
Fe and DO	-0.251
Mn and Hardness	0.69

Table 13. Fixed Radius Method for 50 day Time of Travel calculations.

Flow Rate	11	L/s
Unsaturated Zone Thickness	4.4	m
Porosity	0.3	-

Time of Travel	Radius of Capture Zone (m)
50 days	21
1 year	289
2 years	409
5 years	647
10 years	915

Table 14. Uniform Flow Field Method for 50 day Time of Travel calculations.

Flow Rate	11	L/s
Hydraulic Conductivity	0.000409	m/s
Unsaturated Zone Thickness	4.4	m
Porosity	0.3	-
Gradient	0.02	m/m

Y_L maximum (m)	**X_L Down Grad Null (m)**
1	-49
2	-195
3	-438
4	-778
5	-1216
6	-1751
7	-2383
8	-3113
9	-3940
10	-4864
11	-5886
12	-7004
13	-8220
14	-9534
15	-10944
16	-12452
17	-14057
18	-15760
19	-17560
20	-19457
21	-21451
22	-23542

Note:

Y_L maximum: asymptotic width of the capture zone

X_L Down Grad Null: down gradient distance where no effects of flow are observed

Distance to down-gradient null point:	**X_L =**	48.64	m
Width of Capture Zone in Y-direction:	**Y_L =**	152.81	m
Up-gradient distance at time = 50 days:	**X_t =**	117.79	m

Table 15. Stepwise Gradient Method for 50 day Time of Travel calculations.

Time of Travel at Drawdown Cone Intervals

Steps	Radial Distance (m)	Drawdown (m)	Hydraulic Gradient (-)	Hydraulic Conductivity (m/s)	Darcy Flux (m/s)	Velocity (m/s)	Time of Travel (s)	Time of Travel (days)
0	0	5.06						
1	1	3	2.0600	0.000409	8.43E-04	0.00280847	356	0.00
2	4	1	0.6667	0.000409	2.73E-04	0.00090889	3301	0.04
3	8	0.8	0.0500	0.000409	2.05E-05	6.8167E-05	58680	0.68
4	13	0.6	0.0400	0.000409	1.64E-05	5.4533E-05	91687	1.06
5	20	0.58	0.0029	0.000409	1.17E-06	3.8952E-06	1797066	20.80
6	30	0.55	0.0030	0.000409	1.23E-06	4.09E-06	2444988	28.30
7	**40**	**0.53**	**0.0020**	**0.000409**	**8.18E-07**	**2.7267E-06**	**3667482**	**42.45**
8	**50**	**0.515**	**0.0015**	**0.000409**	**6.14E-07**	**2.045E-06**	**4889976**	**56.60**
9	60	0.5	0.0015	0.000409	6.14E-07	2.045E-06	4889976	56.60

50 day Time of Travel, using the velocity from Step 5 above

Steps	Radial Distance (m)	Drawdown (m)	Hydraulic Gradient (-)	Hydraulic Conductivity (m/s)	Darcy Flux (m/s)	Velocity (m/s)	Time of Travel (s)	Time of Travel (days)
0	0	5.06						
1	1	3	2.0600	0.000409	8.43E-04	0.00280847	356	0.00
2	4	1	0.6667	0.000409	2.73E-04	0.00090889	3301	0.04
3	8	0.8	0.0500	0.000409	2.05E-05	6.8167E-05	58680	0.68
4	13	0.6	0.0400	0.000409	1.64E-05	5.4533E-05	91687	1.06
5	20	0.58	0.0029	0.000409	1.17E-06	3.8952E-06	1797066	20.80
6	30	0.55	0.0030	0.000409	1.23E-06	4.09E-06	2444988	28.30
7	**40**	**0.53**	**0.0020**	**0.000409**	**8.18E-07**	**2.7267E-06**	**3667482**	**42.45**
	48.8	**0.515**	**0.0015**	**0.000409**	**6.135E-07**	**2.045E-06**	**4320000**	**50.00**

Table 16. AVI, ISI, and SAAT Vulnerability Index Method calculations.

Aquifer Vulnerability Index

Thickness of Aquifer, d_i	30	m
K-Factor	0.000409	m/s
log c	4.87	

Intrinsic Susceptibility Index

Average Annual Depth to Water Table, d_i	30	m
K-Factor	2	-
ISI	60	

Surface to Aquifer Advection Time

Average Annual Depth to Water Table, d_{wt}	3.2	m
Mobile Moisture Content of Sand, q_z	10%	
Yearly recharge rate, θ_m	0.4	m/year
	400	mm/year
Years for surface contaminants to reach Water Table, T_{unsat}	0.8	years

Table 17. Summary of Indicators and Techniques relevant to Groundwater and Surface Water Interaction.

Indicators and Techniques	Instrumentation	K22A Site-Specific Result	Value as a Vulnerability Indicator	Applications
Stratigraphy	Borehole logs, drive point logs, regional geology information	Silt layer found in all stratigraphic logs at the site; may or may not have confining properties based on this data; establish initial possibilities for site conceptual model	Determines if the aquifer setting may be confined (not as vulnerable) or unconfined (significantly more vulnerable to surface water sources)	Any aquifer setting
Precipitation Data paired with Surface Water and Groundwater Level Data	Tipping bucket, other rain gauging devices	Higher intensity, duration, and volume rainfall events influenced the water level observed in the monitoring well network and pumping well after a given time lag; less significant rainfall events did not influence water levels	Response to the infiltration associated with significant precipitation events shows a vertical connectivity of the system and the potential impacts on the groundwater system related to surface activities	Relevant for any vertically connected, unconfined or leaky aquifer location subject to precipitation
	Pressure sensor surface water or monitoring well data logger		Precipitation events that influence the subsurface can be classified based on intensity, duration, and volume in order to determine the aquifer threshold for hydraulic responses in the subsurface	Important to conduct extended pumping tests that over their duration experience variable precipitation events in order to understand how recharging water influences the water table; beneficial to have many monitoring wells throughout the site to capture this response
Observation Well water levels	Pressure sensor in monitoring well with data logger	Monitoring well network responded to pumping throughout the entire field site	The aquifer is connected horizontally below the creek so it may be subjected to surface water infiltration	Aquifer setting adjacent to surface water bodies, specifically where no-flow or constant head boundaries should not be applied at all creeks in numerical models
		Radial response to pumping observed throughout the site	Understand horizontal connectivity at the site, with influence extending radially outwards and to the other side of the creek	Surface water body within the capture zone of the supply well

Table 17. (Continued)

Indicators and Techniques	Instrumentation	K22A Site-Specific Result	Value as a Vulnerability Indicator	Applications
Vertical Head Profiles	Pressure sensor in monitoring well with data logger Multi-level Observations Wells	All CMT wells show similar response to water level changes as a result of pumping, with a similar vertical response throughout the shallow and deep groundwater systems	The system is vertically connected, despite the presence of a silt layer; the silt layer is not confining; the aquifer is responsive between shallow and deep groundwater systems, indicating mixing and potential vulnerability	Any aquifer with complex hydrostratigraphy involving layers of fine materials and uncertainty with respect to the vertical connectivity
Drawdown contouring generated by simplistic models compared to actual, measured data	Groundwater levels	Can gain understanding of aquifer response to pumping based on how the model-generated drawdown contours match the actual drawdown contours; here, the Neuman method matched the actual drawdown most closely, helping to reinforce the unconfined assumption	Unconfined aquifers are inherently more vulnerable	Multiple wells required in order to generate site-wide drawdown contours due to pumping; can assist in verifying model assumption and in identifying the shortfalls of simplistic models
Separate shallow and deep drawdown contouring comparison	Water levels using data loggers Surfer software	A rapid response to pumping was observed to the deep groundwater system with a slower but eventual response in the shallow groundwater system; the system is connected both vertically and radially, and the silt layer is non-confining The shallow and deep groundwater contours did not match perfectly, as the surface water and shallow groundwater information collected from the drive points was incorporated	Proving the hydraulic connection of shallow and deep groundwater systems means that the pumping well is vulnerable to the shallow system's water quality The shallow system may be experiencing infiltration from the surface water, increasing the overall aquifer vulnerability	Any aquifer setting with surface water, slightly distinct shallow and deep groundwater systems; multi-level wells and lengthy pumping tests with early and late time data valuable in the process

Table 17. (Continued)

Indicators and Techniques	Instrumentation	K22A Site-Specific Result	Value as a Vulnerability Indicator	Applications
Shallow and deep groundwater comparison between water quality data from early and late time stages in the pumping test	General Chemistry and Metals Sampling	Dilution of calcium and hardness attributed to the shallow groundwater, shows shallow water contributions; iron and sulfate concentrations also increasing, attributed to deeper groundwater contributions	Based on how the water quality changes with depth prior to and after extended pumping, it can be deduced where the water being extracted is originating from, as it may become more similar to either the deep or shallow groundwater system, providing insight into groundwater movement and any subsequent vulnerability	Extended pumping tests allows for water quality data to be collected that shows the gradual influences of deeper or shallower water on the geochemistry of the extracted water; a vast water quality data set permits the determination of naturally occurring shallow and deep groundwater tracers; best to have multiple wells and multi-elevation samples to track vertical differences in water quality
Geochemical parameters that trend similarly throughout the site	General Chemistry and Metals Sampling	Changes in pH data from all wells and surface trended similarly across the site throughout the test	May be an indication of season changes; the collective response shows at least some connectivity throughout the site, between surface water and shallow and deep groundwater	
Continuous Electrical Conductivity	General Chemistry and Metals Sampling Conductivity sensor in data loggers	Fluctuation in electrical conductivity in response to pumping or after precipitation events	Demonstrate that the groundwater below the silt layer is responding to precipitation in water quality, not just quantity, showing connection to surface influences and therefore a vulnerability to the surface	Any aquifer that is potentially susceptible to surface activities and subject to surface water recharge; best to have multiple wells at multiple elevations monitored continuously in order to capture precipitation influence

Table 17. (Continued)

Indicators and Techniques	Instrumentation	K22A Site-Specific Result	Value as a Vulnerability Indicator	Applications
Temperature	Resistance Temperature Detectors	CMT1 showed significant temperature changes as a result of pumping; CMT2 and CMT3 ports experienced little change in temperature	This shows that the shallow groundwater system is responsive to pumping above the silt layer; possible that the only temperature changes observed in the well between the creek and the pumping indicate minor surface water infiltration providing additional evidence for a highly vulnerable aquifer setting	Proximity to surface water, where a mutli-level well positioned between the pumping well and surface water can indicate groundwater-surface water interaction
	Temperature sensor monitoring wells and surface water connected to data loggers	Pumping well became cooler due to pumping from deeper groundwater contributions	Determine approximate depth origin of pumped water	Possible to extrapolate groundwater dynamics based on the temperature responses observed in a pumping well, where increasing temperatures with pumping might indicate shallow groundwater or surface water being extracted by the pumping well
Correlation Coefficients	Calculated from Climate, Sampling, and Continuously recorded data	Included in Table 11 and Table 12	Quickly assess parameters correlations, positive or negative, and the extent: slight, moderate, or high	Large amount of data needed over a long period of time; ability to utilize existing data sets in order to determine potential surrogate parameters and better advise on monitoring and sampling programs for future hydrogeological and geochemical analyses

Chapter 5 – Conclusions

The main objective of this study was to evaluate the utility of a broad range of field site characterization techniques designed to assess the vulnerability of public supply wells to water quality impacts from surface water sources. This was carried out through detailed field investigations at the site of an existing supply well, managed by the Regional Municipality of Waterloo. This newly installed well (TW2-13) is located adjacent a perennial stream, Alder Creek, and the field studies focussed on understanding the groundwater and surface water interaction between the surrounding aquifer and Alder Creek. As conventional well vulnerability analysis depends almost exclusively on predictive modeling tools, a major intention of the current study was to contribute insight into the type of detailed field investigation strategies that could provide information and evidence to improve the evaluation of the vulnerability of public supply wells. This information could also be used to inform and support concurrent modeling efforts.

Through an in-depth hydrogeological analysis conducted over the course of a 60-day pumping test, a series of hydrogeologic and hydrologic parameters deemed pertinent to measure in such assessments were collected and correlated to vulnerability metrics based on the relevant parameter's degree of change. The debate between the utility of longer and shorter term data collection was addressed as part of this work, along with the implementation of an integrated, site-wide monitoring approach designed to incorporate hydrogeologic, hydrologic, and climatic data. A more field-based approach to well vulnerability assessment will likely reduce uncertainty in the quantification of well vulnerability and allow for information to be more easily and definitively conveyed to other parties, such as policy makers and water treatment operators.

The literature review conducted focused on the dynamics of groundwater and surface water interaction, the potential threats to water quality that exist within the Alder Creek Watershed, and presents the current methods by which vulnerability is assessed and source water protection strategies are built. The regulatory framework surrounding vulnerable well determination was also researched, along with the implications of high level pumping on nearby streams, any resultant risks to ecosystem vitality, and the predictions regarding climate change influence moving forward.

A great deal of background information was available regarding the Alder Creek Watershed and specifically at the site of the new supply well, TW2-13, used for this investigation where an existing supply well, K22A, has been in operation for years. This watershed, as part of the Waterloo Moraine, is a highly productive groundwater area, with several high intensity recharge zones and abundant aquifer material as overburden in this hummocky landscape. One particularly important previous study from Stantec, 2013, addressed the water quality concerns for the K22A well. In this study, it was hypothesized that dissolved oxygen in shallower groundwater was drawn to the pumping well screen, changing the pH conditions. Subsequently, this caused iron and manganese to precipitate out of solution. This precipitate material was the expected cause of turbidity spikes observed at K22A after two weeks of pumping.

The field study was conducted throughout 2013 at the K22A site where a 60-day pumping test was conducted on TW2-13. In addition to the six monitoring wells already on the property, two more monitoring wells were drilled on the opposite side of the creek, along with four 7-port multi-level wells around TW2-13, and two drive point piezometers within Alder Creek. This initial data collected through the drilling process was helpful in creating a preliminary hydrogeologic conceptual model. Throughout the pumping test, a large amount of data was collected. Continuous temperature data was collected via thermistors positioned within the multi-level wells; data loggers within the observation wells and drive points were also set up to collect water level data, as well as conductivity and temperature information. Manual measurements of the water levels were also collected intermittently throughout the pumping test to verify and add to this data set. Water quality Sondes were placed in the creek and in a flow through cell monitoring the pumping well water in order to obtain continuous data regarding water chemistry. Samples for general chemistry, dissolved metals, microbiology, and stable water isotopes were also collected prior to and during the test.

These data were processed several different ways. The water level information was used to determine the hydrogeologic parameters of the subsurface, including transmissivity, hydraulic conductivity, and the storage coefficient. Theis, Theis Recovery, Neuman, Boulton, and Theis with Jacob Correction methods were applied in an effort to draw conclusions from the analysis that best fit to the data collected. Surfer was used to create drawdown contour maps of the transient hydraulic head data from throughout the site, which allowed for a comparison of the actual and computed drawdown information. Time of travel was calculated via the fixed-radius method, uniform flow field method, and with piecewise calculations using the drawdown cone periphery. Aquifer Vulnerability Index, the Intrinsic Susceptibility Index, and the Surface to Aquifer Advection Time were all calculated in order to estimate the vulnerability based on conventional metrics. For both the continuous and discrete data sets, correlation coefficients and covariances were calculated, where applicable, in an attempt to determine which parameters have the potential to act as a surrogate for one another when estimating vulnerability with limited information.

The groundwater level data showed a relatively rapid response to pumping in TW2-13 throughout the study site. The drawdown cone extended radially outwards from the pumping well, extending to the other side of Alder Creek and causing rapid declines in hydraulic head throughout the shallow groundwater system, excluding the drive point piezometers. This indicated a direct hydraulic connection between the pumping well and the near surface environment, suggesting the well is vulnerable to surface-sourced contaminants. The drawdown data also confirmed that the zone of influence of the pumping well extended past and under the location of Alder Creek such that water infiltrating from the creek could ultimately be captured by the supply well. Notably, hydraulic responses were observed on the opposite side of Alder Creek from where the pumping well is located both above and below a lower permeability layer encountered at the site in drill logs that appeared to be relatively continuous across the site. This shows that the aquifer is vertically and horizontally continuous, highly connected, and responsive, as well as behaving as an unconfined system which makes it more vulnerable.

All of the pumping test analysis methods applied yielded hydraulic conductivities of the same order of magnitude, with a resulting average hydraulic conductivity for the pumping well estimated at 4.1×10^{-4} m/s. The Neuman method had the best fit to the time drawdown data, suggesting that the aquifer system was responding as an unconfined system regardless of the lower permeability layer noted above. The transient hydraulic head data were also used to monitor the development of the drawdown cone during the course of the test, which were plotted by computer drafting tools. These drawdown plots were compared to those calculated with the pumping test analysis methods using the AquiferTest analytical program, clearly demonstrating the discrepancies between simplified models and actual measured data. This difference between the two sets of drawdown contours emphasizes the importance of measuring data and understanding the local flow conditions, including precipitation contributors. Deep and shallow groundwater system drawdown contour maps were also generated, showing a more rapid response in the deeper system than the shallower one. However, the shallow system did respond to pumping over time, demonstrating that the system is both radially and vertically connected. The mixing of shallow and deep groundwater in the aquifer means that the pumping well is susceptible to the shallow system water quality. Possible infiltration from Alder Creek could also impact the shallow system water quality negatively.

Interestingly, the piezometric levels increased throughout the entire monitoring well network in response to larger precipitation events, with time lag from the start of the precipitation event, illustrating the rapid response of the system to surface infiltration events, which again suggests the aquifer and well are likely vulnerable to impacts from surface sources of contamination. During the course of the pumping test, water levels in Alder Creek and groundwater levels in the shallow stream bed did not appear to be influenced by the pumping process although strong downward hydraulic gradients below Alder Creek persisted throughout the entire field investigation time frame. In addition, stream water levels and stream bed groundwater levels remained well above (~1 m) the local water table suggesting that Alder Creek may be perched at this location, which would likely influence the infiltration characteristics beneath the stream. Further field investigation work is required to determine the nature of the perching conditions beneath the stream.

General water chemistry and metals data provided additional insight regarding water movement at the K22A site. Water quality data from the shallow and deep groundwater systems were compared to the pumping well water at the start and end of the test in order to further investigate the groundwater flow dynamics and to determine if these data could be used to provide more insight into the vulnerability of the supply well. Shallow groundwater and deep groundwater contributions were found to influence the pumping well water quality, showing that the two systems were mixing. Generally, shallow groundwater and surface water samples show dilution in hardness and calcium concentrations at the pumping well. Deeper groundwater had elevated concentrations of sulfate, iron, magnesium, manganese, silicon, and strontium, due to the weathering of minerals and rocks deeper within the aquifer, providing additional evidence that both shallow and deep groundwater were being extracted by TW2-13. Identifying that there was mixing of the shallow and deep system was possible because of the vast amount of water quality data from this extended pumping test which permitted assumptions to be made regarding naturally occurring deep and shallow groundwater tracers; this provided insight groundwater movement and any subsequent vulnerability.

The temperature data for the multi-level wells indicate temperature pulses in the subsurface as a result of warmer shallow groundwater and precipitation. They also showed that while the silt layer was not hydraulically confining, it did influence the temperature pulses observed in the subsurface, with warmer groundwater above the layer and cooler groundwater below it. While the drive point data showed air temperature and surface water temperature to be linked, the groundwater below the stream becomes less influenced by air temperature with increasing depth. The temperature changes in the pumping well and nearby observations wells allude to the groundwater dynamics, where cool groundwater was being drawn up to the pumping well screen elevation and warmer surface water was infiltrating into the subsurface as well. Additionally, it was noted that the multi-level well positioned between Alder Creek and TW2-13 experienced the largest temperature fluctuation, perhaps to do with its proximity to any surface water infiltration that was occurring. Temperature data is very valuable in understanding the mixing of shallow and deep groundwater systems, investigating stratigraphic influences, and potential surface water infiltration. Temperature information is most valuable when collected from a variety of locations and depths at a study site.

The time of travel was calculated in three ways: the fixed-radius method found the time of travel distance was 21 m for 50 days; the uniform flow field method calculated 117.80 m as the distance travelled in 50 days; and the stepwise gradient method for 50 day time of travel resulted in an estimated distance of 48.8 m. Give that Alder Creek is encompassed by the 50-day time of travel information, TW2-13 would be categorizes as a GUDI well for its susceptibility to any potential surface water quality problems. The three vulnerability indices conducted in this study, which yielded limited, moderate, and moderate vulnerability estimations, are very generalized in their assumptions. Improved vulnerability standards should accommodate seasonality or extreme weather events and incorporate other indicators measured in the field, such as temperature, precipitation, turbidity, conductivity, water levels in surrounding surface water bodies. These factors could each be given values for different classes of groundwater and surface water interaction which could be used together to indicate vulnerability that would account for variable conditions in climate, water quality, and surface water proximity.

No adverse ecological effects to Alder Creek were observed due to pumping. However, in a gaining stream segment, the influence of pumping would be more significant, as it could reduce baseflow that are crucial to sustain flow. Climate change impacts may also impact the Alder Creek Watershed as they intensify. High intensity rainfall will cause increased runoff, resulting in spikes in water level within surface water bodies, more erosion causing increase turbidity within surface water, and influence water quality negatively. During reduced precipitation periods, Alder Creek may experience very low flows. Monitoring precipitation and other climate data will be necessary to understand fluctuations in water table elevation.

Correlation coefficients were calculated for continuous and discrete data available. The strongest correlation occurred between the TW2-13 water level and water temperature. Moderate correlations of interest included the water level and turbidity correlation for surface water, where precipitation increased the water, generating a higher sediment load, and spiking turbidity. Moderate, negative correlations were observed between water temperature and conductivity and between conductivity and turbidity for TW2-13. The inverse relationship between conductivity and turbidity might be caused by ions precipitating from solution due to changes in dissolved oxygen and pH, increasing the turbidity.

For the discrete data, several very strong positive correlations were discovered between anions and cations, conductivity, sodium and chloride, concluded all to be connected to surficial road salt application. Calcium and manganese also correlated moderately, possibly due to the subsurface mineral composition and resulting water hardness, which also correlated to manganese. Manganese and iron concentrations correlated positively to one another, yet only had a slight negative correlation to both pH and dissolved oxygen, neither proving nor disproving the previous study hypothesis regarding the geochemical conditions at K22A. Overall, correlation coefficients were helpful in indicating trends pertaining to groundwater flow and water quality relationships. Should air temperature be unavailable during a pumping test, reasonable climate conclusions can be drawn from surface water temperature alone; however, there is no clear surrogate for precipitation data, which will become increasingly useful in pump test analyses.

This method makes it possible for practitioners to quickly utilize existing data sets in order to determine potential surrogate parameters and to better advise on monitoring and sampling programs for future hydrogeological and geochemical analyses.

All of the potential vulnerability indicator methods and techniques were summarized in a table, citing the instrumentation and results specific to the K22A site, along with an explanation of the value of that information as a vulnerability indicator. Further information is given as to the application possibilities for these vulnerability indicator methods. Based on the findings in this research, data collected from extended pumping tests provides great insight into vulnerability. These insights include understanding shallow and deep groundwater system characteristics with geochemical data and their potential mixing due to pumping, developing conceptual models of groundwater movement based on vertical temperature gradients and pulses within the subsurface, and examining the differences and potential interaction of shallow and deep groundwater systems through drawdown contouring. The evidence presented here clearly demonstrates that assessing well vulnerability to surface water sources benefits from in-depth quantitative analyses based on detailed field investigations.

Ultimately, this lengthy data set allowed for the myriad of conclusion made above possible. Particularly in relation to examining the long term water quality changes and impacts of seasonality and precipitation events, the information collected was indicative of groundwater dynamics and the influences of shallow groundwater on the deeper groundwater system. Although there was a mid-test shut off period, which occurred accidently, it allowed for excellent observations and data to be collected, particularly with the occurrence of a large precipitation event and the subsequent impacts on the recovered water levels. This was an excellent example of perseverance and making the best of an unpredictable situation. With information from a pumping test of only 72 hours, the same conclusions could not be drawn and this study would have been limited. When decisions are made in the future regarding pumping test durations and parameters that should be monitored, consideration should be paid to the slower to respond and less predictable variables, including water quality data, surface water fluxes, and climatic influences.

Chapter 6 – Recommendations

There a several key recommendations for further study, both at this site and for any work assessing well vulnerability. In order to more accurately determine the time lag between rainfall events and groundwater recharge, tracers are suggested, which could be added to the surface water and then screened for in the production well, under varied pumping conditions. This could also help in the verification of the 50-day times of travel estimated here within. The microbiology samples collected would be useful for correlation coefficient comparisons with the existing data set, an effort which would address potential water quality concerns connected to vulnerability. Also, turbidity should be measured more accurately. Instead of using handheld turbidity devices and Sondes that are deployed for long periods of time, in-line production well turbidity meters, like the one in the K22A pumphouse, should be implemented to offer a better understanding of the iron, manganese, conductivity, pH, DO, and turbidity relationship.

Additional instrumentation suggested include telemetry systems to transmit the pumping well information to make sure that rapid response is possible in the event of an accidental shut off. This equipment would also be helpful in recognizing precipitation events and coordinating groundwater sampling to capture the recharge water in the subsurface. Automatic water quality samplers in the creek would also be beneficial to capturing the surface water storm surge in the wake of high intensity rainfall. The locating of a downstream drive point may also provide more detailed information regarding the stream bed gradient and the regional flow field. Solar panels could be secured on site to provide a more reliable power source than the deep cycle marine batteries which needed continual charging. The addition of soil moisture probe equipment is also suggested to map the recharge behaviour subsequent to vadose zone changes adjacent to Alder Creek and the pumping well. It might be prudent to measure temperature and soil moisture congruently to determine if there is a correlation between these two parameters, allowing for one to be used as a surrogate for the other. In addition to these suggestions, it would be helpful to measure stream flow throughout a pumping test like this in order to quantify any potential changes in flow volumes as a result of pumping. This would be most relevant in aquifer settings with highly connected surface water and groundwater systems, particularly if the stream is typically gaining groundwater.

Modeling this system is the next step for this data analysis. Through the implementation of an intricate model, in a program such as HydroGeoSphere, it would be possible to generate intricate simulations of data based on the conceptual model described above, including surface water and groundwater interactions and time of travel. The time lag in the precipitation fluxes would also be better understood through the application of a model. Overall, vulnerability indices should not be based on simplifications. Vulnerability metrics should be established for precipitation data and the change in hydraulic gradients under pumping conditions, along with conductivity, turbidity, and temperature fluxes. Consideration should be paid to the proximity of surface water sources and stratigraphic setting. As was discovered herein, a no-flow or constant head boundary should not be applied at Alder Creek, as the aquifer drawdown extends beyond the creek. Modeling tools could generate simulations with these well settings varied in order to observe the changes in these parameters lists and the level of vulnerability anticipated.

Further statistical analysis could offer additional vulnerability metric suggestions. Utilizing the correlation coefficient data could provide clearer insight into water quality issues at a given site, where different corresponding parameters can be easily matched with a certain problem. Within this work, road salt problems can be identified through the correlation of sodium and chloride with the absence of other parameter coalitions. This work could be extended to encompass a myriad of water quality concerns, including septic tank leakage, urban runoff, and agricultural contamination. Additionally, varying coefficient models and significance testing could be applied to determine if parameter correlations are indicative of an actual connection. Other comparison procedures often applied to environmental data include the Mann-Whitney test, Spearman's rank test, and Kruskal Wallis analysis of variance. The Student's t-test and paired t-test are also available as predictive statistical tools, along with more traditional regression and stochastic analyses. Similar to the hydrogeologic model benefits, these tools could be applied to data sets in an effort to understand the likelihood of events that would pose a risk to water quality, such as road salt loading or additional nutrient sources. There are also concentration specific statistical processes that may be useful in determining the vulnerability of an aquifer. These include establishing tolerance intervals, determining allowable effluent concentration, and the criteria for maximum and continuous concentrations. Moving into the future, statistical processes will become more and more useful in order to plan for drinking water safety in a robust way. Given the anticipated effects of increased populations and climate change, the assumptions of stationarity that once governed urban planning have changes. Such alterations to the natural environment could be modeled by a change of stationarity function.

Bibliography

American Society for Testing Materials. (2006). *Standard Practice for Classification of Soils for Engineering Purposes: Unified Soil Classification System*.

Barlow, P. M., & Leake, S. A. (2012). *Streamflow Depletion by Wells — Understanding and Managing the Effects of Groundwater Pumping on Streamflow*. Reston.

Cameron, I. (2010). *Canada-Ontario (COA) Respecting the Great Lakes Basin Ecosystem : Climate Change Monitoring Review Project : Provincial Groundwater Monitoring Network (PGMN) and Stream Monitoring Network (PWQMN) assessment final report : sensitivity mapping and local*. Newmarket.

Campbell Scientific Inc. (2004). CR 1000 measurement & control datalogger. Logan.

CH2MHILL. (2002). *Final Report Hydrogeological Study to Evaluate the GUDI Status of the Mannheim West, Mannheim East, and Peaking Well Fields*. Kitchener.

CH2MHILL. (2004). Recommendations for Monitoring Program and Well Abandonment, Alder Creek Watershed. Kitchener.

CH2MHILL, S. S. Papadopulos & Associates, I. (2003). *Alder Creek Groundwater Study Final Report*. Kitchener.

Chow, R. (2012). *Delineating Base Flow Contribution Areas for Streams : A Model Comparison*. University of Waterloo.

Clark, I., & Aravena, R. (2005). Environmental Isotopes in Ground Water Resource and Contaminant Hydrogeology. In *NGWA Course #394*. San Diego.

Committee on Techniques for Assessing Ground Water Vulnerability. (1993). *Ground Water Vulnerability Assessment: Predicting Relative Contamination Potential Under Conditions of Uncertainty*. (N. R. Council, Ed.). Washington: National Academy Press.

Constantz, J. (2008). Heat as a tracer to determine streambed water exchanges. *Water Resources Research*, *44*(4), n/a–n/a. doi:10.1029/2008WR006996

Contreras, M. (2014). Maxxam: General Chemistry and Metals Information. Waterloo.

De Loë, R. (2009). *Managing Water Shortages for Ontario Agriculture*. Guelph.

Ducharme, A. (2013). Turbidity Meter. Waterloo.

Emelko, M. B., Tufenkji, N., Stone, M., Rudolph, D. L., & Marsalek, J. (2010). *RBF Treatment of Waters Impacted by Urban Stormwater and/or Polluted Rivers. Effects of Urbanization* *on Groundwater: An Engineering Case-based Approach for Sustainable Development.* Reston.

Environment Canada. (2014). *Climate Archives*. Retrieved December 09, 2013, from http://climate.weather.gc.ca/

Freeze, A. R., & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs: Prentice Hall.

Frind, E. O., Molson, J. W., & Rudolph, D. L. (2006). Well vulnerability: a quantitative approach for source water protection. *Ground Water*, *44*(5), 732–42. doi:10.1111/j.1745-6584.2006.00230.x

Gerrits, C. (2013). Pump Manufacturer. Waterloo.

Grand River Conservation Authority. (2000). *Alder Creek Watershed Study: Phase 1 - Discussion Paper*. Kitchener.

Grand River Conservation Authority. (2005). *Establishing Environmental Flow Requirements for Selected Streams in the Grand River Watershed: Pilot Project*. Waterloo.

Hunt, R. J., Coplen, T. B., Haas, N. L., Saad, D. A., & Borchardt, M. A. (2005). Investigating surface water–well interaction using stable isotope ratios of water. *Journal of Hydrology*, *302*(1-4), 154–172. doi:10.1016/j.jhydrol.2004.07.010

Hutton, J. (2014). Region Monitoring Well Loggers. Kitchener.

Internet Center for Management and Business Administration. (2010). *Covariance*. *NetMBA*. Retrieved April 19, 2014, from http://www.netmba.com/statistics/covariance/

Karamous, M., Nazif, S., & Falahi, M. (2013). *Hydrology and Hydroclimatology: Principles and Applications* (1st ed.). Boca Raton: CRC Press Taylor and Francis Group.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J. J., Kupfersberger, H., Kværner, J., … Pulido-Velazquez, M. (2013). Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology*, *6*(37). doi:10.1016/j.jhydrol.2013.06.037

Koch, J. T. (2009). *Evaluating Regional Aquifer Vulnerability and BMP Performance in an Agricultural Environment Using A Multi-Scale Data Integration Approach*. University of Waterloo.

Loomer, H. A. (2008). *The Dynamics of Carbon and Nitrogen Stable Isotope Analysis of Aquatic Organisms within the Grand River Watershed*. University of Waterloo.

Maunder, D., & Hindley, B. (2005). *Establishing Environmental Flow Requirements: Synthesis Report*.

McBean, A., & Rovers, F. (1998). *Statistical Procedures for Analysis of Environmental Monitoring Data & Risk Assessment*. Upper Saddle River: Prentice Hall.

MICRO SWITCH Sensing and Control. (2013). Temperature Sensors Platinum RTDs.

National Water Research Institute. (2001). *Threats to Sources of Drinking Water and Aquatic Health in Canada*. Burlington.

Ontario Ministry of the Environment. (2001). *Delineation of Wellhead Protection Areas Municipal Groundwater Supply Wells under Direct Influence of Surface Water*.

Ontario Ministry of the Environment. (2002). *Technical Terms of Reference Groundwater Studies 2001/2002*. Kingston: Queen's Printer for Ontario.

Ontario Ministry of the Environment. (2004). *Groundwater studies in Ontario: Mapping a hidden treasure*. Kingston.

Process Measurement and Controls Inc. (2013). Depth and Level Pressure Transmitter: Miniature MTM 3000 Series. Danbury.

Regional Municipality of Waterloo. (2014). *Silverlight Viewer*. *GIS Locator Geocortex*. Retrieved March 11, 2014, from http://gis.region.waterloo.on.ca/SilverlightViewer_1_8/Viewer.html?ViewerConfig=http://gis.region.waterloo.on.ca/Geocortex/Essentials/REST/sites/LocatorBasic/viewers/LocatorBasic/virtualdirectory/Config/Viewer.xml

Rong, Y. (Ed.). (2011). *Practical Environmental Statistics and Data Analysis* (1st ed.). Porters Wood: ILM Publications.

Rudolph, D. L. (2011). Complete Proposal Inclusions: Canadian Water Network Secure Source Waters Consortium Proposal Information. Waterloo.

Schlumberger Water Services. (2013). AquiferTest Pro User's Manual. Waterloo.

Schmidt, C., Conant, B., Bayer-Raich, M., & Schirmer, M. (2007). Evaluation and field-scale application of an analytical method to quantify groundwater discharge using mapped streambed temperatures. *Journal of Hydrology*, *347*(3-4), 292–307.

Simcoe Ontario Local Meteoric Water Line. (2013). *University of Waterloo*. Retrieved January 14, 2014, from www.iaea.or.at:80/programs/

Solinst Canada Ltd. (2011). Leveloader Model 3001. Georgetown.

Solinst Canada Ltd. (2012). CMT Multilevel System Model 403. Georgetown.

Solinst Canada Ltd. (2013). *Manual Barometeric Compensation*. Retrieved January 26, 2014, from http://www.solinst.com/Prod/3001/Levelogger-User-Guide/8-Data-Compensation/8-2-Manual-Barometric-Compensation.html

Sophocleous, M. (2000). From safe yield to sustainable development of water resources—the Kansas experience. *Journal of Hydrology*, *235*(1-2), 27–43. doi:10.1016/S0022-1694(00)00263-8

Sousa, M. R. De. (2013). *Using Numerical Models for Managing Water Quality in Public Supply Wells*. University of Waterloo.

Stantec Consulting Ltd. (2013). *Mannheim West Well Field Performance and Water Quality Evaluation Production Well K22A*. Kitchener.

Sutron. (2007). XLITE 9210 DATALOGGER. Sterling.

Treidel, H., Martin-bordes, J. L., & Gurdak, J. J. (2012). Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations. In N. S. Robins (Ed.), *International Association of Hydrogeologists*. London: CRC Press Taylor and Francis Group.

Veale, B. J. (2010). Assessing the Influence and Effectiveness of Watershed Report Cards on Watershed Management : A Study of Watershed Organizations in Canada.

Waterra. (2008). FMT-45 Groundwater Filters: medium turbidity.

YSI Incorporated. (2012). EXO User Manual: Advanced Water Quality Monitoring Platform. Yellow Springs.

Appendix A. Regional Municipality of Waterloo Database Agreement

Region of Waterloo

TRANSPORTATION AND
ENVIRONMENTAL SERVIC
Water Services

150 Frederick Street
Kitchener ON Canada N2G 4J3
Telephone: (519) 575-4426
Fax: (519) 575-4452
www.region.waterloo.on.ca

Date: June 27, 2012
E06-80/UW

Ms. Cailin Hillier
University of Waterloo
200 University Ave W
Waterloo, ON

Dear Ms. Cailin Hillier:

Re: Library Database

Please review the terms of use below, and return a signed copy.

The following are the terms of use of the library database:

- The library database is only for your use for the project "Southern Ontario Water Consortium: Alder Creek Watershed", for July through December 2012, and will not be used by other people or for other purposes
- A copy of the library database will not be put on any shared drive or made available to other people
- The library database will be deleted when the research project is finished

In signing this letter you are agreeing to the terms of use:

Cailin Hillier, Operations Technician, UW

June 27, 2012
Date

Yours truly,

Nicola Bywater
Analyst, Water Protection
T: 519-575-4757 x3177
E: nbywater@regionofwaterloo.ca

cc: Tammy Middleton, Senior Hydrogeologist, ROW

~~#119187 (change number to new DOCS #)~~1198161

Appendix B. Weather Station Data

Time Stamp	Temp. (°C)	Relative Humidity	Precipitation Total (mm)	Wind Vector (deg)	Wind Speed (m/s)	Wind Vector Cell (deg)	Incidental Solar Radiation (Wh/M²)	Total solar radiation (MJ/M²)
14/08/2013	14.11	73.64	0.00	278.26	0.987	29.51	70.595006	70.595006
15/08/2013	13.44	76.23	0.00	263.29	0.686	12.85	64.002297	64.002297
16/08/2013	15.92	75.12	0.00	235.23	0.210	8.70	64.782878	64.782878
17/08/2013	17.28	72.51	0.00	190.56	0.274	16.35	73.500884	73.500884
18/08/2013	18.41	72.88	0.00	213.47	0.295	16.52	68.960625	68.960625
19/08/2013	18.03	75.86	0.00	230.75	0.438	8.84	65.374686	65.374686
20/08/2013	18.90	78.12	0.00	274.75	0.512	14.38	66.028520	66.028520
21/08/2013	20.67	77.59	0.00	281.14	0.483	21.42	62.413674	62.413674
22/08/2013	21.19	80.02	0.03	257.15	0.641	14.88	52.687017	52.687017
23/08/2013	18.17	71.38	0.00	164.40	0.553	19.99	67.271500	67.271500
24/08/2013	16.58	74.70	0.00	224.96	0.186	23.99	67.581781	67.581781
25/08/2013	18.31	74.50	0.00	210.23	0.491	26.54	64.187442	64.187442
26/08/2013	21.67	82.62	0.24	247.37	0.684	19.41	26.993540	26.993540
27/08/2013	21.59	89.51	0.03	220.71	0.217	9.32	41.159439	41.159439
28/08/2013	22.56	87.59	0.00	144.37	0.566	14.92	31.869657	31.874815
29/08/2013	22.95	77.88	0.00	199.01	0.230	8.27	53.104473	53.104473
30/08/2013	21.36	85.07	0.32	223.60	0.527	23.41	34.662012	34.662012
31/08/2013	21.63	87.00	0.00	252.67	0.535	17.80	36.717297	36.717297
01/09/2013	20.90	89.36	0.52	140.52	0.448	26.98	27.375104	27.375104
02/09/2013	18.42	89.39	0.02	253.87	0.878	18.05	30.558694	30.558694
03/09/2013	14.76	85.01	0.00	257.79	1.187	19.84	34.134920	34.134920
04/09/2013	15.39	83.13	0.00	257.24	0.886	15.63	60.883637	60.883637
05/09/2013	12.88	71.54	0.00	214.39	0.627	25.42	66.991095	66.991095
06/09/2013	11.68	71.36	0.00	209.89	0.294	13.30	61.924702	61.924702
07/09/2013	15.77	90.10	0.22	214.20	0.205	12.38	15.144087	15.144087
08/09/2013	16.53	71.13	0.00	134.45	0.868	22.35	64.328642	64.328642
09/09/2013	14.18	83.23	0.00	163.52	0.242	21.88	39.710641	39.710641
10/09/2013	25.48	77.57	0.00	266.86	0.701	25.64	54.204749	54.204749
11/09/2013	23.14	82.97	0.51	243.84	0.485	20.79	44.092242	44.092242
12/09/2013	18.55	85.74	0.05	272.03	0.777	23.26	29.672242	29.672242
13/09/2013	10.60	76.31	0.00	201.43	0.780	44.69	23.048502	23.048502
14/09/2013	9.22	77.36	0.00	269.35	0.415	17.21	61.485313	61.485313
15/09/2013	11.09	85.91	0.04	254.97	0.257	19.88	16.876524	16.876524
16/09/2013	11.51	78.21	0.01	156.16	0.571	27.31	41.007337	41.007337
17/09/2013	9.12	75.83	0.00	170.76	0.400	16.12	58.953371	58.953371
18/09/2013	11.75	77.54	0.00	166.32	0.229	17.91	55.482926	55.482926
19/09/2013	14.44	89.43	0.00	196.24	0.259	22.29	36.838561	36.838561

Appendix B. (Continued)

Time Stamp	Temp. (°C)	Relative Humidity	Precipitation Total (mm)	Wind Vector (deg)	Wind Speed (m/s)	Wind Vector Cell (deg)	Incidental Solar Radiation (Wh/M²)	Total solar radiation (MJ/M²)
20/09/2013	19.10	94.74	0.69	240.46	0.527	37.40	14.149286	14.149286
21/09/2013	14.88	92.62	1.98	220.47	0.589	27.07	10.570074	10.570074
22/09/2013	9.34	76.22	0.01	239.03	0.661	31.15	29.645802	29.645802
23/09/2013	10.41	73.62	0.00	235.97	0.324	16.36	51.998310	51.998310
24/09/2013	9.38	76.47	0.00	176.36	0.326	11.37	55.995918	55.995918
25/09/2013	11.12	76.26	0.00	156.59	0.330	11.23	51.891272	51.891272
26/09/2013	12.45	75.05	0.00	164.24	0.340	12.17	52.844149	52.844149
27/09/2013	12.37	81.88	0.00	172.96	0.522	25.70	51.246295	51.246295
28/09/2013	13.87	85.20	0.00	150.40	0.440	23.49	42.618423	42.618423
29/09/2013	14.91	89.02	0.03	222.41	0.267	25.30	28.815325	28.815325
30/09/2013	16.51	89.53	0.04	237.88	0.318	21.44	23.177275	23.177275
01/10/2013	16.03	85.96	0.01	268.79	0.469	31.38	46.276620	46.276620
02/10/2013	16.79	75.27	0.00	273.06	0.840	18.57	42.907513	42.907513
03/10/2013	12.53	72.39	0.01	153.36	0.284	13.82	36.915142	36.915142
04/10/2013	16.70	95.50	0.63	183.32	0.305	14.82	14.888329	14.888329
05/10/2013	14.16	93.63	0.13	107.59	0.890	27.34	9.886911	9.886911
06/10/2013	16.89	92.99	0.78	157.05	0.702	30.22	9.630733	9.630733
07/10/2013	11.52	88.00	0.83	251.36	1.141	22.78	24.593225	24.593225
08/10/2013	9.18	83.40	0.01	218.20	0.201	8.54	38.481070	38.481070
09/10/2013	9.98	81.71	0.00	163.42	0.262	16.70	44.331587	44.331587
10/10/2013	11.42	81.21	0.00	146.25	0.297	11.18	45.398162	45.398162
11/10/2013	11.48	72.47	0.01	170.40	0.528	13.77	42.993753	42.993753
12/10/2013	12.54	76.45	0.00	127.54	0.460	19.68	41.250949	41.250949
13/10/2013	14.55	90.11	0.23	228.68	0.276	15.90	9.274492	9.274492
14/10/2013	9.83	82.01	0.02	209.63	0.327	19.37	36.684676	36.684676
15/10/2013	8.34	89.63	0.00	164.48	0.414	18.67	22.605307	22.605307

Appendix C. TW2-13 Pumping Well Borehole Log

Test Well: WT-TW2-13

Project:	2011 Municipal Well Construction and Testing	**Drilling method:**	Truck mount, DR 24, air rotary
Client:	Region of Waterloo	**Date started/completed:**	15-Feb-2013
Location:	Mannhiem West Well Field	**Ground surface elevation:**	n/a
Number:	160900651	**Top of casing elevation:**	n/a
Field investigator:	E. Hayman	**Easting:**	n/a
Contractor:	Gerrits Well Drilling	**Northing:**	n/a

SUBSURFACE PROFILE | HYDROGEOLOGY | SAMPLE DETAILS | INSTALLATION DETAILS

Lithologic Description	Depth (m BGS)	Hydro Stratigraphic Unit	Description
Ground Surface			
TOPSOIL medium sand, brown wet	0.00	AFB1/ AFB2	Upper and Lower Moraine Stratified Sediments and Equivalents
SAND fine and little medium sand, trace silt, brown (7.5 YR 4/4), wet medium and little coarse sand, trace silt at 3.05 m BGS trace gravel at 4.57 m BGS	1.52		
SILTY SAND silt and fine sand, brown (7.5 YR 5/2), wet	6.10		
SAND fine and medium sand, trace silt, brown (7.5 YR 5/2), wet medium and some fine sand, sand coarsening with depth trace fine gravel at 12.19 m BGS	7.62		
End of Borehole	15.24		

Sample Number	Sample Type
1	GS
2	GS
3	GS
4	GS
5	GS
6	GS
7	GS
8	GS
9	GS
10	GS

Installation Details – Description:

- Above Ground Casing ~~Stick-Up = 0.6 m~~
- Neat Cement 0 to 7.3 m BGS
- 203 mm OD Steel Casing
- 350 mm Diameter Borehole 0 to 11.0 m BGS
- Bentonite Chips 7.3 to 10.4 m BGS
- Silica Sand 10.4 to 11.0 m BGS
- Native Cave 11.0 to 15.4 m BGS
- 203 mm OD No. 15 slot Stainless Steel Telescopic Screen 11.0 to 13.4 m BGS
- 203 mm OD No. 15 to 20 slot transition Stainless Steel Telescopic Screen 13.4 to 14.0 m BGS
- 203 mm OD No. 20 slot Stainless Steel Telescopic Screen 14.0 to 15.4 m BGS

Screen Interval: 10.97 - 15.24 m BGS
Sand Pack Interval: 10.36 - 15.24 m BGS
Well Seal Interval: 0.00 - 10.36 m BGS

Notes:
m AMSL - metres above mean sea level
m BGS - metres below ground surface
GS - grab sample
n/a - not available

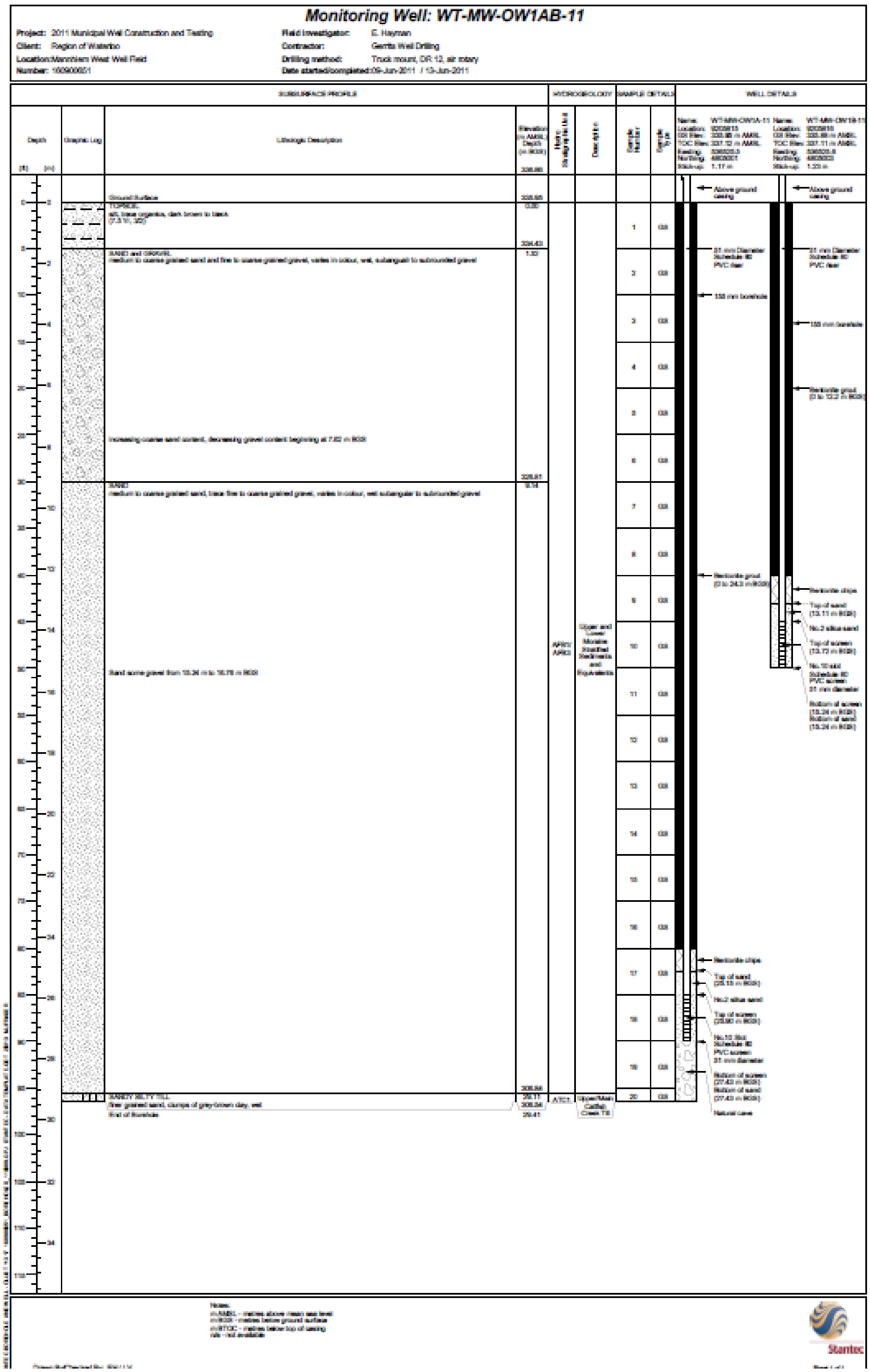
Drawn By/Checked By: EH / LV

Stantec

Sheet 1 of 1

STANTEC BOREHOLE AND WELL V2 160900651_BOREHOLES_110909.GPJ STANTEC - DATA TEMPLATE.GDT 5/27/13 MJFRASER

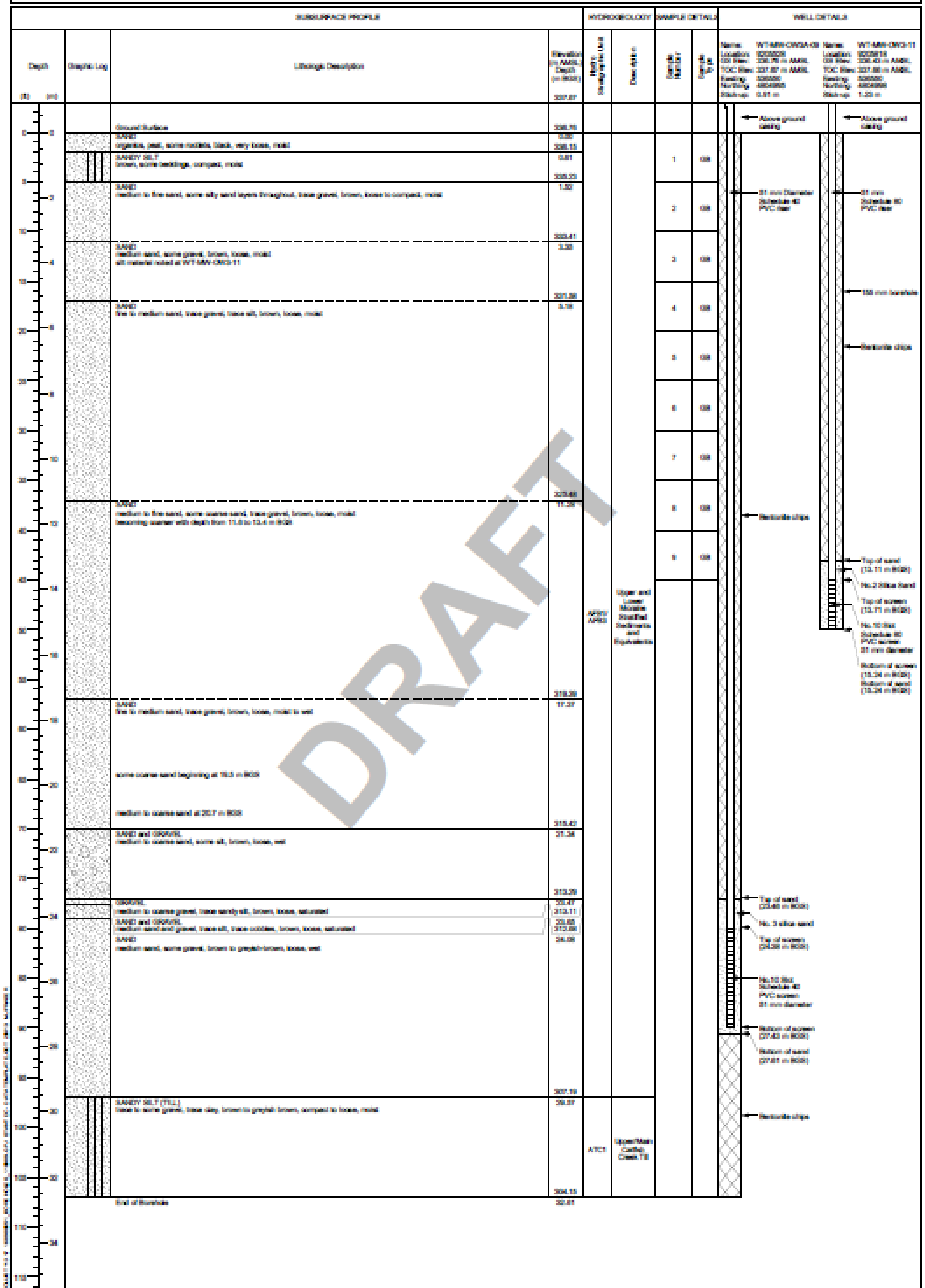
Appendix D. K22A Site Existing Monitoring Well Logs



Monitoring Well: WT-MW-OW3A-09 and WT-MW-OW3-11

Project: 2011 Municipal Well Construction and Testing
Client: Region of Waterloo
Location: Mannheim West Well Field
Number: 160900651

Field Investigator: KS (Golder) and EH (Stantec)
Contractor: Boart Longyear / Gerrits Well Drilling
Drilling method: Sonic / Truck mount, DR 12, air rotary
Date started/completed: 02-Dec-2009 / 14-Jun-2011



Notes:
m AMSL - metres above mean sea level
m BGS - metres below ground surface
m BTOC - metres below top of casing
GR - grab sample
n/a - not available

Stratigraphic description from Golder Associates (2009) for drilling of WT-MW-OW3A-09.
Edits by Stantec based on review of cored material and drilling at WT-MW-OW3-11.
Sample details pertain to WT-MW-OW3-11.

Drawn By/Checked By: EH / LV

Stantec

Sheet 1 of 1

Monitoring Well: WT-MW-OW3B-09 and WT-MW-OW2-11

Project: 2011 Municipal Well Construction and Testing
Client: Region of Waterloo
Location: Mannheim West Well Field
Number: 160900601

Field investigator: KS (Golder) and EH (Stantec)
Contractor: Boart Longyear / Gerrits Well Drilling
Drilling method: Sonic / Truck mount, DR 12, air rotary
Date started/completed: 01-Dec-2009 / 08-Jun-2011

SUBSURFACE PROFILE

Lithologic Description	Elevation (m AMSL) / Depth (m BGS)	Hydro Stratigraphic Unit	Description
	337.40		
Ground Surface	336.49		
TOPSOIL, dark brown to black	0.00 / 336.19		
SAND, medium sand; wet at 1.52 m BGS	0.30 / 334.56		
SILTY SAND	1.93 / 334.36		
SAND, medium to coarse sand	2.13 / 333.44		
SAND and GRAVEL, fine to medium sand, varies in colour, wet, subangular to subrounded gravel	3.05 / 332.60		
SAND, fine to medium sand	3.89 / 327.65		
SILTY SAND	8.84 / 327.34		
SANDY SILT	9.14 / 327.19		
SILTY SAND	9.30 / 326.74		
SAND, medium, some fine sand, becoming coarser with depth, wet	9.75 / 319.12	AFB1/AFB2	Upper and Lower Moraine Stratified Sediments and Equivalents
GRAVEL, medium to coarse gravel	17.37 / 318.96		
SAND, fine to coarse sand, becoming finer with depth	17.53 / 313.02		
SAND and GRAVEL, potentially till material	23.47 / 306.62		
SANDY SILT (TILL)	29.87 / 303.68	ATC1	Upper/Main Catfish Creek Till
End of Borehole	32.81		

SAMPLE DETAILS

Sample Number	Sample Type
1	GR
2	GR
3	GR
4	GR
5	GR
6	GR
7	GR
8	GR

WELL DETAILS

	WT-MW-OW3B-09	WT-MW-OW2-11
Name	WT-MW-OW3B-09	WT-MW-OW2-11
Location	9203029	9205817
GS Elev.	336.49 m AMSL	336.60 m AMSL
TOC Elev.	337.40 m AMSL	337.37 m AMSL
Easting	536524	536526
Northing	4803046	4803047
Stick-up	0.91 m	0.95 m

WT-MW-OW3B-09: Above ground casing; 51 mm Diameter Schedule 40 PVC riser; Bentonite chips; Top of sand (18.31 m BGS); No. 3 silica sand; Top of screen (19.31 m BGS); No.10 Slot Schedule 40 PVC screen 51 mm diameter; Bottom of screen (22.86 m BGS); Bottom of sand (22.86 m BGS); Bentonite chips

WT-MW-OW2-11: Above ground casing; 51 mm Diameter Schedule 80 PVC riser; 155 mm borehole; Bentonite chips; Top of sand (10.05 m BGS); No. 2 silica sand; Top of screen (10.66 m BGS); No.10 Slot Schedule 80 PVC screen 51 mm diameter; Bottom of screen (13.19 m BGS); Bottom of sand (13.19 m BGS)

DRAFT

Notes:
m AMSL - metres above mean sea level
m BGS - metres below ground surface
m BTOC - metres below top of casing
GR - grab sample
n/a - not available

Stratigraphic description from Golder Associates (2009) for drilling of WT-MW-OW3B-09.
Edits by Stantec based on review of cored material and drilling at WT-MW-OW2-11.
Sample details pertain to WT-MW-OW2-11.

Stantec

Drawn By/Checked By: EH / LV

Sheet 1 of 1

Appendix E. New CMT and Monitoring Well Logs

BOREHOLE LOG	**PROJECT** CMT1 Borehole Log (MOE Tag A145142)		**SHEET NO.** 1 of 2	**CORE NO.** 1
SITE LOCATION K22A Mannheim	**COORDINATES**	**LOGGED BY** Cailin Hillier	**DATE LOGGED** 02 July, 2013	
DRILLER/ DRILL EQUIPMENT Tim and Don / Aardvark Drill Rig	**WEATHER CONDITIONS** Sunny, clear	**TOTAL DEPTH** 34.5 ft	**GROUND ELEVATION**	

WELL DESIGN (m)	**MAIN COMPONENT SUMMARY**	**DEPTH (ft)**	**DEPTH (m)**	**SAMPLE COLLECTED**	**U.S.C.S.**	DESCRIPTION AND CLASSIFICATION **Colour, main component, minor component (s), moisture content, consistency description, structure, and depth range.**
0.83 m stick-up	ORGANIC	1.5	0.46	bag	O	Dark brown soil, dry, roots.
	TILL	5	1.52			Dirty TILL, sub-rounded gravel (5-8cm ø). Rocky TILL, larger rock (10cm), still unsaturated zone (4-4.5). TILL/stone/sand/clay (4.5-5). Large piece of granite encountered at 5'.
BENTONITE HOLE PLUG	SAND	10	3.05	bag	SW	Difficult drilling, eventually reach 10'. Coarse sand, damp but not dripping.
3.66 4.06 WELL FILL	SAND	15	4.57	bag	SW	Coarse SAND. Trace gravel. Light brown, clayey SILT (only know from drillers). Core tube still did not fill, deciding if we want to take split spoon samples. Water table at 12'.

5.09		SAND	20	6.10	bag	SW	Coarse sand with fine sand/silt. Trace/some gravel (0.5-1cm ø). Silt/fine sand (15-17). Coarse sand (17-20). Samples taken at ends of tube (@15, 20) (1), 17-20 (2), 15-17 (3).
6.10		SAND/SILT	22	6.71	SS/bag	SW	SAND, wet, coarse grain with finer matrix (20-20.5). Light brown, SAND/SILT, wet/dripping, fine grain, hard-packed, smooth grains, homogeneous (20.5-22).
7.12		SAND	24.5	7.47	SS/bag	SW	SAND Blow-out issues with augers, need to jet out with water. 6' of sand in augers (22.5-23.5). 10 blow counts for 2'.
8.16		SAND	27	8.23	SS/bag	SW	Dark gray-brown, SAND, wet, coarse grain, homogeneous (25-27).
		SAND	29.5	8.99	SS/bag	SW	Dark gray-brown, SAND, wet, coarse grain, homogeneous (27.5-29.5). Trace gravel (0.5cm ø).
9.15	NATURAL SAND	SAND	32	9.75	SS/bag	SW-GW	Dark gray-brown, SAND, wet, coarse grain, homogeneous (30-32).
10.12		SAND	34.5	10.5	SS/bag	SW	Dark gray-brown, SAND, wet, coarse grain, homogeneous (32.5-34.5).

13-0096-00

Ontario Ministry of the Environment

Well Record

Regulation 903 Ontario Water Resources Act

Well Tag No. (Place Sticker and/or Print Below) A145142

Measurements recorded in: ☐ Metric ☑ Imperial

Page 1 of 1

Well Owner's Information

First Name	Last Name / Organization	E-mail Address	☐ Well Constructed by Well Owner
Region of Waterloo			

Mailing Address (Street Number/Name)	Municipality	Province	Postal Code	Telephone No. (inc. area code)
150 Frederick Street	Kitchener	ON	N2G4J3	5195754400

Well Location

Address of Well Location (Street Number/Name)	Township	Lot	Concession
1181 Bleams Rd –	Wilmot		

County/District/Municipality	City/Town/Village	Province	Postal Code
Waterloo	Mannheim	Ontario	

UTM Coordinates Zone	Easting	Northing	Municipal Plan and Sublot Number	Other
NAD 83 17	536651	4805041		

Overburden and Bedrock Materials/Abandonment Sealing Record (see instructions on the back of this form)

General Colour	Most Common Material	Other Materials	General Description	Depth (ft) From	To
black	~~topsoil~~ – sand	silt / stones	topsoil	0	1'
brown	gravel	sand / cobbles	– coarse wet @ 11	1'	11'
brown	sand	silt	silt stringers in sand	11'	~~34.5~~ 33'

Annular Space

Depth Set at (ft) From	To	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
0	2'	concrete	
2'	10'	bentonite – Hole Plug	
10'	33'	sand – grade 3	

Results of Well Yield Testing

After test of well yield, water was: ☐ Clear and sand free ☐ Other, specify

If pumping discontinued, give reason:

Pump intake set at (m/ft)

Pumping rate (l/min / GPM)

Duration of pumping ___ hrs + ___ min

Final water level end of pumping (m/ft)

If flowing give rate (l/min / GPM)

Recommended pump depth (m/ft)

Recommended pump rate (l/min / GPM)

Well production (l/min / GPM)

Disinfected? ☐ Yes ☐ No

Draw Down Time (min)	Water Level (m/ft)	Recovery Time (min)	Water Level (m/ft)
Static Level			
1		1	
2		2	
3		3	
4		4	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

Method of Construction

☐ Cable Tool ☐ Rotary (Conventional) ☒ Rotary (Reverse) ☑ Boring ☐ Air percussion ☐ Other, specify ☐ Diamond ☐ Jetting ☐ Driving ☐ Digging

Well Use

☐ Public ☐ Domestic ☐ Livestock ☐ Irrigation ☐ Industrial ☐ Other, specify ☐ Commercial ☐ Municipal ☑ Test Hole ☐ Cooling & Air Conditioning ☐ Not used ☐ Dewatering ☑ Monitoring

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft) From	To
	7 port CMT.			

Status of Well

☐ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☑ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify ☐ Other, specify

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft) From	To
	7 port CMT.			

Map of Well Location

Please provide a map below following instructions on the back.

Water Details

Water found at Depth 11 (ft) Kind of Water: ☐ Fresh ☑ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Hole Diameter

Depth (ft) From	To	Diameter (in)
0	33'	8.25

Well Contractor and Well Technician Information

Business Name of Well Contractor: Aardvark Drilling Inc.

Well Contractor's Licence No.: 7 2 3 8

Business Address (Street Number/Name): 25-C Lewis Road

Municipality: Guelph

Province: ON Postal Code: N1H 1E9 Business E-mail Address: www.aardvarkdrillinginc.com

Bus. Telephone No. (inc. area code): 5198269340

Name of Well Technician (Last Name, First Name): Grant, Don

Well Technician's Licence No.: 3311

Signature of Technician and/or Contractor

Date Submitted: 20130705

Comments: See attached map – well near creek (MW-1 on map)

Well owner's information package delivered ☐ Yes ☐ No

Date Package Delivered: Y Y Y Y M M D D

Date Work Completed: 20130704

Ministry Use Only

Audit No. Z167382

Received

Ministry's Copy

BOREHOLE LOG	PROJECT CMT2 Borehole Log (MOE Tag A146068)		SHEET NO. 1 of 3	CORE NO. 1
SITE LOCATION K22A Mannheim	COORDINATES	LOGGED BY Cailin Hillier	DATE LOGGED 02 July, 2013	
DRILLER/ DRILL EQUIPMENT Adrian and Don / Aardvark Drill Rig	WEATHER CONDITIONS Sunny, clear	TOTAL DEPTH 67 ft	GROUND ELEVATION	

WELL DESIGN (m)	MAIN COMPONENT SUMMARY	DEPTH (ft)	DEPTH (m)	SAMPLE COLLECTED	U.S.C.S.	DESCRIPTION AND CLASSIFICATION Colour, main component, minor component (s), moisture content, consistency description, structure, and depth range.
0.70 m stick-up; A; B; 0.72 m stick-up	ORGANIC	5	1.52			Dark brown, gravely ORGANIC, Horizon O, low moisture content (0-5 ft).
	SAND	10	3.05		SW	Light brown with reddish tinge (oxidation), SAND, medium grain size, homogeneous (5-10 ft).
BENTONITE HOLE PLUG	SAND	15	4.57		SW	Light brown with increasing reddish colour, SAND, medium grain size, homogenous (10-15 ft).
	SAND	17	5.18	SS/bag	SW	Grayish brown, SAND, wet, medium coarse grain size, homogenous (15-17 ft).
5.61	SAND	19.5	5.94	SS/bag	SW-GW	Grayish brown, SAND, wet, coarse grain size, homogenous (17-18.5 ft). Gravel lens (<1-2cm ø) with sand matrix (18.5-19.5 ft).
6.70	SAND	22	6.71	SS/bag	SW	Grayish brown, SAND, wet, coarse grain size, homogenous (20-22 ft).
	SAND/ SILT	24.5	7.47	SS/bag	SW	Grayish brown, SAND, wet, coarse grain size, homogenous (22.5-24 ft). Gray, SILT, wet, compacted, homogenous (bottom 4").

7.80	SAND/ SILT	27	8.23	SS/bag	SW-CL	Grayish brown, SAND, wet, coarse grain size, homogeneous (25-26.5). Silt lens at 26.5, 2" thick.
8.90	SAND/ gravely SAND	29.5	8.99	SS/bag	SW-GW	Grayish brown, SAND, wet, coarse grain size, homogeneous (27.5-28.7). Thin gravel layer (0.5-1cm ø) with sand matrix (28.7). Grayish brown, SAND, wet, fine grain size, homogeneous (28.8-29.5).
	SAND/ gravely SAND	32	9.75	SS/bag	SW-GW	Grayish brown, SAND, wet, coarse grain size, homogeneous (30-30.5). Fine gravel (0.5cm ø) with trace stones (3cm) with coarse sand matrix (30.5-31.5). Grayish brown, SAND, wet, medium-coarse grain size, homogeneous (31.5-32).
10.00	SAND	34.5	10.52	SS/bag	SW	Grayish brown, SAND, wet, coarse grain size, homogeneous (32.5-34.5).
11.11	SAND	37	11.28	SS/bag	SW	Gray, SAND, wet, coarse grain size, homogeneous (35-37). Trace gravel (1-3cm ø).
	SAND	39.5	12.04	SS/bag	SW	Gray, SAND, wet, coarse grain size, homogeneous (37.5-39.5). Little gravel (1-3cm ø).
12.12	SAND	42	12.80	SS/bag	SW	Gray, SAND, wet, medium-coarse grain size becoming less coarse with depth (40-42). Trace gravel (3mm ø).
13.35	SAND	44.5	13.56	SS/bag	SW	Gray, SAND, wet, coarse/medium grain size, homogeneous (42.5-44.5). Little gravel (5mm ø).
	SAND	47	14.33	SS/bag	SW	Gray, SAND, wet, coarse/medium grain size, homogeneous (45-47). Little gravel (1.5cm ø) (46.5-47).
14.44	SAND	49.5	15.09	SS/bag	SW	Gray, SAND, wet, coarse/medium grain size, homogeneous (47.5-49.5). Little gravel.
15.51	SAND	52	15.85	SS/bag	SW	Gray-brown, SAND, wet, coarse/medium grain size, homogeneous (50-52). No gravel.
	SAND	54.5	16.61	SS/bag	SW	Gray, SAND, wet, medium-slightly coarse grain size (52.5-54.5). Trace gravel (<1cm ø).
16.62 NATURAL SAND	SAND	57	17.37	SS/bag SS/bag	SW	Gray, SAND, wet, medium-slightly coarse grain size (55-56.5). Trace gravel (<1cm ø). Gravel lens (1-2cm ø) with coarse sand matrix (56.5-57).

17.72		SAND	59.5	18.14	SS/bag SS/bag	SW	Gray, SAND, wet, coarse gradually becoming medium-grained sand with depth (57.5-58.5). Gray, SAND, wet, medium grain size (58.5-59.5).
18.76		SAND	62	18.90	SS/bag SS/bag	SW	Gray, SAND, wet, medium grain size (60-61). Gray, SAND, wet, medium-fine grain size, (61-62).
19.89	NATURAL SAND	SAND	64.5	19.66	SS/bag	SW	Gray, SAND, wet, coarse gradually becoming fine-grained sand with depth (62.5-64.5).
		SAND	67	20.42	SS/bag	SW	Gray-brown, SAND, wet, medium grain size, homogeneous (65-67).

13-0096-00

Ontario Ministry of the Environment

Well Tag No. (Place Sticker and/or Print Below): A146068

Well Record

Regulation 903 Ontario Water Resources Act

Page 1 of 1

Measurements recorded in: ☐ Metric ☑ Imperial

Well Owner's Information

First Name / Last Name / Organization: Region of Waterloo

E-mail Address:

☐ Well Constructed by Well Owner

Mailing Address (Street Number/Name): 150 Frederick Street | Municipality: Kitchener | Province: ON | Postal Code: N2G4J3 | Telephone No. (inc. area code): 5195754400

Well Location

Address of Well Location (Street Number/Name): 1181 Bleams Rd | Township: Wilmot | Lot: | Concession:

County/District/Municipality: Waterloo | City/Town/Village: Mannheim | Province: Ontario | Postal Code:

UTM Coordinates: Zone: NAD 83 17 | Easting: 532405 | Northing: 4805043 | Municipal Plan and Sublot Number: | Other:

Overburden and Bedrock Materials/Abandonment Sealing Record

General Colour	Most Common Material	Other Materials	General Description	Depth (m/ft) From	To
brown	sand	silt /stones	topsoil	0	.5
brown	sand + gravel		coarse	.5	6.5
brown	sand (fine-med)	silt	silt stringers - wet @ 15'	6.5'	65'

Annular Space

Depth Set at (m/ft) From	To	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
0	2'	concrete	
2'	13'	bentonite - Hole Plug	
13'	67'	Sand - grade 3	

Results of Well Yield Testing

After test of well yield, water was: ☐ Clear and sand free ☐ Other, specify

If pumping discontinued, give reason:

Pump intake set at (m/ft)

Pumping rate (l/min / GPM)

Duration of pumping ___ hrs + ___ min

Final water level end of pumping (m/ft)

If flowing give rate (l/min / GPM)

Recommended pump depth (m/ft)

Recommended pump rate (l/min / GPM)

Well production (l/min / GPM)

Disinfected? ☐ Yes ☐ No

Draw Down Time (min)	Water Level (m/ft)	Recovery Time (min)	Water Level (m/ft)
Static Level			
1		1	
2		2	
3		3	
4		4	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

Method of Construction

☐ Cable Tool ☐ Rotary (Conventional) ☐ Rotary (Reverse) ☑ Boring ☐ Air percussion ☐ Other, specify ☐ Diamond ☐ Jetting ☐ Driving ☐ Digging

Well Use

☐ Public ☐ Domestic ☐ Livestock ☐ Irrigation ☐ Industrial ☐ Other, specify ☐ Commercial ☐ Municipal ☑ Test Hole ☐ Cooling & Air Conditioning ☐ Not used ☐ Dewatering ☑ Monitoring

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft) From	To
2x7 port CMT				

Status of Well

☐ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☑ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify ☐ Other, specify

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft) From	To
2x7 port CMT				

Map of Well Location

Please provide a map below following instructions on the back.

Water Details

Water found at Depth 15' (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Hole Diameter

Depth (m/ft) From	To	Diameter (cm/in)
0	65'	8.25

Well Contractor and Well Technician Information

Business Name of Well Contractor: Aardvark Drilling Inc. | Well Contractor's Licence No.: 7 2 3 3

Business Address (Street Number/Name): 25 Cloudsdale Road | Municipality: Guelph

Province: ON | Postal Code: N1H 7E9 | Business E-mail Address: www.aardvarkdrillinginc.com

Bus. Telephone No. (inc. area code): 5198263460 | Name of Well Technician (Last Name, First Name): Grant, Don

Well Technician's Licence No.: 3 3 1 1 | Signature of Technician and/or Contractor | Date Submitted: 20130705

Comments: see attached map well on hill - MW-2 on map

Well owner's information package delivered ☐ Yes ☐ No | Date Package Delivered: YYYYMMDD | Date Work Completed: 20130705

Ministry Use Only — Audit No. Z167383 | Received

0506E (2007/12) © Queen's Printer for Ontario, 2007

Ministry's Copy

BOREHOLE LOG

BOREHOLE LOG	**PROJECT** CMT3 Borehole Log (MOE Tag A145143)		**SHEET NO.** 1 of 2	**CORE NO.** 1
SITE LOCATION K22A Mannheim	**COORDINATES**	**LOGGED BY** Cailin Hillier	**DATE LOGGED** 04 July, 2013	
DRILLER/ DRILL EQUIPMENT Tim and Don / Aardvark Drill Rig	**WEATHER CONDITIONS** Sunny, clear	**TOTAL DEPTH** 37 ft	**GROUND ELEVATION**	

WELL DESIGN (m)	MAIN COMPONENT SUMMARY	DEPTH (ft)	DEPTH (m)	SAMPLE COLLECTED	U.S.C.S.	DESCRIPTION AND CLASSIFICATION Colour, main component, minor component (s), moisture content, consistency description, structure, and depth range.
1.01 m stick-up BENTONITE HOLE PLUG	ORGANIC	10	3.05			Top soil then sand.
3.66	SAND	12	3.66	SS/bag	SW	Brown, SAND, damp, medium grain size, homogeneous (10-12ft).
WELL FILL	SAND	14.5	4.42	SS/bag	SW	Brown, SAND, wet, medium becoming more coarse with depth, homogeneous (12.5-14.5).
4.11	SAND	17	5.18	SS/bag	SW	Brown, SAND, wet, coarse, homogeneous (15-17). Trace gravel in bottom 3' (<0.5cm ø).
5.28	SAND	19.5	5.94	SS/bag	SW-GW	Brown, SAND, wet, coarse, homogeneous (17.5-19.5). Some gravel (0.5-1.5cm ø).
	SAND	22	6.71	SS/bag	SW	Brown, SAND, wet, coarse, homogeneous (20-22). Gravel lens 1cm thick (20.5).
6.45	SAND/SILT	24.5	7.47	SS/bag	SW	Brown, SAND, wet, coarse, homogeneous (22.5-24.5). Little gravel (0.5cm ø).
7.60	SAND/SILT	27	8.23	SS/bag SS/bag	SW-CL	Brown, SAND, wet, coarse, homogeneous (25-26). Gravel lens (1-2cm ø) with coarse sand matrix (26-26'2"). Brown, clayey SILT, increasing to fine sand with depth, hard-packed, showed elasticity (26'2"-27).

8.77	SAND/gravelly SAND	29.5	8.99	SS/bag SS/bag	SW-CL	Brown, SAND, wet, coarse, homogeneous (27.5-28). Trace gravel (<0.5cm ø). Brown, SAND, wet, fine, homogeneous (6”). Brown, SILT, wet (3”). Brown, SAND, wet, medium, homogeneous (28’9”-29.5).
	SAND/gravelly SAND	32	9.75	SS/bag SS/bag	SW-GW	Brown, SAND, wet, coarse, homogeneous (30-31). Trace gravel (1-1.5cm ø), sub-angular. Brown, SAND, wet, medium, homogeneous (30-31). Trace gravel (1-4cm long), sub-angular.
9.94	SAND	34.5	10.51	SS/bag	SW	Brown, SAND, wet, coarse-medium becoming finer with depth to fine-medium (32.5-34.5). Trace gravel (<5mm ø).
11.14 NATURAL SAND	SAND	37	11.28	SS/bag	SW	Brown/light brown, SAND, wet, medium grain size (35-37). Little gravel (<5mm ø).

13-009600

Ontario Ministry of the Environment

Well Tag No. (Place Sticker and/or Print Below) A145143

Well Record

Regulation 903 Ontario Water Resources Act

Measurements recorded in: ☐ Metric ☑ Imperial

Page 1 of 1

Well Owner's Information

First Name	Last Name / Organization	E-mail Address	☐ Well Constructed by Well Owner
Region of Waterloo			

Mailing Address (Street Number/Name)	Municipality	Province	Postal Code	Telephone No. (inc. area code)
150 Frederick Street	Kitchener	ON	N2G4J3	5195754400

Well Location

Address of Well Location (Street Number/Name)	Township	Lot	Concession
1181 Bleams Rd			

County/District/Municipality	City/Town/Village	Province	Postal Code
	Mannheim	Ontario	

UTM Coordinates	Zone	Easting	Northing	Municipal Plan and Sublot Number	Other
NAD 83	17	536525	4805052		

Overburden and Bedrock Materials/Abandonment Sealing Record (see instructions on the back of this form)

General Colour	Most Common Material	Other Materials	General Description	Depth (m/ft) From	To
brown	sand	silt / stones	topsoil	0	.5'
brown	sand + gravel		coarse	.5'	5'
brown	sand (med - coarse)	silt	silt stringers	5'	36'

Annular Space

Depth Set at (m/ft) From	To	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
0	2'	concrete	
2'	10'	H.P. - bentonite	
10'	36'	sand - grade 3	

Method of Construction

☐ Cable Tool ☐ Diamond ☐ Rotary (Conventional) ☐ Jetting ☐ Rotary (Reverse) ☐ Driving ☑ Boring ☐ Digging ☐ Air percussion ☐ Other, specify

Well Use

☐ Public ☐ Commercial ☐ Not used ☐ Domestic ☐ Municipal ☐ Dewatering ☐ Livestock ☑ Test Hole ☑ Monitoring ☐ Irrigation ☐ Cooling & Air Conditioning ☐ Industrial ☐ Other, specify

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft) From	To
	7 port CMT			

Status of Well

☐ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☑ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify ☐ Other, specify

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft) From	To
	7 port CMT			

Water Details

Water found at Depth 12' ~~75~~ (m/ft) Kind of Water: ☐ Fresh ☑ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Water found at Depth (m/ft) Kind of Water: ☐ Fresh ☐ Untested ☐ Gas ☐ Other, specify

Hole Diameter

Depth (m/ft) From	To	Diameter (cm/in)
0	36	8.25

Results of Well Yield Testing

After test of well yield, water was: ☐ Clear and sand free ☐ Other, specify

If pumping discontinued, give reason:

Pump intake set at (m/ft)

Pumping rate (l/min / GPM)

Duration of pumping ___ hrs + ___ min

Final water level end of pumping (m/ft)

If flowing give rate (l/min / GPM)

Recommended pump depth (m/ft)

Recommended pump rate (l/min / GPM)

Well production (l/min / GPM)

Disinfected? ☐ Yes ☐ No

Draw Down Time (min)	Water Level (m/ft)	Recovery Time (min)	Water Level (m/ft)
Static Level			
1		1	
2		2	
3		3	
4		4	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

Map of Well Location

Please provide a map below following instructions on the back.

Well Contractor and Well Technician Information

Business Name of Well Contractor: Aardvark Drilling Inc.

Well Contractor's Licence No.: 7238

Business Address (Street Number/Name): 25 Lewis Rd.

Municipality: Guelph

Province: ON Postal Code: N1H1E9 Business E-mail Address: www.aardvarkdrillinginc.com

Bus. Telephone No. (inc. area code): 5198269310

Name of Well Technician (Last Name, First Name): Grant, DON

Well Technician's Licence No.: 3311

Signature of Technician and/or Contractor

Date Submitted: 20130705

Comments: see attached map close to road - MW-3 on map

Well owner's information package delivered ☐ Yes ☐ No

Date Package Delivered: Y Y Y Y M M D D

Date Work Completed: 20130703

Ministry Use Only

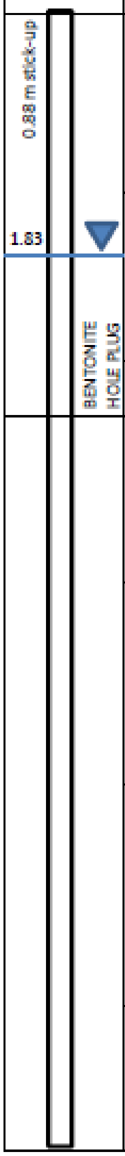
Audit No. Z169155

Received

0506E (2007/12) © Queen's Printer for Ontario, 2007

Ministry's Copy

BOREHOLE LOG	PROJECT MWA Borehole Log (MOE Tag A146040)		SHEET NO. 1 of 2	CORE NO. 1
SITE LOCATION K22A Mannheim	COORDINATES	LOGGED BY Cailin Hillier	DATE LOGGED 11 July, 2013	
DRILLER/ DRILL EQUIPMENT Steve and Mike/ Aardvark Drill Rig	WEATHER CONDITIONS Sunny, clear	TOTAL DEPTH 60 ft	GROUND ELEVATION	



WELL DESIGN (m)	MAIN COMPONENT SUMMARY	DEPTH (ft)	DEPTH (m)	SAMPLE COLLECTED	U.S.C.S.	DESCRIPTION AND CLASSIFICATION **Colour, main component, minor component (s), moisture content, consistency description, structure, and depth range.**
	ORGANIC	5	1.52			Medium brown top soil, fist-sized stones. Sound of large gravel and stones initially.
	ORGANIC/ SAND	9.5	2.90	SS/bag	SW	Empty split spoon with crushed granite and top soil (7.5-8.5). SAND, wet, medium-fine sand, homogeneous. Trace gravel (0.5-1.5cm ø).
	SAND	17	5.18	SS/bag	SW	Light brown, SAND, wet, coarse becoming increasingly fine with depth to medium (15-17). No gravel.
	SAND	22	6.71	SS/bag	SW	Light brown, SAND, wet, medium-fine grain, homogeneous (20-22). Bottom half of auger full.
	SAND	27	8.23	SS/bag	SW-CL	Light brown, SAND, wet, medium-fine grain, homogeneous (25-26.5). Trace gravel (<3mm ø). Grayish brown, clayey SILT, wet, hard-packed, homogeneous (26.5-27).
	SAND	29.5	8.99	SS/bag	SW	Light brown, SAND, wet, fine grain, homogeneous (27.5-29). Light brown, SAND, wet, coarse grain, homogeneous (29-29.5). Trace gravel (~3mm ø).

		SAND/SILT	31.5	9.60	SS/bag	SW	Bottom half of auger full. Light brown, SAND, wet, fine grain, homogeneous (30.5-31). Light brown, SAND, wet, coarse grain, homogeneous (31-31.5).
		SAND/SILT	37	11.28	SS/bag	SW-CL	Grayish-brown, SAND, wet, medium-coarse grain, homogeneous (35-37) Little gravel (~1cm ø).
		SAND/gravel y SAND	42	12.80	SS	SW	Brown, SAND, wet, medium grain, homogeneous (40-42). No gravel.
		SAND/gravel y SAND	47	14.33	SS	SW	Brown, SAND, wet, medium-coarse grain, homogeneous (45-47). Some gravel (<3cm ø) in bottom 6".
		SAND	52	15.85	SS/bag	SW-GW	Brown, SAND, wet, medium-coarse grain, homogeneous (50-52). Gravel lens (1mm-1cm ø, blue, yellow, green, orange, black, gray) in bottom 6".
		SAND	57	17.37	SS/bag	SW	Light-brown, SAND, wet, medium grain, homogeneous (55-56). Gray, SAND, wet, coarse sand intermixed with medium sand (56-57). Gravel (<2cm ø), clay pebbles/blobs.
	NATURAL SAND	SAND	60	18.29	SS	SW	Grayish-brown, SAND, wet, coarse, homogeneous (58-60).
18.43							

13-0096-00

Ontario Ministry of the Environment

Well Tag No. (Place Sticker and/or Print Below)

Tag#: A146040

Well Record

Regulation 903 Ontario Water Resources Act

Page 1 of 1

Measurements recorded in: ☐ Metric ☐ Imperial

Well Owner's Information

First Name	Last Name / Organization	E-mail Address	☐ Well Constructed by Well Owner
University of Waterloo, Physics Research Group c/o Denise Huck			

Mailing Address (Street Number/Name)	Municipality	Province	Postal Code	Telephone No. (inc. area code)
200 University Avenue West	Waterloo	ON	N2L3G1	5198884567

Well Location

Address of Well Location (Street Number/Name)	Township	Lot	Concession
South/West corner of Bleams Rd @ Alder Creek	Wilmot		

County/District/Municipality	City/Town/Village	Province	Postal Code
Waterloo	Manheim	Ontario	

UTM Coordinates	Zone	Easting	Northing	Municipal Plan and Sublot Number	Other
NAD 83	17	536513	4805050		

Overburden and Bedrock Materials/Abandonment Sealing Record (see instructions on the back of this form)

General Colour	Most Common Material	Other Materials	General Description	Depth (m/ft) From	To
Brown	Stones/Sand	FS	Fill	0'	4'
Brown	Sand			4'	60'

Annular Space

Depth Set at (m/ft) From	To	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
60'	11'10"	Sand/Native	
11'10"	18"	Bentonite Chips	
18"	0'	Concrete	

Results of Well Yield Testing

After test of well yield, water was: ☐ Clear and sand free ☐ Other, specify

If pumping discontinued, give reason:

Pump intake set at (m/ft)

Pumping rate (l/min / GPM)

Duration of pumping ___ hrs + ___ min

Final water level end of pumping (m/ft)

If flowing give rate (l/min / GPM)

Recommended pump depth (m/ft)

Recommended pump rate (l/min / GPM)

Well production (l/min / GPM)

Disinfected? ☐ Yes ☐ No

Draw Down Time (min)	Water Level (m/ft)	Recovery Time (min)	Water Level (m/ft)
Static Level			
1		1	
2		2	
3		3	
4		4	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

Method of Construction

☐ Cable Tool ☐ Diamond ☐ Rotary (Conventional) ☐ Jetting ☐ Rotary (Reverse) ☐ Driving ☒ Boring 4¼" H.S.A. ☐ Digging ☐ Air percussion ☐ Other, specify

Well Use

☐ Public ☐ Commercial ☐ Not used ☐ Domestic ☐ Municipal ☐ Dewatering ☐ Livestock ☐ Test Hole ☒ Monitoring ☐ Irrigation ☐ Cooling & Air Conditioning ☐ Industrial ☐ Other, specify

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft) From	To
2"	Plastic	1/8"	50'	+3'

Status of Well

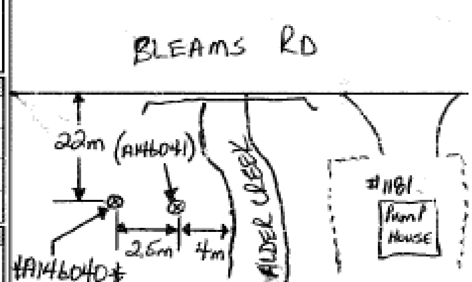
☐ Water Supply ☐ Replacement Well ☐ Test Hole ☐ Recharge Well ☐ Dewatering Well ☒ Observation and/or Monitoring Hole ☐ Alteration (Construction) ☐ Abandoned, Insufficient Supply ☐ Abandoned, Poor Water Quality ☐ Abandoned, other, specify ☐ Other, specify

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft) From	To
2¼"	Plastic	0.010	60'	50'

Map of Well Location

Please provide a map below following instructions on the back.



Comments:

Water Details

Water found at Depth	Kind of Water
8 (m/ft) ☐ Gas	☐ Fresh ☒ Untested ☐ Other, specify
(m/ft) ☐ Gas	☐ Fresh ☐ Untested ☐ Other, specify
(m/ft) ☐ Gas	☐ Fresh ☐ Untested ☐ Other, specify

Hole Diameter

Depth (m/ft) From	To	Diameter (cm/in)
0'	60'	8"

Well Contractor and Well Technician Information

Business Name of Well Contractor	Well Contractor's Licence No.
Aardvark Drilling Inc.	7238

Business Address (Street Number/Name)	Municipality
25-C Lewis Road	Guelph

Province	Postal Code	Business E-mail Address
ON	N1H 1E9	www.aardvarkdrillinginc.com

Bus. Telephone No. (inc. area code)	Name of Well Technician (Last Name, First Name)
5198269348	Grant Mike

Well Technician's Licence No.	Signature of Technician and/or Contractor	Date Submitted
3564		20130715

Well owner's information package delivered	Date Package Delivered	Ministry Use Only
☐ Yes ☐ No	YYYYMMDD	Audit No. Z 169197
	Date Work Completed: 20130711	

0506E (2007/12) © Queen's Printer for Ontario, 2007

Ministry's Copy

BOREHOLE LOG	PROJECT MWB Borehole Log (MOE Tag A146041)		SHEET NO. 1 of 1	CORE NO. 1
SITE LOCATION K22A Mannheim	COORDINATES	LOGGED BY Cailin Hillier	DATE LOGGED 12 July, 2013	
DRILLER/ DRILL EQUIPMENT Mike and Craig/ Aardvark Drill Rig	WEATHER CONDITIONS Sunny, clear	TOTAL DEPTH 42 ft	GROUND ELEVATION	

WELL DESIGN (m)	MAIN COMPONENT SUMMARY	DEPTH (ft)	DEPTH (m)	SAMPLE COLLECTED	U.S.C.S.	DESCRIPTION AND CLASSIFICATION Colour, main component, minor component (s), moisture content, consistency description, structure, and depth range.
0.84 m stick-up	ORGANIC	5	1.52			Top soil with stones.
2.13 BENTONITE HOLE PLUG	SAND/ GRAVEL	12	3.66	SS	SW- GW	SAND, wet, medium-coarse grain, homogeneous (10-11.5). Some gravel. Gravel (sub angular to sub-rounded, 0.5-7cm ø) with medium sand matrix (11.5-12).
	SAND	22	6.71	SS/bag	SW	Brown, SAND, wet, fine-medium grain becoming increasingly coarse in bottom 3", homogeneous (20-22). No gravel.
	SAND	27	8.23	SS/bag	SW	Grayish-brown, SAND, wet, coarse-medium grain, homogenous (25-27). Little gravel (3-6mm ø).
	SAND	32	9.75	SS/bag	SW	Grayish-brown, SAND, wet, coarse-medium, fairly homogeneous (30-32). Little gravel (<5mm ø, one 4cm piece).
	SAND/SILT	37	11.28	SS/bag	SW	Grayish-brown, SAND, wet, finer-coarse, homogeneous (35-37). Little gravel (~5mm ø, sub-rounded).
12.33 NATURAL SAND	SAND/SILT	42	12.80	SS/bag	SW	Grayish-brown, SAND, wet, medium-coarse, homogeneous (40-42). Trace gravel (<1cm ø, one piece >1cm).

13-0096-00

Ontario Ministry of the Environment

Well Tag No. (Place Sticker and/or Print Below) A14... **Tag#: A146041**

Well Record

Regulation 903 Ontario Water Resources Act

Measurements recorded in: ☐ Metric ☐ Imperial

Page 1 of 1

Well Owner's Information

First Name	Last Name / Organization	E-mail Address	☐ Well Constructed by Well Owner
University of Waterloo, Physics Research Group c/o Denise Huck			

Mailing Address (Street Number/Name)	Municipality	Province	Postal Code	Telephone No. (inc. area code)
200 University Avenue West	Waterloo	ON	N2L3G1	5198884567

Well Location

Address of Well Location (Street Number/Name)	Township	Lot	Concession
SOUTH/WEST CORNER OF BLEAMS RD @ ALDER CREEK	Wilmot		

County/District/Municipality	City/Town/Village	Province	Postal Code
WATERLOO	MANHEIM.	Ontario	

UTM Coordinates Zone Easting Northing: NAD 83 | 17 | 536514 | 4805046

Municipal Plan and Sublot Number:

Other:

Overburden and Bedrock Materials/Abandonment Sealing Record (see instructions on the back of this form)

General Colour	Most Common Material	Other Materials	General Description	Depth (m/ft) From	To
BROWN	STONES/SAND		FILL	0'	4'
BROWN	SAND			4'	40'

Annular Space

Depth Set at (m/ft) From	To	Type of Sealant Used (Material and Type)	Volume Placed (m³/ft³)
40'	11'11"	SAND/NATIVE	
11'11"	18"	BENTONITE CHIPS	
18"	0'	CONCRETE.	

Method of Construction

☐ Cable Tool ☐ Diamond
☐ Rotary (Conventional) ☐ Jetting
☐ Rotary (Reverse) ☐ Driving
☒ Boring 4¼" H.S.A. ☐ Digging
☐ Air percussion
☐ Other, specify

Well Use

☐ Public ☐ Commercial ☐ Not used
☐ Domestic ☐ Municipal ☐ Dewatering
☐ Livestock ☐ Test Hole ☒ Monitoring
☐ Irrigation ☐ Cooling & Air Conditioning
☐ Industrial
☐ Other, specify

Construction Record - Casing

Inside Diameter (cm/in)	Open Hole OR Material (Galvanized, Fibreglass, Concrete, Plastic, Steel)	Wall Thickness (cm/in)	Depth (m/ft) From	To
2"	PLASTIC	1/8"	30'	+3'

Status of Well

☐ Water Supply
☐ Replacement Well
☐ Test Hole
☐ Recharge Well
☐ Dewatering Well
☒ Observation and/or Monitoring Hole
☐ Alteration (Construction)
☐ Abandoned, Insufficient Supply
☐ Abandoned, Poor Water Quality
☐ Abandoned, other, specify
☐ Other, specify

Construction Record - Screen

Outside Diameter (cm/in)	Material (Plastic, Galvanized, Steel)	Slot No.	Depth (m/ft) From	To
2¼"	PLASTIC	0.010	40'	30'

Water Details

Water found at Depth 8 (m/ft) ☐ Gas — Kind of Water: ☐ Fresh ☒ Untested ☐ Other, specify

Water found at Depth (m/ft) ☐ Gas — Kind of Water: ☐ Fresh ☐ Untested ☐ Other, specify

Water found at Depth (m/ft) ☐ Gas — Kind of Water: ☐ Fresh ☐ Untested ☐ Other, specify

Hole Diameter

Depth (m/ft) From	To	Diameter (cm/in)
0'	40'	8"

Well Contractor and Well Technician Information

Business Name of Well Contractor	Well Contractor's Licence No.
Aardvark Drilling Inc.	7238

Business Address (Street Number/Name)	Municipality
25-C Lewis Road	Guelph

Province	Postal Code	Business E-mail Address
ON	N1H1E9	www.aardvarkdrillinginc.com

Bus. Telephone No. (inc. area code)	Name of Well Technician (Last Name, First Name)
5198269340	GRANT MIKE

Well Technician's Licence No.	Signature of Technician and/or Contractor	Date Submitted
3564		20130715

Results of Well Yield Testing

After test of well yield, water was: ☐ Clear and sand free ☐ Other, specify

If pumping discontinued, give reason:

Pump intake set at (m/ft)

Pumping rate (l/min / GPM)

Duration of pumping ___ hrs + ___ min

Final water level end of pumping (m/ft)

If flowing give rate (l/min / GPM)

Recommended pump depth (m/ft)

Recommended pump rate (l/min / GPM)

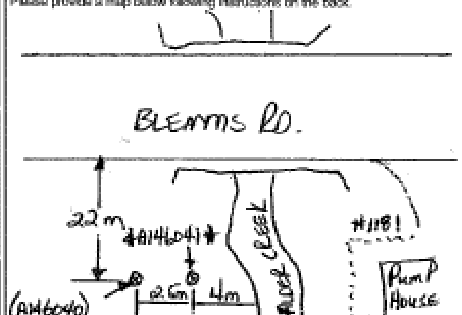
Well production (l/min / GPM)

Disinfected? ☐ Yes ☐ No

Draw Down Time (min)	Water Level (m/ft)	Recovery Time (min)	Water Level (m/ft)
Static Level			
1		1	
2		2	
3		3	
4		4	
5		5	
10		10	
15		15	
20		20	
25		25	
30		30	
40		40	
50		50	
60		60	

Map of Well Location

Please provide a map below following instructions on the back.



Comments:

Well owner's information package delivered	Date Package Delivered	Ministry Use Only
☐ Yes ☐ No	YYYYMMDD	Audit No. Z 169198
	Date Work Completed 20130712	Received

0506E (2007/12) © Queen's Printer for Ontario, 2007 — Ministry's Copy

Appendix F. Survey Data for Wells on K22A Site

Description	Northing (m)	Easting (m)	Elevation (masl)	Elevation TOC (masl)
1A-11	4805001.10	536525.58	335.94	336.82
1B-11	4805002.68	536525.40	335.91	336.74
2-11	4805046.71	536526.29	336.71	337.66
3B-09	4805046.53	536524.66	336.46	337.41
3A-09	4804995.20	536550.89	336.65	337.61
3-11	4804997.82	536550.01	336.57	337.44
TW 2-13	4805044.10	536525.62	336.40	337.10
UW MWA	4805041.61	536510.32	335.91	336.91
UW MWB	4805041.67	536512.51	335.88	336.78
DP 1-13	4805042.31	536517.22	335.06	336.41
DP 2-13	4805051.44	536515.15	335.30	336.51
CMT1-1	4805043.25	536520.99	336.06	336.91
CMT1-2			336.06	336.91
CMT1-3			336.06	336.91
CMT1-4			336.06	336.91
CMT1-5			336.06	336.91
CMT1-6			336.06	336.91
CMT1-7			336.06	336.91
CMT2A-1	4805044.61	536531.42	337.79	338.46
CMT2A-2			337.79	338.46
CMT2A-3			337.79	338.46
CMT2A-4			337.79	338.46
CMT2A-5			337.79	338.46
CMT2A-6			337.79	338.46
CMT2A-7			337.79	338.46
CMT2B-1	4805044.62	536531.25	337.79	338.50
CMT2B-2			337.79	338.50
CMT2B-3			337.79	338.50
CMT2B-4			337.79	338.50
CMT2B-5			337.79	338.50
CMT2B-6			337.79	338.50
CMT2B-7			337.79	338.50
CMT3-1	4805056.21	536525.08	336.94	338.00
CMT3-2			336.94	338.00
CMT3-3			336.94	338.00
CMT3-4			336.94	338.00
CMT3-5			336.94	338.00
CMT3-6			336.94	338.00
CMT3-7			336.94	338.00

Appendix G. Initial Permit to Take Water

CONTENT COPY OF ORIGINAL

Ontario

Ministry of the Environment
Ministère de l'Environnement

PERMIT TO TAKE WATER
Ground Water
NUMBER 5116-97GNA2

Pursuant to Section 34 of the Ontario Water Resources Act, R.S.O. 1990 this Permit To Take Water is hereby issued to:

	The Regional Municipality of Waterloo 150 Frederick St 7th Floor Kitchener, Ontario N2G 4J3
For the water taking from:	Test Well (TW2-13)
Located at:	Lot 2, Concession German Block SBR, Geographic Township of Wilmot Wilmot, Regional Municipality of Waterloo

For the purposes of this Permit, and the terms and conditions specified below, the following definitions apply:

DEFINITIONS

(a) "Director" means any person appointed in writing as a Director pursuant to section 5 of the OWRA for the purposes of section 34, OWRA.

(b) "Provincial Officer" means any person designated in writing by the Minister as a Provincial Officer pursuant to section 5 of the OWRA.

(c) "Ministry" means Ontario Ministry of the Environment.

(d) "District Office" means the Guelph District Office.

(e) "Permit" means this Permit to Take Water No. 5116-97GNA2 including its Schedules, if any, issued in accordance with Section 34 of the OWRA.

(f) "Permit Holder" means The Regional Municipality of Waterloo.

(g) "OWRA " means the *Ontario Water Resources Act*, R.S.O. 1990, c. O. 40, as amended.

You are hereby notified that this Permit is issued subject to the terms and conditions outlined below:

TERMS AND CONDITIONS

1. Compliance with Permit

1.1 Except where modified by this Permit, the water taking shall be in accordance with the application for this Permit To Take Water, dated April 16, 2013 and signed by Richard Wootton, and all Schedules included in this Permit.

1.2 The Permit Holder shall ensure that any person authorized by the Permit Holder to take water under this Permit is provided with a copy of this Permit and shall take all reasonable measures to ensure that any such person complies with the conditions of this Permit.

1.3 Any person authorized by the Permit Holder to take water under this Permit shall comply with the conditions of this Permit.

Appendix H. Pumping Rate and Totalizer Readings

Date	Flow Meter (L/s)	Totalizer (m^3 x .1)
19/08/2013 10:40	15	17148
19/08/2013 11:40	13	
19/08/2013 14:44	13	17343.7
20/08/2013 9:49	12.6 - 13	18243
20/08/2013 12:00	12.6 - 13	18345.6
20/08/2013 16:10	12.6 - 13	18541.7
20/08/2013 11:44	13	18332.9
21/08/2013 11:35	13	19455.8
21/08/2013 12:00	11	
21/08/2013 13:58	11	19554.3
22/08/2013 9:45	11	20355.8
22/08/2013 14:51	11	20562.6
26/08/2013 11:06	11	24344.1
26/08/2013 11:30	10.5 - 11	24320.2
28/08/2013 12:48	10.5 - 11	26311.4
29/08/2013 11:20	11	27214.9
29/08/2013 13:30	10.3 - 11	27315
30/08/2013 11:35	10.5 - 11	28185.6
01/09/2013 8:35		
03/09/2013 14:03	10.3 - 10.7	32115.7
04/09/2013 10:19	10.5	32923.4
06/09/2013 12:00	10.5-10.8	34904.8
13/09/2013 10:25	10.5-10.8	41532.1
23/09/2013 10:22		48352.5
24/09/2013 9:47	6.5	48917
26/09/2013 12:47	11	50678.8
27/09/2013 13:32	11	51696
9/30/13 9:40	11	54505.7
10/1/13 0:00	11	55656.4
10/8/13 10:15	11	62464.3
10/9/13 11:36	11	63516.6
10/15/13 13:15	11	69597.5
10/16/13 13:05	11.2	70596.9
10/17/13 14:55	11	71684.5
10/17/13 15:00	--	71684.5

Appendix I. Second Permit to Take Water

Ministry of the Environment	Ministère de l'Environnement
West-Central Region	Direction régionale du Centre-Ouest
Technical Support Section	Secteur du Soutien Technique
12th Floor	12e étage
119 King St W	119 rue King W
Hamilton ON L8P 4Y7	Hamilton ON L8P 4Y7
Fax: (905)521-7820	Télécopieur: (905)521-7820
Tel: (905) 521-7720	Tél:(905) 521-7720

Ontario

September 23, 2013

The Regional Municipality of Waterloo
150 Frederick St 7th Floor
Kitchener, Ontario
N2G 4J3

Attention: Mr. Richard Wooton

Dear Mr. Wooton

RE: Test Well (TW2-13)
Amendment to Table A
Reference Number 8718-96ZLKX

NOTICE

Pursuant to s. 100, Ontario Water Resources Act, R.S.O. 1990, c. O.40 as amended, I am issuing notice that, as Director of Section 34 of the Ontario Water Resources Act, I am exercising my discretion to amend Permit to Take Water 5116-97GNA2 Table A. All other terms and conditions of Permit to Take Water 5116-97GNA2 shall continue in force.

The reason for this amendment is an email dated September 20, 2013 from Mr. Richard Wooton requesting additional days of pumping test due to unforeseen interruption of the testing regime.

Table A is hereby revoked and replaced as follows:

	Source Name / Description:	Source: Type:	Taking Specific Purpose:	Taking Major Category:	Max. Taken per Minute (litres):	Max. Num. of Hrs Taken per Day:	Max. Taken per Day (litres):	Max. Num. of Days Taken per Year:	Zone/ Easting/ Northing:
1	Test Well TW2-13	Well Drilled	Pumping Test	Miscellaneous	1,200	24	1,728,000	60	17 536554 4805002
						Total Taking:	1,728,000		

Appendix J. The Resistance Temperature Detector Data

Note: Temperature in °C

	CMT 1						
Date	**CMT1-1**	**CMT1-2**	**CMT1-3**	**CMT1-4**	**CMT1-5**	**CMT1-6**	**CMT1-7**
16/08/2013	14.865	12.582	13.580	8.279	7.946	7.907	7.806
17/08/2013	14.851	12.902	13.617	8.384	7.954	7.862	7.894
18/08/2013	14.863	12.786	13.647	8.401	7.978	7.964	7.919
19/08/2013	14.822	13.040	14.341	8.732	8.455	8.267	8.590
20/08/2013	14.812	13.296	15.254	9.335	9.002	8.569	9.315
21/08/2013			15.406	9.303	8.987	8.714	9.307
22/08/2013			15.488	9.303	8.984	8.964	9.315
23/08/2013			15.622	9.386	9.076	9.179	9.363
24/08/2013			15.709	9.457	9.122	9.273	9.576
25/08/2013			15.773	9.511	9.147	9.279	9.744
26/08/2013	14.938	14.078	15.794	9.551	9.164	9.262	9.838
27/08/2013	14.930	14.089	15.840	9.614	9.204	9.287	9.792
28/08/2013	14.936	14.092	15.856	9.658	9.236	9.291	9.910
29/08/2013	14.941	14.096	15.876	9.699	9.238	9.269	9.919
30/08/2013	14.941	14.095	15.896	9.728	9.261	9.285	9.969
31/08/2013	14.997	14.093	15.902	9.756	9.282	9.305	10.019
01/09/2013	15.049	14.095	15.886	9.788	9.305	9.299	10.025
02/09/2013	15.096	14.095	15.879	9.809	9.340	9.309	10.058
03/09/2013	15.083	14.106	15.858	9.805	9.352	9.278	10.047
04/09/2013	15.283	14.126	15.891	9.841	9.431	9.720	10.562
05/09/2013	15.488	14.160	15.911	9.855	9.473	9.323	10.093
06/09/2013	15.545	14.182	15.951	9.869	9.498	9.325	10.092
07/09/2013	15.644	14.304	15.988	9.867	9.514	9.329	10.096
08/09/2013	15.672	14.480	16.024	9.894	9.549	9.347	10.099
09/09/2013	15.694	14.625	16.088	9.935	9.582	9.378	10.097
10/09/2013	15.596	14.726	16.081	9.930	9.567	9.392	10.100
11/09/2013	15.699	14.848	16.166	9.994	9.621	9.337	10.117
12/09/2013	15.698	14.870	16.221	10.047	9.658	9.399	10.165
13/09/2013	15.696	14.883	16.277	10.119	9.693	9.423	10.122
14/09/2013	15.697	14.885	16.313	10.155	9.724	9.442	10.110
15/09/2013	15.694	14.861	16.345	10.187	9.745	9.494	10.124
16/09/2013	15.608	14.853	16.322	10.184	9.745	9.553	10.128
17/09/2013	15.692	14.807	16.389	10.270	9.792	9.621	10.183
18/09/2013	15.788	14.889	16.398	10.269	9.805	9.607	10.189
19/09/2013	15.782	14.895	16.426	10.293	9.836	9.625	10.211
20/09/2013	15.712	14.804	16.182	9.799	9.304	9.223	9.601
21/09/2013	15.705	14.711	15.873	9.983	9.073	9.094	8.967
22/09/2013	15.476	14.482	16.115	11.569	10.072	9.789	9.639

Appendix J. (Continued)

Date	CMT 1						
	CMT1-1	CMT1-2	CMT1-3	CMT1-4	CMT1-5	CMT1-6	CMT1-7
23/09/2013	15.013	14.143	15.944	10.974	9.938	9.656	9.706
24/09/2013	14.908	14.129	16.045	10.739	10.167	10.081	10.210
25/09/2013	14.900	14.295	16.111	10.589	10.094	10.077	10.515
26/09/2013	14.908	14.340	16.195	10.583	10.130	10.039	10.797
27/09/2013	14.896	14.423	16.233	10.563	10.156	9.976	10.754
28/09/2013	14.896	14.453	16.260	10.571	10.201	10.056	10.793
29/09/2013	14.895	14.455	16.282	10.602	10.276	10.103	10.844
30/09/2013	14.898	14.376	16.294	10.657	10.359	10.111	10.882
01/10/2013	14.895	14.440	16.300	10.686	10.377	10.101	10.883
02/10/2013	14.890	14.421	16.307	10.730	10.385	10.113	10.903
03/10/2013	14.886	14.367	16.323	10.775	10.394	10.115	10.897
04/10/2013	14.873	14.304	16.317	10.790	10.386	10.112	10.888
05/10/2013	14.833	14.228	16.313	10.822	10.387	10.110	10.876
06/10/2013	14.775	14.172	16.287	10.814	10.381	10.111	10.853
07/10/2013	14.556	14.127	16.280	11.400	10.621	10.339	11.236
08/10/2013	14.427	14.119	16.239	11.574	10.751	10.354	11.122
09/10/2013	14.539	14.122	16.235	11.159	10.599	10.146	10.896
10/10/2013	14.560	14.097	16.237	11.033	10.558	10.121	10.892
11/10/2013	14.541	14.094	16.252	10.999	10.547	10.115	10.894
12/10/2013	14.527	14.094	16.261	11.001	10.565	10.118	10.885
13/10/2013	14.597	14.094	16.269	11.024	10.609	10.116	10.889
14/10/2013	14.680	14.496	16.282	11.050	10.685	10.115	10.892
15/10/2013	14.995	15.339	16.282	11.052	10.703	10.118	10.887
16/10/2013	14.482	14.353	16.268	11.054	10.701	10.150	10.892
17/10/2013	14.174	14.076	16.119	10.749	10.280	9.809	10.310
18/10/2013	14.208	14.073	15.763	10.431	9.595	9.310	9.081
19/10/2013	14.166	14.046	15.692	10.424	9.580	9.309	9.077
20/10/2013	14.119	14.033	15.633	10.437	9.625	9.310	9.107
21/10/2013	14.102	14.011	15.576	10.430	9.621	9.309	9.151
22/10/2013	14.093	13.827	15.539	10.445	9.643	9.309	9.181
23/10/2013	14.092	13.787	15.488	10.449	9.665	9.310	9.245
24/10/2013	14.090	13.709	15.467	10.460	9.711	9.315	9.261
25/10/2013	14.087	13.577	15.444	10.473	9.753	9.310	9.273
26/10/2013	14.074	13.494	15.400	10.475	9.778	9.326	9.272
27/10/2013	13.996	13.428	15.454	10.549	9.895	9.359	9.278
28/10/2013	13.883	13.384	15.461	10.573	9.910	9.368	9.286

Appendix J. (Continued)

Date	CMT 2A				CMT 2B			
	CMT2A-1	CMT2A-3	CMT2A-5	CMT2A-7	CMT2B-1	CMT2B-3	CMT2B-5	CMT2B-7
16/08/2013	11.697	8.855	6.910	7.689	8.721	9.089	9.309	9.160
17/08/2013	11.681	9.005	6.926	7.686	8.033	8.518	9.312	9.233
18/08/2013	11.695	9.157	7.003	7.700	8.188	8.514	9.309	9.238
19/08/2013	11.705	9.599	7.023	7.604	7.988	8.537	9.309	9.274
20/08/2013	11.701	10.094	6.962	6.948	7.716	8.558	9.309	9.277
21/08/2013	11.689	10.091	6.898	6.866	7.623	8.616	9.309	9.257
22/08/2013	11.379	10.010	6.892	6.697	7.593	8.760	9.309	9.227
23/08/2013	11.086	9.893	6.891	6.584	7.615	8.972	9.306	9.237
24/08/2013	10.901	9.556	6.856	6.523	7.689	9.170	9.305	9.201
25/08/2013	10.889	9.362	6.748	6.652	7.710	9.258	9.307	9.248
26/08/2013	10.766	9.297	6.624	6.752	7.720	9.308	9.303	9.193
27/08/2013	10.356	9.285	6.636	6.888	7.726	9.309	9.300	9.149
28/08/2013	10.114	9.180	6.727	6.909	7.771	9.312	9.295	9.080
29/08/2013	10.096	8.821	6.846	6.941	7.721	9.111	9.170	8.928
30/08/2013	10.071	8.518	6.755	7.029	8.146	9.313	9.288	9.027
31/08/2013	9.906	8.494	6.898	7.560	8.378	9.317	9.275	8.958
01/09/2013	9.624	8.485	7.075	7.704	8.494	9.323	9.263	8.964
02/09/2013	9.341	8.469	7.488	7.722	8.515	9.325	9.288	8.928
03/09/2013	9.300	8.388	7.681	7.901	8.545	9.330	9.259	8.829
04/09/2013	9.318	8.358	7.703	8.217	8.466	9.252	9.269	8.801
05/09/2013	9.312	8.382	7.867	8.458	8.649	9.316	9.247	8.807
06/09/2013	9.317	8.412	8.211	8.339	8.856	9.313	9.008	8.444
07/09/2013	9.361	8.488	8.472	8.513	9.035	9.315	9.250	8.754
08/09/2013	9.408	8.494	8.489	8.557	9.218	9.316	9.223	8.752
09/09/2013	9.572	8.514	8.555	8.742	9.284	9.315	9.219	8.716
10/09/2013	9.779	8.614	8.891	9.042	9.298	9.315	9.150	8.633
11/09/2013	9.980	8.937	9.211	9.249	9.315	9.314	9.210	8.697
12/09/2013	10.065	9.188	9.283	9.298	9.314	9.312	9.199	8.683
13/09/2013	10.087	9.287	9.285	9.306	9.313	9.310	9.193	8.702
14/09/2013	10.093	9.292	9.318	9.317	9.316	9.310	9.152	8.658
15/09/2013	10.093	9.293	9.478	9.323	9.316	9.310	9.135	8.641
16/09/2013	10.105	9.327	9.802	9.393	9.315	9.299	9.089	8.620
17/09/2013	10.134	9.405	9.931	9.446	9.032	9.055	8.800	8.220
18/09/2013	10.256	9.510	10.063	9.686	9.340	9.304	9.050	8.581
19/09/2013	10.362	9.638	10.083	9.838	9.338	9.294	9.017	8.586
20/09/2013	10.452	9.707	10.084	9.897	9.345	9.260	8.941	8.567
21/09/2013	10.456	9.565	10.086	9.817	9.339	9.263	8.959	8.570
22/09/2013	10.833	9.630	10.085	9.868	9.348	9.287	8.900	8.586
23/09/2013	11.454	9.914	10.086	9.926	9.366	9.252	8.887	8.550

Appendix J. (Continued)

Date	CMT 2A				CMT 2B			
	CMT2A-1	CMT2A-3	CMT2A-5	CMT2A-7	CMT2B-1	CMT2B-3	CMT2B-5	CMT2B-7
24/09/2013	11.687	10.093	10.086	10.012	9.341	9.227	8.874	8.531
25/09/2013	11.693	10.097	10.086	10.051	9.388	9.241	8.863	8.534
26/09/2013	11.685	10.142	10.087	10.093	9.473	9.244	8.822	8.520
27/09/2013	11.662	10.175	10.088	10.105	9.512	9.191	8.783	8.511
28/09/2013	11.632	10.249	10.094	10.102	9.499	9.191	8.783	8.511
29/09/2013	11.629	10.269	10.108	10.108	9.540	9.106	8.703	8.511
30/09/2013	11.590	10.335	10.168	10.108	9.562	9.103	8.686	8.517
01/10/2013	11.560	10.435	10.289	10.078	9.576	9.032	8.625	8.491
02/10/2013	11.560	10.435	10.430	10.109	9.623	9.002	8.620	8.509
03/10/2013	11.512	10.485	10.598	10.114	9.647	8.962	8.581	8.508
04/10/2013	11.461	10.521	10.711	10.108	9.650	8.859	8.581	8.508
05/10/2013	11.414	10.584	10.805	10.111	9.680	8.792	8.567	8.507
06/10/2013	11.416	10.614	10.827	10.117	9.642	8.745	8.546	8.508
07/10/2013	11.542	10.708	10.871	10.117	9.691	8.709	8.548	8.507
08/10/2013	11.719	10.892	10.877	10.120	9.682	8.615	8.521	8.509
09/10/2013	11.922	10.904	10.884	10.143	9.831	8.667	8.526	8.482
10/10/2013	11.967	10.927	10.887	10.152	9.862	8.629	8.532	8.504
11/10/2013	11.916	10.904	10.881	10.190	9.881	8.606	8.512	8.503
12/10/2013	11.795	10.902	10.887	10.154	9.865	8.570	8.509	8.509
13/10/2013	11.728	10.895	10.886	10.172	9.848	8.563	8.518	8.507
14/10/2013	11.708	10.892	10.884	10.159	9.807	8.556	8.509	8.500
15/10/2013	11.693	10.881	10.887	10.150	9.823	8.545	8.500	8.461
16/10/2013	11.693	10.889	10.887	10.154	9.757	8.526	8.512	8.506
17/10/2013	11.676	10.869	10.886	10.141	9.641	8.527	8.509	8.505
18/10/2013	11.692	10.899	10.847	10.080	9.440	8.474	8.461	8.426
19/10/2013	11.692	10.882	10.885	10.107	9.481	8.518	8.507	8.504
20/10/2013	11.698	10.891	10.862	10.107	9.478	8.526	8.505	8.501
21/10/2013	11.754	10.889	10.865	10.107	9.495	8.535	8.508	8.498
22/10/2013	11.979	10.891	10.859	10.106	9.433	8.517	8.507	8.495
23/10/2013	12.271	10.894	10.851	10.106	9.392	8.520	8.506	8.500
24/10/2013	12.453	10.905	10.806	10.069	9.407	8.542	8.464	8.439
25/10/2013	12.456	10.887	10.795	10.099			8.506	8.501
26/10/2013	12.487	10.890	10.775	10.101			8.506	8.495
27/10/2013	12.492	10.905	10.748	10.098			8.506	8.503
28/10/2013	12.492	10.925	10.751	10.095			8.505	8.503

Appendix J. (Continued)

Date	CMT 3			
	CMT3-1	CMT3-3	CMT3-5	CMT3-7
16/08/2013	15.700	13.297	9.294	8.517
17/08/2013	15.699	13.296	9.303	8.506
18/08/2013	15.700	13.296	9.297	8.516
19/08/2013	15.720	13.543	9.658	8.519
20/08/2013	15.760	14.067	10.607	8.517
21/08/2013	15.741	14.069	10.894	8.520
22/08/2013	15.663	13.595	10.976	8.518
23/08/2013	15.711	13.287	11.426	8.517
24/08/2013	15.687	12.706	11.556	8.516
25/08/2013	15.534	12.487	11.485	8.516
26/08/2013	15.078	12.240	11.154	8.517
27/08/2013	14.901	11.824	10.959	8.517
28/08/2013	14.885	11.721	10.897	8.517
29/08/2013	14.822	11.698	10.882	8.492
30/08/2013	14.633	11.696	10.840	8.517
31/08/2013	14.463	11.696	10.694	8.514
01/09/2013	14.311	11.694	10.526	8.517
02/09/2013	14.202	11.691	10.367	8.517
03/09/2013	14.128	11.671	10.205	8.515
04/09/2013	14.214	11.733	10.178	8.516
05/09/2013	14.120	11.629	10.108	8.515
06/09/2013	14.102	11.551	10.101	8.467
07/09/2013	14.109	11.341	10.093	8.515
08/09/2013	14.105	11.176	10.093	8.522
09/09/2013	14.101	10.979	10.087	8.518
10/09/2013	14.101	10.948	9.871	8.063
11/09/2013	14.097	10.917	10.035	8.523
12/09/2013	14.095	10.901	9.968	8.519
13/09/2013	14.094	10.898	9.869	8.513
14/09/2013	14.094	10.905	9.797	8.514
15/09/2013	14.091	10.898	9.683	8.513
16/09/2013	14.044	10.892	9.617	8.514
17/09/2013	14.088	10.893	9.587	8.469
18/09/2013	14.088	10.893	9.557	8.514
19/09/2013	14.080	10.892	9.529	8.515
20/09/2013	14.042	10.879	9.400	8.516
21/09/2013	14.056	11.212	9.318	8.515
22/09/2013	16.242	14.109	10.033	8.514
23/09/2013	16.531	14.923	10.348	8.515

Appendix J. (Continued)

	CMT 3			
Date	**CMT3-1**	**CMT3-3**	**CMT3-5**	**CMT3-7**
24/09/2013	16.493	15.068	10.819	8.238
25/09/2013	16.484	14.977	11.406	8.526
26/09/2013	16.451	14.896	11.693	8.526
27/09/2013	16.362	14.634	11.727	8.533
28/09/2013	16.229	14.117	11.807	8.519
29/09/2013	15.920	13.881	11.802	8.522
30/09/2013	15.733	13.310	11.724	8.520
01/10/2013	15.701	13.186	11.693	8.531
02/10/2013	15.678	12.637	11.687	8.528
03/10/2013	15.554	12.500	11.514	8.524
04/10/2013	15.245	12.465	11.130	8.526
05/10/2013	14.980	12.399	10.926	8.525
06/10/2013	14.916	12.236	10.892	8.526
07/10/2013	15.123	12.800	10.903	8.538
08/10/2013	15.700	14.705	11.602	8.529
09/10/2013	15.703	14.889	11.693	8.487
10/10/2013	15.704	14.461	11.699	8.535
11/10/2013	15.704	14.089	11.693	8.546
12/10/2013	15.698	13.837	11.693	8.541
13/10/2013	15.697	13.374	11.692	8.539
14/10/2013	15.693	13.282	11.686	8.535
15/10/2013	15.590	13.040	11.660	8.538
16/10/2013	15.385	12.558	11.472	8.545
17/10/2013	15.120	12.502	11.122	8.538
18/10/2013	14.954	12.493	10.877	8.528
19/10/2013	14.920	12.499	10.869	8.535
20/10/2013	14.931	12.667	10.838	8.566
21/10/2013	14.948	13.075	10.828	8.579
22/10/2013	14.953	13.279	10.843	8.591
23/10/2013	14.962	13.293	10.829	8.633
24/10/2013	15.022	13.290	10.823	8.640
25/10/2013	15.055	13.293	10.849	8.801
26/10/2013	15.102	13.307	10.867	8.864
27/10/2013	15.138	13.377	10.868	8.925
28/10/2013	15.157	13.444	10.880	8.940

Appendix K. Drive Point Surface Water and Groundwater Elevation Data

	DP1-13 GW			DP1-13 SW		
Date	Water Level Depth (mTOC)	Water Level Elevation (masl)	Temperature (°C)	Water Level Depth (mTOC)	Water Level Elevation (masl)	Temperature (°C)
14/08/2013	2.0239	334.3861	15.18	1.0803	335.3297	17.35
15/08/2013	2.0248	334.3852	15.01	1.0814	335.3286	14.48
16/08/2013	2.0258	334.3842	14.76	1.0772	335.3328	14.71
17/08/2013	2.0259	334.3841	15.21	1.0810	335.3290	15.83
18/08/2013	2.0256	334.3844	15.92	1.0851	335.3249	16.32
19/08/2013	2.0265	334.3835	16.32	1.0877	335.3223	16.60
20/08/2013	2.0261	334.3839	16.60	1.0938	335.3162	17.16
21/08/2013	2.0268	334.3832	17.40	1.0973	335.3127	18.25
22/08/2013	2.0246	334.3854	18.35	1.0954	335.3146	19.05
23/08/2013	2.0256	334.3844	18.33	1.1034	335.3066	17.83
24/08/2013	2.0268	334.3832	17.36	1.1098	335.3002	16.70
25/08/2013	2.0263	334.3837	16.83	1.1109	335.2991	16.69
26/08/2013	2.0235	334.3865	17.79	1.1032	335.3068	18.36
27/08/2013	2.0263	334.3837	17.80	1.1074	335.3026	18.31
28/08/2013	2.0237	334.3863	18.56	1.1035	335.3065	18.92
29/08/2013	2.0281	334.3819	18.51	1.1008	335.3092	18.90
30/08/2013	2.0248	334.3852	18.86	1.1009	335.3091	18.88
31/08/2013	2.0246	334.3854	19.01	1.0875	335.3225	19.17
01/09/2013	2.0244	334.3856	18.78	1.0903	335.3197	18.58
02/09/2013	2.0245	334.3855	18.41	1.0675	335.3425	17.73
03/09/2013	2.0252	334.3848	17.33	1.0819	335.3281	16.03
04/09/2013	2.0241	334.3859	15.92	1.0852	335.3248	15.52
05/09/2013	2.0247	334.3853	16.18	1.0913	335.3187	15.38
06/09/2013	2.0246	334.3854	14.74	1.0920	335.3180	13.06
07/09/2013	2.0233	334.3867	14.40	1.0863	335.3237	14.04
08/09/2013	2.0228	334.3872	14.79	1.0820	335.3280	15.68
09/09/2013	2.0236	334.3864	14.82	1.0850	335.3250	13.82
10/09/2013	2.0252	334.3848	15.68	1.0896	335.3204	18.94
11/09/2013	2.0268	334.3832	18.78	1.0922	335.3178	20.28
12/09/2013	2.0249	334.3851	19.11	1.0276	335.3824	18.14
13/09/2013	2.0265	334.3835	17.01	1.0727	335.3373	14.11
14/09/2013	2.0241	334.3859	13.93	1.0870	335.3230	11.98
15/09/2013	2.0232	334.3868	13.09	1.0952	335.3148	11.62
16/09/2013	2.0232	334.3868	12.81	1.1007	335.3093	12.84
17/09/2013	2.0229	334.3871	12.49	1.1062	335.3038	11.29
18/09/2013	2.0228	334.3872	11.97	1.1094	335.3006	11.65

Appendix K. (Continued)

Date	DP1-13 GW Water Level Depth (mTOC)	DP1-13 GW Water Level Elevation (masl)	DP1-13 GW Temperature (°C)	DP1-13 SW Water Level Depth (mTOC)	DP1-13 SW Water Level Elevation (masl)	DP1-13 SW Temperature (°C)
19/09/2013	2.0216	334.3884	12.47	1.1101	335.2999	13.23
20/09/2013	2.0212	334.3888	14.12	1.1017	335.3083	15.84
21/09/2013	1.9260	334.4840	15.37	0.9953	335.4147	16.15
22/09/2013	1.9071	334.5029	15.21	1.2180	335.1920	13.86
23/09/2013	2.0241	334.3859	14.00	1.0539	335.3561	13.08
24/09/2013	2.0236	334.3864	12.95	1.0326	335.3774	11.84
25/09/2013	2.0227	334.3873	12.24	1.0517	335.3583	11.77
26/09/2013	2.0224	334.3876	12.18	1.0663	335.3437	12.07
27/09/2013	2.0220	334.3880	12.34	1.0803	335.3297	12.36
28/09/2013	2.0220	334.3880	12.63	1.0931	335.3169	12.93
29/09/2013	2.0220	334.3881	13.06	1.0950	335.3150	13.18
30/09/2013	2.0220	334.3880	13.78	1.0932	335.3168	14.60
01/10/2013	2.0225	334.3875	14.09	1.0943	335.3157	14.70
02/10/2013	2.0229	334.3871	14.99	1.0979	335.3121	15.49
03/10/2013	2.0235	334.3865	14.09	1.0964	335.3136	12.60
04/10/2013	2.0223	334.3877	13.86	1.0146	335.3954	14.22
05/10/2013	2.0232	334.3868	14.29	1.0172	335.3928	14.23
06/10/2013	2.0221	334.3879	14.06	1.0231	335.3869	14.32
07/10/2013	1.9695	334.4405	14.60	0.6049	335.8051	14.52
08/10/2013	2.0247	334.3853	13.94	0.8635	335.5465	12.77
09/10/2013	2.0234	334.3866	12.90	0.9701	335.4399	11.98
10/10/2013	2.0228	334.3872	12.39	1.0046	335.4054	12.00
11/10/2013	2.0227	334.3873	12.04	1.0214	335.3886	11.38
12/10/2013	2.0218	334.3882	11.64	1.0420	335.3680	11.57
13/10/2013	2.0219	334.3881	12.44	1.0437	335.3663	12.89
14/10/2013	2.0231	334.3869	12.17	1.0489	335.3611	11.44
15/10/2013	2.0217	334.3883	11.45	1.0568	335.3532	11.04
16/10/2013	2.0213	334.3887	12.28	1.0370	335.3730	13.45
17/10/2013	2.0231	334.3869	12.72	1.0349	335.3751	12.19
18/10/2013	2.0232	334.3868	12.07	0.9922	335.4178	11.31
19/10/2013	2.0230	334.3870	11.01	1.0046	335.4054	9.55
20/10/2013	2.0219	334.3881	10.02	0.9759	335.4341	9.10
21/10/2013	2.0210	334.3890	9.88	1.0027	335.4073	9.94
22/10/2013	2.0221	334.3879	9.88	0.9787	335.4313	8.60
23/10/2013	2.0214	334.3886	8.83	1.0075	335.4025	7.82
24/10/2013	2.0207	334.3893	8.14	1.0131	335.3969	6.28

Appendix K. (Continued)

Date	DP2-13 GW Water Level Depth (mTOC)	DP2-13 GW Water Level Elevation (masl)	DP2-13 GW Temperature (°C)	DP2-13 SW Water Level Depth (mTOC)	DP2-13 SW Water Level Elevation (masl)	DP2-13 SW Temperature (°C)
14/08/2013	0.202	336.308	16.13	1.0917	335.4183	17.35
15/08/2013	0.627	335.883	15.53	1.0941	335.4159	14.47
16/08/2013	1.034	335.476	15.28	1.0910	335.4190	14.70
17/08/2013	1.330	335.180	15.28	1.0966	335.4134	15.83
18/08/2013	1.559	334.951	15.38	1.1024	335.4076	16.31
19/08/2013	1.741	334.769	15.65	1.1065	335.4035	16.60
20/08/2013	1.910	334.600	15.94	1.1084	335.4016	17.15
21/08/2013	2.024	334.486	16.26	1.1103	335.3997	18.25
22/08/2013	2.020	334.490	16.75	1.1078	335.4022	19.05
23/08/2013	2.021	334.489	17.34	1.1101	335.3999	17.83
24/08/2013	2.022	334.488	17.59	1.1142	335.3958	16.71
25/08/2013	2.022	334.488	17.43	1.1150	335.3950	16.71
26/08/2013	2.019	334.491	17.25	1.1001	335.4099	18.32
27/08/2013	2.022	334.488	17.40	1.0974	335.4126	18.31
28/08/2013	2.018	334.492	17.63	1.1009	335.4091	18.89
29/08/2013	2.022	334.488	17.96	1.1104	335.3997	18.87
30/08/2013	2.018	334.492	18.20	1.1101	335.3999	18.87
31/08/2013	2.018	334.492	18.43	1.0904	335.4196	19.15
01/09/2013	2.017	334.493	18.62	1.0936	335.4164	18.56
02/09/2013	2.018	334.492	18.64	1.0652	335.4448	17.74
03/09/2013	2.019	334.491	18.46	1.0836	335.4264	16.04
04/09/2013	2.020	334.490	17.90	1.0904	335.4196	15.53
05/09/2013	2.021	334.489	17.22	1.0989	335.4111	15.40
06/09/2013	2.023	334.487	16.74	1.1022	335.4078	13.09
07/09/2013	2.023	334.487	16.01	1.0954	335.4146	14.04
08/09/2013	2.023	334.487	15.51	1.0906	335.4194	15.69
09/09/2013	2.023	334.487	15.39	1.0960	335.4140	13.83
10/09/2013	2.025	334.485	15.30	1.1004	335.4096	18.91
11/09/2013	2.024	334.486	15.84	1.1011	335.4089	20.25
12/09/2013	2.020	334.490	17.06	1.0174	335.4926	18.16
13/09/2013	2.022	334.488	17.71	1.0731	335.4369	14.13
14/09/2013	2.022	334.488	17.14	1.0901	335.4199	11.99
15/09/2013	2.024	334.486	15.87	1.0979	335.4121	11.60
16/09/2013	2.025	334.485	14.81	1.1031	335.4069	12.85
17/09/2013	2.025	334.485	14.25	1.1077	335.4023	11.29
18/09/2013	2.026	334.484	13.60	1.1094	335.4006	11.66
19/09/2013	2.025	334.485	13.17	1.1105	335.3995	13.24

Appendix K. (Continued)

Date	DP2-13 GW Water Level Depth (mTOC)	DP2-13 GW Water Level Elevation (masl)	DP2-13 GW Temperature (°C)	DP2-13 SW Water Level Depth (mTOC)	DP2-13 SW Water Level Elevation (masl)	DP2-13 SW Temperature (°C)
20/09/2013	2.023	334.487	13.19	1.1006	335.4094	15.83
21/09/2013	2.024	334.486	14.17	0.6239	335.8861	16.13
22/09/2013	2.025	334.485	15.20	0.7351	335.7749	13.87
23/09/2013	2.025	334.485	14.93	0.9708	335.5392	13.08
24/09/2013	2.026	334.484	14.39	1.0250	335.4850	11.85
25/09/2013	2.025	334.485	13.76	1.0539	335.4561	11.77
26/09/2013	2.025	334.485	13.21	1.0735	335.4365	12.05
27/09/2013	2.025	334.485	12.90	1.0859	335.4241	12.37
28/09/2013	2.024	334.486	12.77	1.0932	335.4168	12.90
29/09/2013	2.022	334.488	12.82	1.0957	335.4143	13.15
30/09/2013	2.021	334.489	13.00	1.0928	335.4172	14.59
01/10/2013	2.022	334.488	13.36	1.0946	335.4154	14.67
02/10/2013	2.022	334.488	13.74	1.1001	335.4099	15.51
03/10/2013	2.023	334.487	14.17	1.1043	335.4057	12.61
04/10/2013	2.022	334.488	14.13	1.0170	335.4930	14.18
05/10/2013	2.022	334.488	14.02	1.0150	335.4950	14.23
06/10/2013	2.021	334.489	14.10	1.0220	335.4880	14.30
07/10/2013	2.023	334.487	14.25	0.5377	335.9723	14.52
08/10/2013	2.024	334.486	14.38	0.8366	335.6734	12.78
09/10/2013	2.023	334.487	14.00	0.9567	335.5533	12.00
10/10/2013	2.023	334.487	13.46	0.9950	335.5150	12.01
11/10/2013	2.023	334.487	13.03	1.0145	335.4955	11.39
12/10/2013	2.021	334.489	12.65	1.0393	335.4707	11.57
13/10/2013	2.020	334.490	12.39	1.0394	335.4706	12.88
14/10/2013	2.021	334.489	12.45	1.0466	335.4634	11.46
15/10/2013	2.020	334.490	12.34	1.0564	335.4536	11.04
16/10/2013	2.011	334.499	12.11	1.0318	335.4782	13.43
17/10/2013	2.012	334.498	12.28	1.0294	335.4806	12.20
18/10/2013	2.013	334.497	12.43	0.9796	335.5304	11.33
19/10/2013	2.013	334.497	12.25	0.9966	335.5134	9.59
20/10/2013	2.011	334.499	11.70	0.9614	335.5486	9.13
21/10/2013	2.007	334.503	11.06	0.9934	335.5166	9.93
22/10/2013	2.006	334.504	10.69	0.9663	335.5437	8.67
23/10/2013	2.005	334.505	10.33	1.0025	335.5075	7.86
24/10/2013	2.002	334.508	9.88	1.0109	335.4991	6.36

Appendix L. Region Monitoring Well Logger Data

Date	OW1A-11 Waterlevel (masl)	OW1B-11 Waterlevel (masl)	OW3A-09 Waterlevel (masl)	OW3-11 Waterlevel (masl)	OW2-11 Waterlevel (masl)	OW3B-09 Waterlevel (masl)
19/07/2013	333.487	333.476	333.445	333.459		
20/07/2013	333.514	333.507	333.461	333.486		
21/07/2013	333.502	333.494	333.454	333.470		
22/07/2013	333.495	333.482	333.443	333.458		
23/07/2013	333.497	333.485	333.443	333.460		
24/07/2013	333.479	333.472	333.432	333.450		
25/07/2013	333.461	333.453	333.417	333.434		
26/07/2013	333.455	333.448	333.409	333.425		
27/07/2013	333.462	333.453	333.414	333.429		
28/07/2013	333.473	333.463	333.426	333.438		
29/07/2013	333.468	333.460	333.424	333.437		
30/07/2013	333.448	333.441	333.405	333.419		
31/07/2013	333.451	333.445	333.404	333.419		
01/08/2013	333.500	333.497	333.443	333.462	333.434	333.393
02/08/2013	333.521	333.523	333.467	333.490	333.461	333.418
03/08/2013	333.534	333.540	333.481	333.503	333.478	333.432
04/08/2013	333.513	333.515	333.458	333.478	333.450	333.407
05/08/2013	333.482	333.482	333.432	333.447	333.418	333.376
06/08/2013	333.468	333.468	333.419	333.437	333.403	333.363
07/08/2013	333.455	333.460	333.421	333.427	333.397	333.356
08/08/2013	333.448	333.447	333.408	333.419	333.385	333.344
09/08/2013	333.444	333.444	333.409	333.413	333.382	333.342
10/08/2013	333.434	333.430	333.396	333.409	333.368	333.327
11/08/2013	333.425	333.422	333.386	333.400	333.360	333.320
12/08/2013	333.420	333.420	333.385	333.395	333.360	333.320
13/08/2013	333.419	333.413	333.378	333.386	333.349	333.321
14/08/2013	333.403	333.395	333.369	333.379	333.342	333.310
15/08/2013	333.407	333.398	333.374	333.382	333.347	333.308
16/08/2013	333.390	333.386	333.359	333.368	333.337	333.294
17/08/2013	333.378	333.375	333.349	333.357	333.328	333.277
18/08/2013	333.377	333.369	333.341	333.356	333.326	333.274
19/08/2013	333.292	333.287	333.276	333.290	332.852	333.114
20/08/2013	333.136	333.121	333.139	333.143	332.358	332.884
21/08/2013	333.091	333.077	333.093	333.099	332.356	332.847
22/08/2013	333.090	333.078	333.085	333.092	332.400	332.852
23/08/2013	333.075	333.059	333.058	333.074	332.379	332.832
24/08/2013	333.054	333.033	333.034	333.053	332.356	332.810

Appendix L. (Continued)

Date	OW1A-11 Waterlevel (masl)	OW1B-11 Waterlevel (masl)	OW3A-09 Waterlevel (masl)	OW3-11 Waterlevel (masl)	OW2-11 Waterlevel (masl)	OW3B-09 Waterlevel (masl)
25/08/2013	333.039	333.024	333.019	333.039	332.345	332.799
26/08/2013	333.036	333.020	333.016	333.039	332.343	332.797
27/08/2013	333.038	333.018	333.016	333.038	332.341	332.791
28/08/2013	333.031	333.014	333.011	333.026	332.338	332.785
29/08/2013	333.011	332.996	332.990	333.007	332.327	332.771
30/08/2013	333.011	332.994	332.978	333.006	332.320	332.772
31/08/2013	333.006	332.989	332.969	332.999	332.312	332.768
01/09/2013	332.993	332.983	332.967	332.997	332.307	332.763
02/09/2013	332.992	332.982	332.968	332.996	332.303	332.758
03/09/2013	332.971	332.974	332.962	332.961	332.297	332.742
04/09/2013	332.956	332.959	332.954	332.925	332.293	332.730
05/09/2013	332.945	332.946	332.944	332.918	332.280	332.716
06/09/2013	332.932	332.936	332.932	332.907	332.272	332.710
07/09/2013	332.937	332.939	332.936	332.907	332.278	332.716
08/09/2013	332.931	332.936	332.930	332.904	332.268	332.705
09/09/2013	332.925	332.930	332.926	332.899	332.263	332.701
10/09/2013	332.911	332.924	332.925	332.889	332.262	332.699
11/09/2013	332.907	332.918	332.913	332.885	332.256	332.692
12/09/2013	332.917	332.925	332.920	332.891	332.263	332.699
13/09/2013	332.916	332.918	332.914	332.883	332.250	332.687
14/09/2013	332.905	332.905	332.900	332.874	332.240	332.678
15/09/2013	332.900	332.900	332.898	332.870	332.236	332.674
16/09/2013	332.884	332.891	332.894	332.888	332.222	332.663
17/09/2013	332.869	332.878	332.888	332.892	332.207	332.653
18/09/2013	332.876	332.886	332.890	332.900	332.214	332.660
19/09/2013	332.881	332.890	332.891	332.902	332.209	332.658
20/09/2013	332.946	332.955	332.943	332.958	332.544	332.779
21/09/2013	333.177	333.194	333.144	333.164	333.136	333.088
22/09/2013	333.429	333.454	333.378	333.406	333.431	333.365
23/09/2013	333.345	333.364	333.315	333.337	333.129	333.222
24/09/2013	333.203	333.218	333.193	333.204	332.745	333.029
25/09/2013	333.130	333.143	333.129	333.141	332.563	332.929
26/09/2013	333.038	333.052	333.048	333.053	332.376	332.819
27/09/2013	332.998	333.008	333.004	333.011	332.328	332.775
28/09/2013	332.964	332.979	332.980	332.983	332.304	332.752
29/09/2013	332.953	332.963	332.963	332.970	332.290	332.739
30/09/2013	332.939	332.950	332.954	332.955	332.275	332.723
01/10/2013	332.942	332.951	332.960	332.960	332.273	332.722

Appendix L. (Continued)

Date	OW1A-11 Waterlevel (masl)	OW1B-11 Waterlevel (masl)	OW3A-09 Waterlevel (masl)	OW3-11 Waterlevel (masl)	OW2-11 Waterlevel (masl)	OW3B-09 Waterlevel (masl)
02/10/2013	332.927	332.934	332.938	332.941	332.257	332.705
03/10/2013	332.907	332.916	332.923	332.925	332.242	332.691
04/10/2013	332.904	332.911	332.919	332.919	332.238	332.686
05/10/2013	332.904	332.909	332.914	332.915	332.233	332.681
06/10/2013	332.911	332.920	332.924	332.924	332.245	332.693
07/10/2013	333.071	333.083	333.066	333.068	332.416	332.851
08/10/2013	333.167	333.191	333.163	333.175	332.535	332.966
09/10/2013	333.069	333.096	333.087	333.096	332.430	332.869
10/10/2013	333.017	333.042	333.036	333.049	332.372	332.813
11/10/2013	332.992	333.012	333.012	333.017	332.334	332.775
12/10/2013	332.965	332.978	332.978	332.985	332.304	332.746
13/10/2013	332.942	332.954	332.956	332.961	332.277	332.720
14/10/2013	332.921	332.936	332.936	332.940	332.255	332.698
15/10/2013	332.909	332.922	332.924	332.929	332.248	332.697
16/10/2013	332.915	332.924	332.923	332.929	332.245	332.698
17/10/2013	332.956	332.966	332.957	332.965	332.523	332.769
18/10/2013	333.119	333.131	333.098	333.110	333.066	332.997
19/10/2013	333.155	333.168	333.130	333.145	333.115	333.041
20/10/2013	333.176	333.189	333.150	333.165	333.133	333.059
21/10/2013	333.184	333.193	333.155	333.172	333.146	333.071
22/10/2013	333.197	333.207	333.166	333.187	333.149	333.080
23/10/2013	333.205	333.212	333.178	333.193	333.148	333.088
24/10/2013	333.201	333.211	333.175	333.193	333.142	333.080
25/10/2013	333.183	333.201	333.164	333.181	333.138	333.077
26/10/2013	333.205	333.219	333.180	333.192	333.169	333.110
27/10/2013	333.229	333.243	333.204	333.219	333.184	333.123
28/10/2013	333.217	333.232	333.196	333.209	333.170	333.109
29/10/2013	333.196	333.210	333.175	333.187	333.157	333.097
30/10/2013	333.202	333.213	333.175	333.192	333.167	333.107
31/10/2013	333.220	333.237	333.193	333.210	333.195	333.136
01/11/2013	333.398	333.418	333.347	333.367	333.382	333.311
02/11/2013	333.445	333.465	333.402	333.426	333.420	333.351
03/11/2013	333.362	333.378	333.329	333.353	333.316	333.251
04/11/2013	333.310	333.322	333.280	333.299	333.267	333.206
05/11/2013	333.289	333.305	333.264	333.284	333.250	333.191
06/11/2013	333.289	333.305	333.264	333.279	333.256	333.197
07/11/2013	333.295	333.311	333.275	333.284	333.246	333.186

Appendix M. TW2-13 Logger Data

Date	Waterlevel (masl)
19/08/2013	328.308
20/08/2013	327.800
21/08/2013	328.084
22/08/2013	328.443
23/08/2013	328.415
24/08/2013	328.375
25/08/2013	328.349
26/08/2013	328.341
27/08/2013	328.341
28/08/2013	328.349
29/08/2013	328.332
30/08/2013	328.325
31/08/2013	328.325
01/09/2013	328.317
02/09/2013	328.315
03/09/2013	328.293
04/09/2013	328.284
05/09/2013	328.263
06/09/2013	328.242
07/09/2013	328.249
08/09/2013	328.237
09/09/2013	328.230
10/09/2013	328.227
11/09/2013	328.218
12/09/2013	328.222
13/09/2013	328.202
14/09/2013	328.189
15/09/2013	328.184
16/09/2013	328.162
17/09/2013	328.150
18/09/2013	328.155
19/09/2013	328.116
20/09/2013	330.262
21/09/2013	333.051
22/09/2013	333.337
23/09/2013	331.867
24/09/2013	329.952

Date	Waterlevel (masl)
25/09/2013	329.045
26/09/2013	328.257
27/09/2013	328.201
28/09/2013	328.167
29/09/2013	328.149
30/09/2013	328.130
01/10/2013	328.126
02/10/2013	328.092
03/10/2013	328.066
04/10/2013	328.061
05/10/2013	328.038
06/10/2013	328.048
07/10/2013	328.218
08/10/2013	328.345
09/10/2013	328.244
10/10/2013	328.196
11/10/2013	328.159
12/10/2013	328.125
13/10/2013	328.098
14/10/2013	328.073
15/10/2013	328.066
16/10/2013	328.058
17/10/2013	329.844
18/10/2013	332.980
19/10/2013	333.028
20/10/2013	333.047
21/10/2013	333.061
22/10/2013	333.070
23/10/2013	333.079
24/10/2013	333.075

Appendix N. UW Monitoring Well Logger Data

Date	UW MW A Waterlevel (masl)	UW MW B Waterlevel (masl)
14/08/2013	333.022	332.632
15/08/2013	333.030	332.647
16/08/2013	333.033	332.660
17/08/2013	333.034	332.690
18/08/2013	333.035	332.672
19/08/2013	332.896	332.683
20/08/2013	332.691	332.818
21/08/2013	332.658	332.798
22/08/2013	332.675	332.833
23/08/2013	332.664	332.942
24/08/2013	332.642	332.986
25/08/2013	332.632	332.959
26/08/2013	332.629	332.888
27/08/2013	332.624	332.849
28/08/2013	332.593	332.617
29/08/2013	332.550	332.385
30/08/2013	332.549	332.336
31/08/2013	332.543	332.301
01/09/2013	332.537	332.300
02/09/2013	332.532	332.281
03/09/2013	332.550	332.326
04/09/2013	332.584	332.350
05/09/2013	332.571	332.374
06/09/2013	332.565	332.390
07/09/2013	332.571	332.322
08/09/2013	332.558	332.332
09/09/2013	332.556	332.333
10/09/2013	332.553	332.286
11/09/2013	332.547	332.288
12/09/2013	332.554	332.250
13/09/2013	332.542	332.278
14/09/2013	332.532	332.317
15/09/2013	332.529	332.310
16/09/2013	332.520	332.427
17/09/2013	332.516	332.537
18/09/2013	332.524	332.462
19/09/2013	332.522	332.420

Date	UW MW A Waterlevel (masl)	UW MW B Waterlevel (masl)
20/09/2013	332.650	332.520
21/09/2013	332.978	332.844
22/09/2013	333.261	333.212
23/09/2013	333.101	333.085
24/09/2013	332.900	332.864
25/09/2013	332.797	332.730
26/09/2013	332.684	332.632
27/09/2013	332.634	332.630
28/09/2013	332.607	332.597
29/09/2013	332.595	332.522
30/09/2013	332.578	332.485
01/10/2013	332.577	332.484
02/10/2013	332.559	332.481
03/10/2013	332.546	332.485
04/10/2013	332.541	332.463
05/10/2013	332.537	332.474
06/10/2013	332.551	332.411
07/10/2013	332.722	332.571
08/10/2013	332.836	332.841

Appendix O. Submersible Resistive Transmitter TW2-13 Data

Date	Waterlevel (masl)
19/08/2013	328.308
20/08/2013	327.800
21/08/2013	328.084
22/08/2013	328.443
23/08/2013	328.415
24/08/2013	328.375
25/08/2013	328.349
26/08/2013	328.341
27/08/2013	328.341
28/08/2013	328.349
29/08/2013	328.332
30/08/2013	328.325
31/08/2013	328.325
01/09/2013	328.317
02/09/2013	328.315
03/09/2013	328.293
04/09/2013	328.284
05/09/2013	328.263
06/09/2013	328.242
07/09/2013	328.249
08/09/2013	328.237
09/09/2013	328.230
10/09/2013	328.227
11/09/2013	328.218
12/09/2013	328.222
13/09/2013	328.202
14/09/2013	328.189
15/09/2013	328.184
16/09/2013	328.162
17/09/2013	328.150
18/09/2013	328.155
19/09/2013	328.116
20/09/2013	330.262
21/09/2013	333.051
22/09/2013	333.337
23/09/2013	331.867
24/09/2013	329.952

Date	Waterlevel (masl)
25/09/2013	329.045
26/09/2013	328.257
27/09/2013	328.201
28/09/2013	328.167
29/09/2013	328.149
30/09/2013	328.130
01/10/2013	328.126
02/10/2013	328.092
03/10/2013	328.066
04/10/2013	328.061
05/10/2013	328.038
06/10/2013	328.048
07/10/2013	328.218
08/10/2013	328.345
09/10/2013	328.244
10/10/2013	328.196
11/10/2013	328.159
12/10/2013	328.125
13/10/2013	328.098
14/10/2013	328.073
15/10/2013	328.066
16/10/2013	328.058
17/10/2013	329.844
18/10/2013	332.980
19/10/2013	333.028
20/10/2013	333.047
21/10/2013	333.061
22/10/2013	333.070
23/10/2013	333.079
24/10/2013	333.075

Appendix P. Conductivity Data Measured in OW2-11, OW3B-09, UW MWB, and TW2-13

Date	OW2-11 Specific Conductivity (µS/s)	OW3B-09 Specific Conductivity (µS/s)	UW-MW-B Conductivity (uS/cm)	TW2-13 Conductivity (uS/cm)
14/08/2013	895.97	865.05	1279.71	
15/08/2013	893.60	865.11	1302.89	
16/08/2013	892.50	863.00	1288.31	
17/08/2013	896.29	860.72	1284.31	
18/08/2013	893.83	861.05	1314.75	
19/08/2013	892.02	860.22	1465.15	1230.66
20/08/2013	886.35	858.84	1432.69	1056.95
21/08/2013	879.19	852.56	1318.90	923.90
22/08/2013	859.78	853.12	1297.12	854.07
23/08/2013	890.67	852.56	1309.36	829.65
24/08/2013	919.44	839.45	1226.60	821.36
25/08/2013	905.50	837.82	995.73	815.47
26/08/2013	894.77	837.62	922.37	803.79
27/08/2013	903.92	830.08	971.22	790.56
28/08/2013	955.26	828.84	1078.57	780.58
29/08/2013	1042.99	829.54	1134.02	770.89
30/08/2013	1101.69	829.96	1206.89	762.03
31/08/2013	1209.80	829.91	1157.95	755.60
01/09/2013	1210.46	830.13	1111.93	749.84
02/09/2013	1273.32	826.34	1094.13	744.39
03/09/2013	1335.18	825.99	1041.97	739.47
04/09/2013	1372.98	826.75	997.59	736.85
05/09/2013	1407.27	827.00	966.79	733.78
06/09/2013	1391.38	827.01	931.93	731.16
07/09/2013	1410.00	826.76	899.30	729.55
08/09/2013	1377.29	826.83	878.80	728.61
09/09/2013	1357.43	826.94	824.39	724.68
10/09/2013	1321.93	826.99	750.15	727.45
11/09/2013	1311.23	827.45	716.69	723.75
12/09/2013	1303.51	827.75	684.76	719.99
13/09/2013	1312.62	828.60	666.78	713.79
14/09/2013	1313.93	828.37	674.79	711.56
15/09/2013	1308.83	828.67	706.27	708.63
16/09/2013	1268.07	828.24	779.49	706.90
17/09/2013	1223.40	830.07	841.44	703.60
18/09/2013	1212.76	829.96	876.84	

Appendix P. (Continued)

Date	OW2-11 Specific Conductivity (µS/s)	OW3B-09 Specific Conductivity (µS/s)	UW-MW-B Conductivity (uS/cm)	TW2-13 Conductivity (uS/cm)
19/09/2013	1216.74	829.60	857.37	
20/09/2013	1169.14	829.31	825.83	
21/09/2013	1114.09	829.08	894.97	
22/09/2013	1326.11	829.09	1166.27	
23/09/2013	1192.37	829.25	1177.67	
24/09/2013	1316.19	829.27	904.50	
25/09/2013	1402.21	829.32	871.34	
26/09/2013	1286.84	829.42	852.91	
27/09/2013	1109.83	830.00	862.45	
28/09/2013	1070.46	829.96	856.51	
29/09/2013	1132.35	829.64	857.05	
30/09/2013	1242.97	829.54	883.55	
01/10/2013	1266.39	829.79	890.07	
02/10/2013	1140.57	829.58	894.05	
03/10/2013	1088.10	829.32	885.06	
04/10/2013	1082.43	829.19	872.07	
05/10/2013	1076.61	829.12	891.90	
06/10/2013	1072.98	829.13	862.10	
07/10/2013	1081.74	828.14	879.98	
08/10/2013	1119.31	825.80	885.70	
09/10/2013	1086.12	825.30		
10/10/2013	1059.83	825.06		
11/10/2013	1003.50	827.30		
12/10/2013	984.32	827.08		
13/10/2013	978.48	826.81		
14/10/2013	954.70	826.65		
15/10/2013	974.12	826.35		
16/10/2013	997.51	826.17		
17/10/2013	991.08	826.21		
18/10/2013	941.20	826.48		
19/10/2013	956.14	827.40		
20/10/2013	1060.68	827.42		
21/10/2013	992.62	827.43		
22/10/2013	962.56	827.46		
23/10/2013	950.16	827.33		
24/10/2013	944.04	827.30		
25/10/2013	922.26	826.26		

Appendix P. (Continued)

Date	OW2-11 Specific Conductivity (µS/s)	OW3B-09 Specific Conductivity (µS/s)	UW-MW-B Conductivity (uS/cm)	TW2-13 Conductivity (uS/cm)
26/10/2013	899.60	828.63		
27/10/2013	906.07	829.47		
28/10/2013	883.48	829.18		
29/10/2013	867.39	829.06		
30/10/2013	905.33	829.01		
31/10/2013	928.67	829.04		
01/11/2013	871.44	828.94		
02/11/2013	838.15	828.87		
03/11/2013	848.62	828.78		
04/11/2013	854.48	828.78		
05/11/2013	871.80	828.93		
06/11/2013	1001.60	828.97		
07/11/2013	929.80	828.98		

Appendix Q. Continuous Sonde Data: TW2-13 and Alder Creek

Date	DO (mg/L)	pH	Turbidity (FNU)	Temp (°C)	Conductivity (μS/cm)	TDS (mg/L)
08/08/2013	11.610	8.52	0.475	17.95	845	549
09/08/2013	4.848	8.36	0.495	16.95	136628	88808
10/08/2013	1.138	8.35	0.167	15.73	274228	178248
11/08/2013	0.774	8.37	0.135	13.49	284763	185096
12/08/2013	0.804	8.33	0.067	13.82	282779	183807
13/08/2013	0.872	8.37	-0.019	14.28	282479	183611
14/08/2013	0.803	8.39	0.072	13.74	288145	187294
15/08/2013	3.009	8.36	-0.170	13.20	289793	188365
16/08/2013	3.615	8.36	-0.193	13.40	292903	190387
17/08/2013	3.280	8.35	-0.194	14.48	296201	192531
18/08/2013	2.297	8.33	-0.200	14.94	295228	191898
19/08/2013	1.785	8.32	-0.204	15.20	294211	191237
20/08/2013	0.912	8.32	-0.298	15.74	289721	188318
21/08/2013	0.979	8.29	-0.268	16.81	287511	186882
22/08/2013	1.004	8.30	-0.196	17.60	285459	185549
23/08/2013	0.890	8.32	-0.267	16.38	286466	186203
24/08/2013	0.836	8.32	-0.168	15.26	286401	186161
25/08/2013	0.863	8.34	-0.001	15.26	285422	185524
26/08/2013	0.872	8.30	1.113	16.91	282353	183530
27/08/2013	0.890	8.27	1.600	16.86	283109	184021
28/08/2013	0.960	8.30	-0.169	17.44	280711	182462
29/08/2013	1.011	8.32	0.059	17.41	279285	181535
30/08/2013	0.998	8.33	0.894	17.39	277887	180626
31/08/2013	0.973	8.33	0.998	17.64	277115	180125
01/09/2013	0.956	7.53	1.874	17.08	276874	179968
02/09/2013	0.832	8.02	2.801	16.23	278155	180801
03/09/2013	0.782	8.96	1.115	14.54	278924	181301
04/09/2013	0.796	9.27	0.701	14.03	278702	181156
05/09/2013	0.788	9.31	0.541	13.88	277307	180250
06/09/2013	3.293	9.30	0.626	11.60	278641	181117
07/09/2013	0.676	9.30	1.741	12.58	276050	179433
08/09/2013	0.882	9.29	1.569	14.18	272607	177194
09/09/2013	0.738	9.27	0.996	12.33	274734	178577
10/09/2013	1.201	9.23	0.440	17.40	265612	172648
11/09/2013	1.267	9.22	1.423	18.63	261248	169811
12/09/2013	0.898	9.30	8.320	16.54	265662	172680
13/09/2013	0.748	9.31	1.825	12.51	267098	173614
14/09/2013	2.437	9.30	0.475	10.45	266005	172903

Appendix Q. (Continued)

Date	DO (mg/L)	pH	Turbidity (FNU)	Temp (°C)	Conductivity (µS/cm)	TDS (mg/L)
15/09/2013	0.675	9.29	0.748	10.08	263926	171552
16/09/2013						
17/09/2013						
18/09/2013						
19/09/2013						
20/09/2013	1.414	9.03	4.058	15.55	240297	156193
21/09/2013	0.830	9.24	52.343	14.65	251143	163243
22/09/2013	0.769	9.27	22.502	12.31	255022	165764
23/09/2013	0.834	9.22	9.564	11.56	255061	165790
24/09/2013	0.972	9.16	4.117	10.38	248566	161568
25/09/2013	0.830	9.15	1.664	10.30	251253	163315
26/09/2013	0.891	9.12	1.509	10.61	249365	162087
27/09/2013	0.961	9.11	1.158	10.91	247606	160944
28/09/2013	1.044	9.10	1.183	11.47	245827	159788
29/09/2013	1.075	9.10	0.655	11.71	244753	159089
30/09/2013	1.214	9.10	0.616	13.11	242088	157357
01/10/2013	1.297	9.11	0.424	13.21	240888	156577
02/10/2013	1.408	9.11	0.439	13.97	237200	154180
03/10/2013	1.212	9.10	0.403	11.15	236124	153480
04/10/2013	1.161	9.16	19.614	12.84	230307	149700
05/10/2013	1.590	9.21	5.684	12.77	212031	137820
06/10/2013	1.784	9.22	5.671	12.92	204479	132911
07/10/2013	1.375	9.36	75.773	13.07	206030	133920
08/10/2013	1.583	9.33	21.842	11.37	205697	133703
09/10/2013	1.707	7.80	10.305	10.67	201794	131166
10/10/2013	1.781	8.50	6.264	10.67	199914	129944
11/10/2013	1.762	8.47	4.169	10.02	198814	129229
12/10/2013	1.922	8.77	2.901	10.21	193974	126083
13/10/2013	2.042	8.85	3.341	11.52	190177	123615
14/10/2013	2.002	8.74	1.994	10.08	191416	124420
15/10/2013	1.985	8.66	2.529	9.70	190668	123934
16/10/2013	2.072	8.78	5.003	12.09	186726	121372
17/10/2013	2.040	9.18	4.132	10.86	186458	121197
18/10/2013	1.859	9.24	11.166	9.96	187143	121643
19/10/2013	2.110	9.26	8.279	8.26	173540	112801
20/10/2013	2.478	9.31	7.055	7.81	162253	105464
21/10/2013	2.182	9.33	2.865	8.65	175407	114015
22/10/2013	2.627	9.30	8.475	7.35	163033	105971

Appendix R. Sampling Record

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Volume Removed (L)	Temperature (°C)	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-MW-A	13-Aug-13	3.61	UW-MW-A-1	R-comprehensive	15	10.507	1035.4	7.39	4216.73	1.81
					30	10.084	1076.7	7.36	2450.3	1.98
					45	9.84	1074.8	7.32	2933.53	2.14
UW-CMT2A-2	14-Aug-13	5.211	UW-CMT2A-2-1	R-comprehensive	5	13.921	722.3	7.44	152.64	2.06
					10	13.868	356	7.51	48.4	3
					15	14.392	364.5	7.47	14.46	2.86
UW-CMT2A-6	14-Aug-13	5.21	UW-CMT2A-6-1	R-comprehensive	5	12.385	676.1	7.62	244.88	2.53
					10	11.321	328.1	7.57	22.7	2.87
					15	12.675	651.6	7.64	11.57	2.54
UW-CMT2B-2	14-Aug-13	5.24	UW-CMT2B-2-1	R-comprehensive	5	12.815	797.4	7.49	56.75	2.73
					10	12.776	829.4	7.44	4.61	2.39
					15	12.578	799.2	7.48	2.22	2.54
UW-CMT2B-6	14-Aug-13	5.264	UW-CMT2B-6-1	R-comprehensive	5	13.434	1481.5	7.08	111.78	1.98
					10	12.319	1585.5	7.05	6.12	1.5
					18	12.779	1590.2	7.06	2.48	1.43
UW-CMT3-2	14-Aug-13	4.728	UW-CMT3-2-1	R-comprehensive	5	17.1	N/A	7.38	443.51	2.8
					10	17.007	634.3	7.34	48.56	2.85
					20	16.963	803	7.27	15	1.58
UW-CMT3-6	14-Aug-13	4.728	UW-CMT3-6-1	R-comprehensive	5	13.323	726	7.64	18.87	2.13
					13	13.166	720.2	7.63	3.99	1.63
					20	13.137	705	7.64	1.52	2.85
UW-CMT1-2	14-Aug-13	3.651	UW-CMT1-2-1	R-comprehensive	10	17.847	850.4	7.46	131.63	1.6
					15	16.219	746.7	N/A	13.67	1.46
					20	16.117	734.2	N/A	11.13	1.87
UW-CMT1-6	14-Aug-13	3.658	UW-CMT1-6-1	R-comprehensive	5	14.205	572.2	N/A	8.96	2.14
					10	12.28	533.4	N/A	1.2	2.55
UW-CMT1-2	19-Aug-13	3.67	UW-CMT1-2-1b	Microbiology	10	13.8	701.1	N/A	15.25	1.33
					15	14.063	698.5	N/A	5.55	2.72
UW-CMT1-6	19-Aug-13	3.68	UW-CMT1-6-1b	Microbiology	5	11.207	500.5	N/A	3.75	2.51
					13	10.84	248.4	N/A	1.32	2.07

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)
Alder Creek SW	19-Aug-13	-	AlderCreekSW-0819	R-comprehensive, microbiology	-	15.733	898.1	N/A	2.16	12.15
Alder Creek SW	20-Aug-13	-	AlderCreekSW-0820	R-comprehensive, microbiology	-	14.072	873.7	N/A	0.87	10.75
WT-MW-OW3B-09	22-Aug-13	4.555	WT-MW-OW3B-09-1	R-comprehensive	30	10.767	1018.7	N/A	531.5	16
					60	10.292	998	N/A	661.7	1.72
					90	10.489	985.4	N/A	490.1	1.04
					120	10.146	972.3	N/A	420.13	1.43
WT-MW-OW2-11	22-Aug-13	5.268	WT-MW-OW2-11-2	R-comprehensive	16	10.865	606.9	N/A	2.38	1.16
					32	10.873	604.5	N/A	0.65	1.82
					48	10.38	599.2	N/A	0.35	1.58
WT-MW-OW1B-11	22-Aug-13	3.814	WT-MW-OW1B-11-2	R-comprehensive	25	12.263	780.2	N/A	2.26	2.66
					50	10.976	733.5	N/A	3.26	2.48
					75	10.814	732.2	N/A	0.2	2.87
WT-MW-OW1A-11	22-Aug-13	3.871	WT-MW-OW1A-11-2	R-comprehensive	30	11.841	601.7	N/A	7.32	2.52
					60	11.207	591.9	N/A	1.31	1.73
					90	10.783	584.3	N/A	2.53	2.3
					120	10.872	583.9	N/A	2.24	3.25
					150	10.616	579.3	N/A	2.66	1.67
WT-MW-OW3-11	22-Aug-13	4.504	WT-MW-OW3-11-2	R-comprehensive	25	9.949	766.7	N/A	6.82	2.19
					50	9.836	787.6	N/A	0.25	0.77
					71	9.919	992.6	N/A	0.27	1.83
WT-MW-OW3A-09	22-Aug-13	4.657	WT-MW-OW3A-09-2	R-comprehensive	30	10.61	677.4	N/A	265.94	2.12
					60	9.961	658.1	N/A	190.52	0.97
					90	10.042	661.3	N/A	245.31	2.11
					120	9.836	655.9	N/A	208.06	1.25
					145	9.939	657.7	N/A	115.32	2.1
UW-MW-B	22-Aug-13	4.036	UW-MW-B-2	R-comprehensive	15	11.071	1504	N/A	225.43	1.12
					25	10.851	1460	N/A	260.12	2.32
					35	10.855	1449.5	N/A	288.03	2.48
					55	10.277	1435.7	N/A	170.48	2.11

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (μS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-MW-A	22-Aug-13	4.098	UW-MW-A-2	R-comprehensive	15	12.785	954.8	N/A	1726	1.83
					25	11.195	855.1	N/A	2438	2.16
					35	10.81	846.6	N/A	1577	2.13
					45	11.407	875.3	N/A	900.46	1.99
					55	11.362	870.9	N/A	906.14	2.07
UW-CMT2A-2	22-Aug-13	5.8	UW-CMT2A-2-2	R-comprehensive	5	-	-	N/A	-	-
					14	20.194	875.1	N/A	25.1	2.22
					22	19.779	864.9	N/A	7.9	2.21
UW-CMT2A-6	22-Aug-13	5.96	UW-CMT2A-6-2	R-comprehensive	3	-	-	N/A	-	-
					13	18.706	790.2	N/A	16.73	1.71
					18	18.491	792.7	N/A	9.77	2.46
UW-CMT2B-2	22-Aug-13	6.04	UW-CMT2B-2-2	R-comprehensive	3	-	-	N/A	-	-
					8	17.543	738.9	N/A	10.55	3.44
					13	19.525	776.4	N/A	2	1.61
UW-CMT2B-6	22-Aug-13	5.96	UW-CMT2B-6-2	R-comprehensive	2	-	-	N/A	-	-
					7	17.265	739.5	N/A	9.82	2
					15	17.071	738.4	N/A	4.1	1.48
UW-CMT3-2	22-Aug-13	5.29	UW-CMT3-2-2	R-comprehensive	15	19.553	661	N/A	23.44	1.32
					25	20.07	330.9	N/A	3.6	3.24
					30	19.257	325.9	N/A	2.41	2.52
UW-CMT3-6	22-Aug-13	5.35	UW-CMT3-6-2	R-comprehensive	15	16.396	690.1	N/A	6.45	2.17
					22	17.471	712	N/A	2.05	1.84
UW-CMT1-2	22-Aug-13	4.303	UW-CMT1-2-2	R-comprehensive, microbiology	10	17.285	845.5	N/A	25.31	2.85
					20	15.842	797.6	N/A	4.09	2.29
UW-CMT1-6	22-Aug-13	4.56	UW-CMT1-6-2	R-comprehensive, microbiology	10	15.856	370.7	N/A	0.54	1.94
					18	15.148	418.9	N/A	0.15	1.86
Alder Creek SW	22-Aug-13	-	AlderCreekSW-0822	R-comprehensive, microbiology	-	16.474	932	N/A	1.42	7.77
UW-CMT1-2	26-Aug-13	4.345	UW-CMT1-2-3	R-comprehensive, microbiology	8	17.013	822.8	N/A	6.33	3.42
					23	17.35	805.3	N/A	1.79	3.15

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (μS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-CMT1-6	26-Aug-13	3.73	UW-CMT1-6-3	R-comprehensive, microbiology	10	15.761	1235.3	N/A	1.06	2.21
					18	15.505	1309.2	N/A	0.21	2.27
Alder Creek SW	26-Aug-13	-	AlderCreekSW-0826	R-comprehensive, microbiology	-	17.324	959.9	N/A	1.29	8.31
WT-MW-OW3B-09	03-Sep-13	4.67	WT-MW-OW3B-09-4	R-comprehensive	30	10.773	641.9	N/A	466.8	1.34
					60	10.668	588	N/A	447.25	1.92
					90	10.6	587.8	N/A	226.45	2.01
					120	10.524	590.4	N/A	135.8	1.5
WT-MW-OW2-11	03-Sep-13	5.368	WT-MW-OW2-11-4	R-comprehensive	15	10.329	832.5	N/A	2.36	1.25
					30	10.336	836.1	N/A	1.2	2.12
					45	10.004	856.4	N/A	0.68	1.56
WT-MW-OW1B-11	03-Sep-13	3.923	WT-MW-OW1B-11-4	R-comprehensive	30	11.339	548.2	N/A	1.34	2.99
					60	11.012	525.5	N/A	0.37	2.32
					75	10.664	521.9	N/A	0.11	1.67
WT-MW-OW1A-11	03-Sep-13	3.984	WT-MW-OW1A-11-4	R-comprehensive	30	10.592	569.2	N/A	3.13	0.91
					60	10.531	564.3	N/A	5.44	1.68
					90	10.287	561.2	N/A	1.34	0.97
					120	10.271	560.3	N/A	3.17	1.06
					150	10.561	566.5	N/A	3.68	2.22
WT-MW-OW3-11	03-Sep-13	4.619	WT-MW-OW3-11-4	R-comprehensive	30	9.59	848.7	N/A	2.6	2.33
					60	9.44	900.8	N/A	4	1.37
WT-MW-OW3A-09	03-Sep-13	4.672	WT-MW-OW3A-09-4	R-comprehensive	30	9.56	609.5	N/A	82.39	1.03
					60	9.798	607.2	N/A	96.67	2.48
					90	9.61	602.9	N/A	122.32	1.29
					120	9.859	608.6	N/A	93.68	1.42
					150	9.529	600.3	N/A	205.66	0.94
UW-MW-B	03-Sep-13	4.137	UW-MW-B-4	R-comprehensive	15	11.309	1270.4	N/A	105.09	2.34
					30	10.3	1236.5	N/A	97.12	1.15
					45	10.374	1232.1	N/A	106.47	1.2

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-MW-A	03-Sep-13	4.198	UW-MW-A-4	R-comprehensive	15	10.72	756.6	N/A	616.69	1.46
					30	10.07	721	N/A	349.2	0.77
					45	10.128	725.4	N/A	206.7	1.12
UW-CMT2A-2	03-Sep-13	5.92	UW-CMT2A-2-4	R-comprehensive	15	11.254	872.5	N/A	11.58	6.55
					30	11.195	874.9	N/A	3.02	6.54
								N/A		
UW-CMT2A-6	03-Sep-13	6.04	UW-CMT2A-6-4	R-comprehensive	10	12.083	806.3	N/A	5.98	2.48
					20	11.88	827.3	N/A	2.71	2.85
								N/A		
UW-CMT2B-2	03-Sep-13	5.985	UW-CMT2B-2-4	R-comprehensive	15	11.866	687.7	N/A	9	1.55
					30	12.099	686.6	N/A	6.47	1.34
								N/A		
UW-CMT2B-6	03-Sep-13	6.32	UW-CMT2B-6-4	R-comprehensive	10	12.32	638	N/A	6.15	1.49
					20	12.622	642.4	N/A	1.2	1.48
								N/A		
UW-CMT3-2	03-Sep-13	6.03	UW-CMT3-2-4	R-comprehensive	15	13.566	896.3	N/A	8.49	1.81
					30	14.188	851.7	N/A	2.15	1.83
								N/A		
UW-CMT3-6	03-Sep-13	5.455	UW-CMT3-6-4	R-comprehensive	10	13.061	697.9	N/A	1.01	1.7
					20	12.952	695.3	N/A	0.21	1.81
UW-CMT1-2	03-Sep-13	4.415	UW-CMT1-2-4	R-comprehensive, microbiology	10	14.554	811.8	N/A	5.48	2.53
					25	15.68	773.5	N/A	0.39	2.2
					35	16.177	785.7	N/A	1.31	2.69
UW-CMT1-6	03-Sep-13	4.535	UW-CMT1-6-4	R-comprehensive, microbiology	15	11.679	1412.7	N/A	3.31	1.3
					35	11.427	1424.8	N/A	10.64	0.71

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)
Alder Creek SW	03-Sep-13	-	AlderCreekSW-0903	R-comprehensive, microbiology	-	15.099	755.8	N/A	1.6	8.47
UW-CMT1-2	10-Sep-13	4.41	UW-CMT1-2-5	R-comprehensive, microbiology	10	22.134	971.5	N/A	3.77	2.14
					25	26.425	990.9	N/A	11.82	7.79
UW-CMT1-6	10-Sep-13	4.26	UW-CMT1-6-5	R-comprehensive, microbiology	15	22.209	1777.2	N/A	0.93	1.27
					25	21.885	1704.9	N/A	0.29	1.2
Alder Creek SW	10-Sep-13	-	AlderCreekSW-0910	R-comprehensive, microbiology	-			N/A		
WT-MW-OW3B-09	16-Sep-13	4.74	WT-MW-OW3B-09-6	R-comprehensive	30	10.569	604.3	N/A	296.97	0.78
					60	9.951	591.3	N/A	660.93	1.32
					90	10.05	593.6	N/A	451.97	1.01
					120	9.794	589.9	N/A	528.62	0.79
WT-MW-OW2-11	16-Sep-13	5.45	WT-MW-OW2-11-6	R-comprehensive	15	10.444	880.2	N/A	4.09	2.36
					30	9.785	828.2	N/A	1.89	1.35
					45	9.331	805.8	N/A	0.63	1.41
WT-MW-OW1B-11	16-Sep-13	4	WT-MW-OW1B-11-6	R-comprehensive	30	10.767	424.1	N/A	0.85	2.33
					60	10.342	413.3	N/A	0.38	1.23
					75	10.248	413.9	N/A	2	1.53
WT-MW-OW1A-11	16-Sep-13	4.064	WT-MW-OW1A-11-6	R-comprehensive	30	10.35	568.6	N/A	5.72	1.7
					60	10.09	563.8	N/A	5.11	2.29
					90	10.027	564.6	N/A	2.67	1.67
					120	9.88	567.8	N/A	1.69	1.42
					150	9.792	562.4	N/A	3.72	1.08
WT-MW-OW3-11	16-Sep-13	4.694	WT-MW-OW3-11-6	R-comprehensive	30	8.962	796.4	N/A	1.86	1.5
					60	9.152	799.5	N/A	0.04	0.86
					75	9.107	772.9	N/A	3.25	2.62

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)
WT-MW-OW3A-09	16-Sep-13	4.874	WT-MW-OW3A-09-6	R-comprehensive	30	9.413	585.1	N/A	155.56	2.09
					60	9.339	579.8	N/A	181.48	0.89
					90	9.372	578.6	N/A	140.92	0.99
					120	9.388	577.4	N/A	133.27	1.12
					150	9.574	579.2	N/A	78.43	1.64
UW-MW-B	16-Sep-13	4.222	UW-MW-B-6	R-comprehensive	15	10.373	882.2	N/A	80.02	1.25
					30	10.018	867.2	N/A	95.06	1.09
					45	9.973	883.3	N/A	120.22	2.36
UW-MW-A	16-Sep-13	4.3	UW-MW-A-6	R-comprehensive	15	10.847	747.2	N/A	182.92	2.36
					30	10.271	725	N/A	286.07	3.16
					45	10.041	726.7	N/A	290.57	3.27
UW-CMT2A-2	16-Sep-13	5.94	UW-CMT2A-2-6	R-comprehensive	15	10.886	760.8	N/A	21.63	6.12
					35	10.603	752.3	N/A	2.58	5.48
								N/A		
UW-CMT2A-6	16-Sep-13	6.125	UW-CMT2A-6-6	R-comprehensive	10	11.122	1059.5	N/A	9.05	2.4
					20	10.942	1061.2	N/A	4.13	2.34
								N/A		
UW-CMT2B-2	16-Sep-13	6.195	UW-CMT2B-2-6	R-comprehensive	15	10.238	642.6	N/A	1.7	1.8
					30	10.374	639.4	N/A	0.95	2
								N/A		
UW-CMT2B-6	16-Sep-13	6.14	UW-CMT2B-6-6	R-comprehensive	10	10.501	630.5	N/A	11.7	1.68
					20	10.429	594.6	N/A	0.93	2.11
								N/A		
UW-CMT3-2	16-Sep-13	5.465	UW-CMT3-2-6	R-comprehensive	15	12.709	698.7	N/A	12.01	1.59
					25	12.728	711.2	N/A	12.28	2.4
								N/A		
UW-CMT3-6	16-Sep-13	5.52	UW-CMT3-6-6	R-comprehensive	15	10.911	648.9	N/A	2.06	1.3
					25	10.818	653.8	N/A	0.57	1.57

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (μS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-CMT1-2	16-Sep-13	4.515	UW-CMT1-2-6	R-comprehensive, microbiology	20	14.543	830.4	N/A	5.94	3.11
					40	15.492	844.4	N/A	1.42	2.4
UW-CMT1-6	16-Sep-13	4.72	UW-CMT1-6-6	R-comprehensive, microbiology	13	12.446	1334.7	N/A	0.51	1.72
					26	12.987	1332.8	N/A	0.24	1.61
Alder Creek SW	16-Sep-13	-	AlderCreekSW-0903	R-comprehensive, microbiology	-	13.143	792.1	N/A	3.04	11.5
WT-MW-OW3B-09	17-Oct-13	4.736	WT-MW-OW3B-09-7	R-comprehensive	30	10.048	518.5	N/A	282.4	0.79
					60	9.876	515.4	N/A	259.6	2
					90	9.584	511.6	N/A	313.51	0.76
					120	9.907	516	N/A	171.3	1.24
WT-MW-OW2-11	17-Oct-13	5.438	WT-MW-OW2-11-7	R-comprehensive	15	10.594	615.3	N/A	11.57	1.49
					30	10.38	590.4	N/A	1.33	2.06
					45	9.942	579.5	N/A	2.93	1.21
WT-MW-OW1B-11	17-Oct-13	3.977	WT-MW-OW1B-11-7	R-comprehensive	30	10.131	454	N/A	1.75	1.96
					60	9.777	475.6	N/A	1.88	1.22
					75	9.899	473.5	N/A	0.77	2.13
WT-MW-OW1A-11	17-Oct-13	4.035	WT-MW-OW1A-11-7	R-comprehensive	30	9.949	530.9	N/A	11.04	1.5
					60	9.949	530.6	N/A	2.04	1.36
					90	9.865	530.4	N/A	3.61	0.97
					120	9.747	527.5	N/A	0.99	1
					150	9.868	529	N/A	1.02	0.96
WT-MW-OW3-11	17-Oct-13	4.679	WT-MW-OW3-11-7	R-comprehensive	30	9.362	477	N/A	11.28	1.01
					60	9.336	458.2	N/A	0.87	1.93
					75	9.271	454.4	N/A	2.17	1.56
WT-MW-OW3A-09	17-Oct-13	4.853	WT-MW-OW3A-09-7	R-comprehensive	30	9.99	471.2	N/A	94.35	0.93
					60	9.474	472.8	N/A	43.82	1.55
					90	9.799	484.9	N/A	33.12	1.01
					120	9.503	476.2	N/A	66.03	0.92
					150	9.546	477.9	N/A	48.93	1.63

Appendix R. (Continued)

Monitoring ID	Date	Water Level (mbTOC)	Sampling ID	Analysis	Total Volume Removed (L)	Temperature (°C)	Conductivity (μS/cm)	pH	Turbidity (NTU)	DO (mg/L)
UW-MW-B	17-Oct-13	4.202	UW-MW-B-7	R-comprehensive	20	10.265	767.6	N/A	87.11	1.01
					40	10.388	774.8	N/A	41.09	2.31
					60	9.714	766.8	N/A	56.04	1.32
UW-MW-A	17-Oct-13	4.262	UW-MW-A-7	R-comprehensive	15	9.949	555.5	N/A	227.8	1.01
					30	9.872	537.2	N/A	182.3	1.33
UW-CMT2A-2	17-Oct-13	5.95	UW-CMT2A-2-7	R-comprehensive	20	12.355	648.8	N/A	6.8	5.92
					40	11.936	640.7	N/A	0.46	6.22
UW-CMT2A-6	17-Oct-13	6.115	UW-CMT2A-6-7	R-comprehensive	15	13.612	813	N/A	0.83	3.11
					25		N/A			
					40	12.756	786.4	N/A	0.26	1.8
UW-CMT2B-2	17-Oct-13	6.2	UW-CMT2B-2-7	R-comprehensive	20	10.887	541.5	N/A	0.17	1
					35	10.567	530.2	N/A	0.36	1.39
UW-CMT2B-6	17-Oct-13	5.96	UW-CMT2B-6-7	R-comprehensive	10	10.61	error	N/A	15.23	5.28
					20	10.434	524.9	N/A	7.96	1.93
UW-CMT3-2	17-Oct-13	5.47	UW-CMT3-2-7	R-comprehensive	15	13.612	720.7	N/A	5.75	1.95
					35	14.165	709.9	N/A	0.36	1.24
UW-CMT3-6	17-Oct-13	5.51	UW-CMT3-6-7	R-comprehensive	10	11.918	246.6	N/A	1.2	2.69
					30	12.684	660.6	N/A	error	2.1
UW-CMT1-2	17-Oct-13	4.455	UW-CMT1-2-7	R-comprehensive, microbiology	10	13.91	535.5	N/A	15.21	4.65
					25	13.961	525.8	N/A	3.83	3.68
					40	13.792	523.5	N/A	1.63	3.89
UW-CMT1-6	17-Oct-13	4.605	UW-CMT1-6-7	R-comprehensive, microbiology	15	11.715	1057.8	N/A	0.41	1.34
					25	11.698	1030.3	N/A	0.18	1.78
					32	11.238	1030.2	N/A	error	2.07
Alder Creek SW	17-Oct-13	-	AlderCreekSW-1017	R-comprehensive, microbiology	-	11.75	587	N/A	4.04	9.22

Appendix S. General Chemistry and Metals Results

Sample Location		Alder Creek SW							
Sample Date		**19-Aug-13**	**19-Aug-13**	**22-Aug-13**	**26-Aug-13**	**03-Sep-13**	**10-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**0819**	**0820**	**0822**	**0826**	**0903**	**0910**	**0916**	**1017**
General Chemistry									
Alkalinity, Bicarbonate (as CaCO3)	mg/L	270	280	280	280	270	280	280	290
Alkalinity, Carbonate (as CaCO3)	mg/L	5.8	5.9	5	4.4	6.8	5.1	6.6	6.6
Alkalinity, Total (as CaCO3)	mg/L	280	290	290	290	280	290	290	290
Ammonia (as N)	mg/L	0.12	0.071	0.05	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	10.6	10.7	10.9	10.8	9.6	10.3	10.2	9.29
Cation Sum	meq/L	11.1	11.3	11.5	11.2	9.38	10.9	10.9	9.64
Chloride	mg/L	150	150	150	150	120	130	130	96
Dissolved Organic Carbon (DOC)	mg/L	3.6	3.4	3.5	3.2	**5.50**	3.3	3.3	**5.80**
Electrical Conductivity, Lab	µmhos/cm	1100	1100	1100	1100	950	1100	1100	900
Hardness (as CaCO3)	mg/L	**350.00**	**360.00**	**360.00**	**350.00**	**320.00**	**350.00**	**360.00**	**340.00**
Ion Balance	%	2.3	2.78	2.73	1.9	1.15	2.81	3.39	1.82
Langelier Index (at 20 C)	none	1.33	1.34	1.28	1.21	1.38	1.27	1.4	1.4
Langelier Index (at 4 C)	none	1.08	1.1	1.03	0.959	1.13	1.03	1.15	1.15
Nitrate (as N)	mg/L	1.4	1.5	1.6	1.8	1.7	2.1	2.4	2.8
Nitrate + Nitrite (as N)	mg/L	1.4	1.5	1.6	1.8	1.7	2.1	2.4	2.8
Nitrite (as N)	mg/L	0.01	0.01	0.011	0.01	0.01	0.012	0.01	0.016
Orthophosphate(as P)	mg/L	0.01	0.013	0.011	0.025	0.064	0.034	0.043	0.052
pH	S.U.	8.35	8.35	8.28	8.22	8.43	8.28	8.39	8.39
Saturation pH (at 20 C)	none	7.03	7.01	7	7.02	7.06	7	7	7
Saturation pH (at 4 C)	none	7.27	7.25	7.25	7.26	7.3	7.25	7.24	7.25
Sulfate	mg/L	30	30	30	31	29	28	29	25
Total Dissolved Solids (Calculated)	mg/L	**580.00**	**586.00**	**600.00**	**590.00**	**515.00**	**568.00**	**570.00**	**510.00**
UV%Transmittance	%								
Metals									
Aluminum	mg/L	0.01	0.01	0.014	0.012	0.014	0.012	0.014	0.02
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.0012	0.00	0.00	0.00
Barium	mg/L	0.067	0.068	0.073	0.065	0.061	0.069	0.065	0.051
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.016	0.017	0.017	0.016	0.021	0.01	0.018	0.018
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	100	100	110	100	94	100	110	100
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0016	0.007	0.017	0.013	0.013	0.01	0.0071	0.0056
Iron	mg/L	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	23	23	23	23	21	23	23	22
Manganese	mg/L	0.00	0.014	0.018	0.018	0.018	0.015	0.011	0.024
Molybdenum	mg/L	0.00059	0.00056	0.00066	0.00	0.00084	0.00078	0.00	0.00
Nickel	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	2.1	1.9	2.1	2	3.7	2.3	2.5	3.4
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	1.9	2	2.3	3.1	4.3	3.7	4.3	4
Silver	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium	mg/L	**93.00**	**95.00**	**97.00**	**95.00**	**66.00**	**87.00**	**83.00**	**62.00**
Strontium	mg/L	0.2	0.2	0.2	0.19	0.17	0.2	0.2	0.18
Thallium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.001	0.0011	0.0011	0.001	0.00096	0.0011	0.0011	0.0011
Vanadium	mg/L	0.00099	0.00092	0.00063	0.0013	0.0013	0.00078	0.0017	0.001
Zinc	mg/L	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.0073

Appendix S. (Continued)

Sample Location		UW-CMT1-2					
Sample Date		14-Aug-13	22-Aug-13	03-Sep-13	10-Sep-13	16-Sep-13	17-Oct-13
Sample ID		1	2	4	5	6	7
General Chemistry							
Alkalinity, Bicarbonate (as CaCO3)	mg/L	270.00	290	270	270	270	250
Alkalinity, Carbonate (as CaCO3)	mg/L	1.70	1.8	2.4	1.4	1.7	3.3
Alkalinity, Total (as CaCO3)	mg/L	280.00	290	270	270	280	250
Ammonia (as N)	mg/L	0.26	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	9.06	9.82	9.4	9.96	9.9	7.79
Cation Sum	meq/L	9.00	9.61	9.3	9.98	10.7	8.16
Chloride	mg/L	100.00	110	120	140	130	78
Dissolved Organic Carbon (DOC)	mg/L	3.10	3.1	2.8	2.6	2.5	3.6
Electrical Conductivity, Lab	µmhos/cm	890.00	970	950	1000	1100	780
Hardness (as CaCO3)	mg/L	**320.00**	**340.00**	**320.00**	**330.00**	**350.00**	**290.00**
Ion Balance	%	0.33	1.1	0.56	0.07	4.09	2.27
Langelier Index (at 20 C)	none	0.789	0.821	0.926	0.693	0.811	1.02
Langelier Index (at 4 C)	none	0.541	0.573	0.678	0.445	0.564	0.776
Nitrate (as N)	mg/L	1.1	1.4	0.68	0.65	0.59	1.1
Nitrate + Nitrite (as N)	mg/L	1.1	1.4	0.68	0.65	0.59	1.1
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.018	0.046	0.091	0.07	0.07	0.089
pH	S.U.	7.82	7.82	7.99	7.74	7.83	8.15
Saturation pH (at 20 C)	none	7.04	7	7.06	7.05	7.02	7.13
Saturation pH (at 4 C)	none	7.28	7.25	7.31	7.3	7.26	7.38
Sulfate	mg/L	28	31	27	26	27	25
Total Dissolved Solids (Calculated)	mg/L	490	**530.00**	**505.00**	**539.00**	**550.00**	430
UV%Transmittance	%	-	-	-	-	-	-
Metals							
Aluminum	mg/L	0.012	0.017	0.011	0.011	0.015	0.017
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.0011	0.0012
Barium	mg/L	0.081	0.083	0.065	0.065	0.065	0.046
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.014	0.024	0.021	0.015	0.021	0.02
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	97	100	95	99	110	85
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0075	0.0088	0.0076	0.0076	0.0079	0.0098
Iron	mg/L	0.10	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	19	20	20	21	22	18
Manganese	mg/L	0.0021	0.00	0.00	0.00	0.00	0.00
Molybdenum	mg/L	0.0022	0.0017	0.0011	0.0012	0.0012	0.0011
Nickel	mg/L	0.00	0.0021	0.00	0.00	0.0011	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10	0.13
Potassium	mg/L	3.2	3.4	3.2	3.3	3.6	3.2
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	4.5	4.5	4.4	4.4	4.6	4.5
Silver	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Sodium	mg/L	**57.00**	**64.00**	**66.00**	**75.00**	**82.00**	**54.00**
Strontium	mg/L	0.21	0.21	0.18	0.2	0.21	0.15
Thallium	mg/L	0.000059	0.000068	0.000066	0.000068	0.000081	0.000056
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0015	0.0014	0.001	0.0011	0.0012	0.00093
Vanadium	mg/L	0.00	0.00	0.00057	0.0007	0.0012	0.00083
Zinc	mg/L	0.0096	0.015	0.011	0.013	0.014	0.015

Appendix S. (Continued)

Sample Location		UW-CMT1-6					
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**10-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**5**	**6**	**7**
General Chemistry							
Alkalinity, Bicarbonate (as CaCO3)	mg/L	230	280	340	330	340	360
Alkalinity, Carbonate (as CaCO3)	mg/L	1.8	3.4	2.6	1.5	1.8	4.3
Alkalinity, Total (as CaCO3)	mg/L	230	280	340	330	340	360
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	7.24	10.3	18.5	17.6	16.8	15.2
Cation Sum	meq/L	7.37	10.5	18.9	18.4	18.1	17.2
Chloride	mg/L	62	130	**360.00**	**340.00**	**300.00**	230
Dissolved Organic Carbon (DOC)	mg/L	2.5	2.5	2.4	2.3	2.3	2.4
Electrical Conductivity, Lab	µmhos/cm	710	1000	2000	1900	1800	1600
Hardness (as CaCO3)	mg/L	**260.00**	**360.00**	**470.00**	**450.00**	**460.00**	**440.00**
Ion Balance	%	0.86	1.08	1	2.21	3.87	6.29
Langelier Index (at 20 C)	none	0.728	1.11	1.03	0.775	0.881	1.25
Langelier Index (at 4 C)	none	0.48	0.861	0.785	0.529	0.635	1
Nitrate (as N)	mg/L	4.1	2.8	0.10	0.10	0.10	0.23
Nitrate + Nitrite (as N)	mg/L	4.1	2.8	0.10	0.10	0.10	0.23
Nitrite (as N)	mg/L	0.01	0.021	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.92	8.11	7.9	7.68	7.74	8.1
Saturation pH (at 20 C)	none	7.19	7.01	6.87	6.91	6.86	6.86
Saturation pH (at 4 C)	none	7.44	7.25	7.12	7.15	7.11	7.1
Sulfate	mg/L	29	44	67	72	75	74
Total Dissolved Solids (Calculated)	mg/L	400	**570.00**	**1030.00**	**994.00**	**960.00**	**890.00**
UV%Transmittance	%	-	-	-	-	-	-
Metals							
Aluminum	mg/L	0.012	0.014	0.013	0.0093	0.017	0.015
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.083	0.12	0.2	0.19	0.2	0.14
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.01	0.017	0.019	0.011	0.02	0.021
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	78	110	140	130	140	130
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0067	0.006	0.0044	0.0042	0.0043	0.0042
Iron	mg/L	0.10	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	16	23	30	28	27	26
Manganese	mg/L	0.047	**0.07**	**0.10**	**0.11**	**0.11**	**0.10**
Molybdenum	mg/L	0.0017	0.0014	0.00087	0.00096	0.00079	0.00052
Nickel	mg/L	0.00	0.0013	0.0014	0.00	0.0016	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	3	3.8	4.6	4.6	4.7	4.3
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	3.5	3.8	4.1	3.9	4.3	4.6
Silver	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Sodium	mg/L	**47.00**	**73.00**	**210.00**	**210.00**	**200.00**	**190.00**
Strontium	mg/L	0.15	0.21	0.28	0.28	0.3	0.29
Thallium	mg/L	0.00	0.00	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0013	0.0031	0.008	0.0092	0.011	0.0069
Vanadium	mg/L	0.00	0.00	0.0008	0.00072	0.0015	0.00055
Zinc	mg/L	0.0056	0.008	0.011	0.011	0.01	0.012

Appendix S. (Continued)

Sample Location		UW-CMT2A-2				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	270	290	320	300	310
Alkalinity, Carbonate (as CaCO3)	mg/L	1.8	2.2	2.8	1.9	3.1
Alkalinity, Total (as CaCO3)	mg/L	280	300	320	300	310
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	9.37	9.82	11.8	10.8	10.2
Cation Sum	meq/L	9.39	9.8	12.1	11.3	10.5
Chloride	mg/L	120	120	130	100	75
Dissolved Organic Carbon (DOC)	mg/L	2.7	2.6	2.5	2.1	1.9
Electrical Conductivity, Lab	µmhos/cm	940	980	1200	1100	980
Hardness (as CaCO3)	mg/L	**330.00**	**340.00**	**440.00**	**420.00**	**420.00**
Ion Balance	%	0.11	0.14	1.34	2.37	1.48
Langelier Index (at 20 C)	none	0.806	0.905	1.09	0.909	1.14
Langelier Index (at 4 C)	none	0.558	0.657	0.847	0.661	0.887
Nitrate (as N)	mg/L	0.37	0.47	1.1	1	1.6
Nitrate + Nitrite (as N)	mg/L	0.37	0.47	1.1	1	1.6
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.84	7.9	7.97	7.82	8.03
Saturation pH (at 20 C)	none	7.03	6.99	6.88	6.91	6.9
Saturation pH (at 4 C)	none	7.28	7.24	7.13	7.16	7.14
Sulfate	mg/L	23	22	77	87	86
Total Dissolved Solids (Calculated)	mg/L	500	**530.00**	**650.00**	**610.00**	**570.00**
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.013	0.012	0.015	0.01	0.01
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.11	0.13	0.16	0.18	0.1
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.016	0.025	0.025	0.02	0.018
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	99	100	130	130	120
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.006	0.0065	0.0063	0.0063	0.005
Iron	mg/L	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	19	20	28	25	27
Manganese	mg/L	0.00	0.0038	0.00	0.00	0.00
Molybdenum	mg/L	0.0011	0.00095	0.00062	0.00074	0.00072
Nickel	mg/L	0.0012	0.0016	0.0019	0.002	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	2.7	2.9	3.4	6.2	2.5
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	4.4	4.5	4.5	4.6	5.1
Silver	mg/L	0.00024	0.00	0.00	0.00	0.00
Sodium	mg/L	**65.00**	**68.00**	**75.00**	**65.00**	**46.00**
Strontium	mg/L	0.2	0.21	0.26	0.28	0.26
Thallium	mg/L	0.000051	0.00006	0.000053	0.000092	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0013	0.0013	0.0016	0.0024	0.0029
Vanadium	mg/L	0.00	0.00	0.00	0.00	0.00
Zinc	mg/L	0.0068	0.0057	0.0064	0.014	0.0076

Appendix S. (Continued)

Sample Location		UW-CMT2A-6				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	250	260	300	340	350
Alkalinity, Carbonate (as CaCO3)	mg/L	1.8	3.3	2.8	1.9	3.7
Alkalinity, Total (as CaCO3)	mg/L	250	260	310	340	350
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	8.83	9.16	11.2	14	12.1
Cation Sum	meq/L	8.62	9.26	11.2	15	13.1
Chloride	mg/L	100	110	120	220	140
Dissolved Organic Carbon (DOC)	mg/L	2.4	2.3	2.6	2.5	2.4
Electrical Conductivity, Lab	µmhos/cm	870	920	1200	1500	1200
Hardness (as CaCO3)	mg/L	**300.00**	**310.00**	**410.00**	**470.00**	**430.00**
Ion Balance	%	1.21	0.54	0.09	3.32	3.62
Langelier Index (at 20 C)	none	0.769	1.04	1.05	0.937	1.22
Langelier Index (at 4 C)	none	0.521	0.793	0.807	0.691	0.969
Nitrate (as N)	mg/L	2.6	2	3.7	1.8	3.4
Nitrate + Nitrite (as N)	mg/L	2.6	2	3.7	1.8	3.4
Nitrite (as N)	mg/L	0.011	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.89	8.13	7.99	7.78	8.05
Saturation pH (at 20 C)	none	7.12	7.09	6.94	6.84	6.84
Saturation pH (at 4 C)	none	7.37	7.34	7.19	7.09	7.08
Sulfate	mg/L	39	28	64	37	47
Total Dissolved Solids (Calculated)	mg/L	480	500	**613.00**	**780.00**	**680.00**
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.011	0.011	0.013	0.01	0.01
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.084	0.09	0.16	0.19	0.1
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.01	0.013	0.011	0.013	0.016
Cadmium	mg/L	0.00	0.00	0.00	0.00012	0.00
Calcium	mg/L	89	91	120	140	130
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0049	0.0054	0.0055	0.0059	0.0052
Iron	mg/L	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	19	21	27	28	24
Manganese	mg/L	0.015	0.0044	0.00	0.002	0.00
Molybdenum	mg/L	0.0013	0.0013	0.00085	0.00087	0.00063
Nickel	mg/L	0.00	0.0011	0.0017	0.0014	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	2.7	2.7	3.1	3.9	3.2
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	3.4	3.2	3.6	4.2	4.4
Silver	mg/L	0.00015	0.00	0.00	0.00	0.00
Sodium	mg/L	**58.00**	**68.00**	**69.00**	**130.00**	**100.00**
Strontium	mg/L	0.21	0.21	0.28	0.32	0.26
Thallium	mg/L	0.000063	0.000058	0.000082	0.000081	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0014	0.0014	0.0028	0.0043	0.007
Vanadium	mg/L	0.00	0.00	0.00051	0.00075	0.00
Zinc	mg/L	0.0085	0.0071	0.058	0.011	0.0077

Appendix S. (Continued)

Sample Location		UW-CMT2B-2				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	270	240	300	290	270
Alkalinity, Carbonate (as CaCO3)	mg/L	1.6	2	3	1.7	3.1
Alkalinity, Total (as CaCO3)	mg/L	270	240	300	290	280
Ammonia (as N)	mg/L	0.05	0.64	0.05	0.05	0.05
Anion Sum	meq/L	10.3	8.69	9.67	9.28	8.59
Cation Sum	meq/L	10.3	9.05	9.47	9.7	8.94
Chloride	mg/L	140	110	85	70	63
Dissolved Organic Carbon (DOC)	mg/L	2.6	2.4	2.1	2.2	2.3
Electrical Conductivity, Lab	µmhos/cm	1100	880	950	920	850
Hardness (as CaCO3)	mg/L	**310.00**	**290.00**	**380.00**	**400.00**	**390.00**
Ion Balance	%	0.15	2.01	1.05	2.22	1.97
Langelier Index (at 20 C)	none	0.73	0.786	1.08	0.863	1.12
Langelier Index (at 4 C)	none	0.482	0.538	0.829	0.615	0.876
Nitrate (as N)	mg/L	1.5	0.6	2	4.4	4.4
Nitrate + Nitrite (as N)	mg/L	1.6	0.68	2	4.4	4.4
Nitrite (as N)	mg/L	0.14	0.084	0.012	0.024	0.019
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.8	7.94	8.03	7.8	8.08
Saturation pH (at 20 C)	none	7.07	7.15	6.96	6.93	6.96
Saturation pH (at 4 C)	none	7.32	7.4	7.2	7.18	7.21
Sulfate	mg/L	39	34	55	53	47
Total Dissolved Solids (Calculated)	mg/L	**560.00**	480	**517.00**	**510.00**	470
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.01	0.013	0.01	0.012	0.016
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.12	0.11	0.12	0.13	0.11
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.01	0.012	0.022	0.027	0.019
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	94	85	110	120	120
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0041	0.005	0.0049	0.0059	0.0047
Iron	mg/L	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	19	18	25	26	25
Manganese	mg/L	0.042	0.036	0.046	0.049	0.041
Molybdenum	mg/L	0.0012	0.0015	0.0013	0.0011	0.00095
Nickel	mg/L	0.00	0.001	0.0014	0.0016	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	3	2.9	2.9	3.1	3.4
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	3.6	3.4	3.7	4.1	3.8
Silver	mg/L	0.00015	0.00	0.00	0.00	0.00
Sodium	mg/L	**90.00**	**74.00**	**43.00**	**39.00**	**25.00**
Strontium	mg/L	0.18	0.16	0.2	0.22	0.21
Thallium	mg/L	0.00	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0018	0.0016	0.0023	0.0024	0.0028
Vanadium	mg/L	0.00	0.00	0.00	0.00057	0.00055
Zinc	mg/L	0.01	0.01	0.006	0.0051	0.0072

Appendix S. (Continued)

Sample Location		UW-CMT2B-6				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	400	320	310	290	270
Alkalinity, Carbonate (as CaCO3)	mg/L	1.5	1.7	3.2	1.7	3.2
Alkalinity, Total (as CaCO3)	mg/L	400	320	320	290	280
Ammonia (as N)	mg/L	0.079	0.05	0.05	0.05	0.085
Anion Sum	meq/L	20.6	9.56	9.4	9.52	9.15
Cation Sum	meq/L	20.6	9.71	9.06	9.53	9.51
Chloride	mg/L	**390.00**	33	24	18	18
Dissolved Organic Carbon (DOC)	mg/L	1.9	1.1	1	1.2	1.3
Electrical Conductivity, Lab	µmhos/cm	2100	890	860	850	840
Hardness (as CaCO3)	mg/L	**620.00**	**450.00**	**430.00**	**460.00**	**460.00**
Ion Balance	%	0.03	0.75	1.84	0.02	1.92
Langelier Index (at 20 C)	none	0.902	0.949	1.16	0.883	1.16
Langelier Index (at 4 C)	none	0.656	0.701	0.909	0.636	0.911
Nitrate (as N)	mg/L	0.10	0.10	0.10	0.10	0.10
Nitrate + Nitrite (as N)	mg/L	0.10	0.10	0.10	0.10	0.10
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.6	7.76	8.03	7.78	8.09
Saturation pH (at 20 C)	none	6.7	6.81	6.88	6.9	6.93
Saturation pH (at 4 C)	none	6.94	7.06	7.12	7.15	7.18
Sulfate	mg/L	81	100	120	150	150
Total Dissolved Solids (Calculated)	mg/L	**1100.00**	**530.00**	**505.00**	**530.00**	**520.00**
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.013	0.013	0.01	0.012	0.01
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.13	0.045	0.038	0.042	0.041
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.014	0.02	0.016	0.016	0.016
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	190	140	120	130	130
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.0011	0.00	0.00	0.00	0.00
Iron	mg/L	**0.83**	**0.97**	**0.74**	**0.69**	**0.56**
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	39	24	29	33	35
Manganese	mg/L	**0.21**	**0.14**	**0.14**	**0.14**	**0.11**
Molybdenum	mg/L	0.00077	0.00064	0.00052	0.0005	0.00
Nickel	mg/L	0.00	0.00	0.00	0.00	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	3.3	1.7	1.8	2.5	3
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	6.1	5.8	5.3	5.8	6.5
Silver	mg/L	0.00016	0.00	0.00	0.00	0.00
Sodium	mg/L	**190.00**	12	8.9	7.3	6.6
Strontium	mg/L	0.43	0.28	0.25	0.25	0.34
Thallium	mg/L	0.00	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0043	0.0033	0.003	0.0032	0.0017
Vanadium	mg/L	0.00	0.00	0.00	0.00	0.00
Zinc	mg/L	0.0073	0.0061	0.0051	0.01	0.01

Appendix S. (Continued)

Sample Location		UW-CMT3-2				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	310	240	280	260	280
Alkalinity, Carbonate (as CaCO3)	mg/L	1.6	2	2.8	2	3.6
Alkalinity, Total (as CaCO3)	mg/L	310	240	280	260	280
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05	0.05
Anion Sum	meq/L	9.72	7.58	10.4	9.34	10.1
Cation Sum	meq/L	9.6	7.65	10.5	9.75	11
Chloride	mg/L	110	80	150	120	130
Dissolved Organic Carbon (DOC)	mg/L	3.7	3.8	3.6	3.2	3
Electrical Conductivity, Lab	µmhos/cm	950	760	1100	960	1000
Hardness (as CaCO3)	mg/L	**320.00**	**240.00**	**320.00**	**330.00**	**360.00**
Ion Balance	%	0.61	0.47	0.34	2.12	4.38
Langelier Index (at 20 C)	none	0.741	0.762	0.973	0.858	1.12
Langelier Index (at 4 C)	none	0.493	0.513	0.725	0.61	0.876
Nitrate (as N)	mg/L	0.88	0.32	0.35	0.34	0.66
Nitrate + Nitrite (as N)	mg/L	0.89	0.32	0.35	0.34	0.68
Nitrite (as N)	mg/L	0.016	0.01	0.01	0.01	0.022
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.73	7.95	8.04	7.91	8.14
Saturation pH (at 20 C)	none	6.99	7.19	7.06	7.05	7.02
Saturation pH (at 4 C)	none	7.24	7.44	7.31	7.3	7.26
Sulfate	mg/L	25	21	29	24	29
Total Dissolved Solids (Calculated)	mg/L	**520.00**	410	**565.00**	**510.00**	**560.00**
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.01	0.01	0.01	0.01	0.0052
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.083	0.058	0.07	0.075	0.085
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.018	0.022	0.022	0.023	0.017
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	98	74	94	99	100
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.011	0.012	0.01	0.01	0.0092
Iron	mg/L	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	18	14	20	20	24
Manganese	mg/L	0.025	0.021	0.039	**0.05**	0.0051
Molybdenum	mg/L	0.001	0.0014	0.0013	0.0011	0.00089
Nickel	mg/L	0.0026	0.0028	0.0031	0.0035	0.0022
Phosphorus	mg/L	0.10	0.10	0.10	0.10	0.10
Potassium	mg/L	5.8	4.7	4.2	4.1	3.6
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	4.1	3.6	3.3	3.7	4.1
Silver	mg/L	0.00	0.00	0.00	0.00	0.00
Sodium	mg/L	**71.00**	**62.00**	**93.00**	**70.00**	**87.00**
Strontium	mg/L	0.21	0.15	0.18	0.19	0.19
Thallium	mg/L	0.00046	0.00034	0.0003	0.00022	0.00013
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0017	0.0013	0.0016	0.0014	0.0011
Vanadium	mg/L	0.00	0.00	0.00	0.00056	0.00
Zinc	mg/L	0.037	0.027	0.033	0.032	0.03

Appendix S. (Continued)

Sample Location		UW-CMT3-6				
Sample Date		**14-Aug-13**	**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**1**	**2**	**4**	**6**	**7**
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	230	240	250	280	260
Alkalinity, Carbonate (as CaCO3)	mg/L	1.9	3.3	3.1	2.4	3.9
Alkalinity, Total (as CaCO3)	mg/L	240	240	250	290	270
Ammonia (as N)	mg/L	0.16	0.15	0.05	0.05	0.05
Anion Sum	meq/L	9.22	8.48	9.04	9.23	7.86
Cation Sum	meq/L	9.17	8.54	8.72	9.41	8.47
Chloride	mg/L	120	100	110	99	64
Dissolved Organic Carbon (DOC)	mg/L	2.7	2.7	2.6	2.7	2.4
Electrical Conductivity, Lab	µmhos/cm	920	850	910	920	760
Hardness (as CaCO3)	mg/L	**330.00**	**300.00**	**290.00**	**340.00**	**310.00**
Ion Balance	%	0.29	0.36	1.8	1.01	3.74
Langelier Index (at 20 C)	none	0.82	1.02	0.983	0.936	1.13
Langelier Index (at 4 C)	none	0.572	0.775	0.735	0.688	0.877
Nitrate (as N)	mg/L	4	2.5	2.2	0.6	2
Nitrate + Nitrite (as N)	mg/L	4.1	2.5	2.3	0.6	2
Nitrite (as N)	mg/L	0.056	0.01	0.02	0.01	0.012
Orthophosphate(as P)	mg/L	0.067	0.085	0.091	0.088	0.076
pH	S.U.	7.93	8.16	8.12	7.95	8.2
Saturation pH (at 20 C)	none	7.11	7.14	7.13	7.02	7.07
Saturation pH (at 4 C)	none	7.36	7.39	7.38	7.27	7.32
Sulfate	mg/L	36	29	32	32	28
Total Dissolved Solids (Calculated)	mg/L	500	460	483	500	430
UV%Transmittance	%	-	-	-	-	-
Metals						
Aluminum	mg/L	0.01	0.01	0.01	0.01	0.01
Antimony	mg/L	0.00	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.00	0.00
Barium	mg/L	0.038	0.028	0.028	0.032	0.025
Beryllium	mg/L	0.00	0.00	0.00	0.00	0.00
Boron	mg/L	0.01	0.016	0.017	0.019	0.014
Cadmium	mg/L	0.00	0.00	0.00	0.00	0.00
Calcium	mg/L	98	87	85	98	91
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00	0.00
Copper	mg/L	0.006	0.0056	0.0057	0.0078	0.0063
Iron	mg/L	0.10	0.10	0.10	0.10	0.10
Lead	mg/L	0.00	0.00	0.00	0.00	0.00
Magnesium	mg/L	21	20	20	23	21
Manganese	mg/L	0.032	0.026	0.026	0.028	0.019
Molybdenum	mg/L	0.00076	0.00074	0.00089	0.00081	0.00065
Nickel	mg/L	0.00	0.00	0.001	0.0012	0.00
Phosphorus	mg/L	0.10	0.11	0.1	0.1	0.12
Potassium	mg/L	2.7	2.7	2.7	3.2	2.7
Selenium	mg/L	0.00	0.00	0.00	0.00	0.00
Silicon	mg/L	2.9	2.8	2.7	3.2	3.8
Silver	mg/L	0.00	0.00	0.00	0.00	0.00
Sodium	mg/L	**56.00**	**58.00**	**64.00**	**58.00**	**49.00**
Strontium	mg/L	0.18	0.16	0.16	0.19	0.16
Thallium	mg/L	0.00	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01	0.01
Uranium	mg/L	0.0014	0.0013	0.0014	0.0015	0.00093
Vanadium	mg/L	0.00	0.00	0.00	0.00082	0.00065
Zinc	mg/L	0.0068	0.01	0.01	0.01	0.0064

Appendix S. (Continued)

Sample Location		UW-MWA			
Sample Date		22-Aug-13	03-Sep-13	16-Sep-13	17-Oct-13
Sample ID		2	4	6	7
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	300	300	300	290
Alkalinity, Carbonate (as CaCO3)	mg/L	2.6	2.8	2.1	3.1
Alkalinity, Total (as CaCO3)	mg/L	310	310	300	290
Ammonia (as N)	mg/L	0.3	0.22	0.2	0.22
Anion Sum	meq/L	12	10.8	10.9	9.1
Cation Sum	meq/L	12.6	10.5	11.2	9.72
Chloride	mg/L	130	82	85	39
Dissolved Organic Carbon (DOC)	mg/L	1.2	1.1	1.2	1.2
Electrical Conductivity, Lab	µmhos/cm	1200	1000	1000	860
Hardness (as CaCO3)	mg/L	**440.00**	**440.00**	**460.00**	**420.00**
Ion Balance	%	2.44	1.07	1.27	3.33
Langelier Index (at 20 C)	none	1.03	1.07	0.959	1.11
Langelier Index (at 4 C)	none	0.782	0.822	0.711	0.863
Nitrate (as N)	mg/L	0.10	0.10	0.10	0.10
Nitrate + Nitrite (as N)	mg/L	0.10	0.10	0.10	0.10
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.97	7.99	7.86	8.06
Saturation pH (at 20 C)	none	6.94	6.92	6.9	6.95
Saturation pH (at 4 C)	none	7.18	7.17	7.15	7.2
Sulfate	mg/L	110	110	110	100
Total Dissolved Solids (Calculated)	mg/L	**680.00**	**589.00**	**610.00**	**510.00**
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.011	0.01	0.013	0.01
Antimony	mg/L	0.00	0.00	0.00	0.00
Arsenic	mg/L	0.00	0.00	0.00	0.001
Barium	mg/L	0.14	0.12	0.13	0.1
Beryllium	mg/L	0.00	0.00	0.00	0.00
Boron	mg/L	0.019	0.018	0.02	0.016
Cadmium	mg/L	0.00	0.00	0.00	0.00
Calcium	mg/L	120	120	130	110
Chromium (Total)	mg/L	0.01	0.01	0.01	0.01
Cobalt	mg/L	0.00	0.00	0.00	0.00
Copper	mg/L	0.0014	0.001	0.00	0.00
Iron	mg/L	**1.60**	**1.90**	**2.20**	**2.00**
Lead	mg/L	0.00	0.00	0.00	0.00
Magnesium	mg/L	33	34	34	32
Manganese	mg/L	**0.07**	**0.06**	**0.06**	**0.05**
Molybdenum	mg/L	0.00095	0.00055	0.00068	0.00088
Nickel	mg/L	0.00	0.00	0.00	0.00
Phosphorus	mg/L	0.10	0.10	0.10	0.10
Potassium	mg/L	2.4	2.1	2.2	2
Selenium	mg/L	0.00	0.00	0.00	0.00
Silicon	mg/L	7.8	7.4	7.8	7.9
Silver	mg/L	0.00	0.00	0.00	0.00
Sodium	mg/L	**85.00**	**36.00**	**42.00**	**29.00**
Strontium	mg/L	0.44	0.44	0.49	0.45
Thallium	mg/L	0.00	0.00	0.00	0.00
Titanium	mg/L	0.01	0.01	0.01	0.01
Uranium	mg/L	0.00027	0.00018	0.00018	0.00012
Vanadium	mg/L	0.00	0.00	0.00	0.00
Zinc	mg/L	0.0054	0.01	0.01	0.01

Appendix S. (Continued)

Sample Location		UW-MWB			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	350	340	310	310
Alkalinity, Carbonate (as CaCO3)	mg/L	2.1	2.8	2.1	2.8
Alkalinity, Total (as CaCO3)	mg/L	350	340	310	310
Ammonia (as N)	mg/L	0.15	0.11	0.11	0.21
Anion Sum	meq/L	19	16.7	12.6	12
Cation Sum	meq/L	20.6	16.3	13.5	13.4
Chloride	mg/L	**370**	**290**	160	150
Dissolved Organic Carbon (DOC)	mg/L	2.3	1.7	1.7	1.8
Electrical Conductivity, Lab	µmhos/cm	2000	1800	1300	1200
Hardness (as CaCO3)	mg/L	**490**	**430**	**440**	**460**
Ion Balance	%	4.04	1.19	3.77	5.48
Langelier Index (at 20 C)	none	0.958	1.06	0.961	1.09
Langelier Index (at 4 C)	none	0.713	0.81	0.714	0.846
Nitrate (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrate + Nitrite (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.8	7.95	7.85	7.98
Saturation pH (at 20 C)	none	6.84	6.89	6.89	6.89
Saturation pH (at 4 C)	none	7.09	7.14	7.14	7.14
Sulfate	mg/L	67	77	91	78
Total Dissolved Solids (Calculated)	mg/L	**1100**	**922**	**720**	**690**
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.016	0.005	0.005	0.0052
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.081	0.054	0.043	0.039
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.021	0.021	0.017	0.016
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	150	130	130	130
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0007	0.0005	0.0005	0.0005
Copper	mg/L	0.0014	0.0016	0.0012	0.001
Iron	mg/L	0.13	0.23	0.27	0.24
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	30	27	26	31
Manganese	mg/L	**0.14**	**0.098**	**0.095**	**0.075**
Molybdenum	mg/L	0.0005	0.0005	0.0005	0.0005
Nickel	mg/L	0.0013	0.0011	0.001	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	3.5	2.7	2.2	1.7
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	5.7	6	6.2	6.6
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**240**	**170**	**110**	**97**
Strontium	mg/L	0.41	0.35	0.37	0.37
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.004	0.0018	0.0013	0.00056
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.0081	0.008	0.0066	0.006

Appendix S. (Continued)

Sample Location		WT-TW2-13			
Sample Date		**19-Aug-13**	**19-Aug-13**	**22-Aug-13**	**26-Aug-13**
Sample ID		**20130819**	**20130820**	**20130822**	**20130826**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	320	320	300	310
Alkalinity, Carbonate (as CaCO3)	mg/L	2.3	2.7	1.9	2.1
Alkalinity, Total (as CaCO3)	mg/L	320	320	300	310
Ammonia (as N)	mg/L	0.068	0.19	0.09	0.079
Anion Sum	meq/L	14.6	13.1	11.7	11.7
Cation Sum	meq/L	15.9	13.9	12.8	11.6
Chloride	mg/L	250	180	140	130
Dissolved Organic Carbon (DOC)	mg/L	2.2	2	1.9	2
Electrical Conductivity, Lab	µmhos/cm	1600	1400	1200	1200
Hardness (as CaCO3)	mg/L	**450**	**430**	**420**	**400**
Ion Balance	%	4.21	2.94	4.59	0.61
Langelier Index (at 20 C)	none	0.991	1.06	0.884	0.93
Langelier Index (at 4 C)	none	0.745	0.808	0.637	0.683
Nitrate (as N)	mg/L	1.8	1.1	1	0.95
Nitrate + Nitrite (as N)	mg/L	-	-	-	-
Nitrite (as N)	mg/L	0.038	0.022	0.018	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.88	7.96	7.82	7.86
Saturation pH (at 20 C)	none	6.89	6.9	6.93	6.93
Saturation pH (at 4 C)	none	7.14	7.15	7.18	7.18
Sulfate	mg/L	52	69	78	80
Total Dissolved Solids (Calculated)	mg/L	**836**	**740**	**668**	**643**
UV%Transmittance	%	89	89	90	89
Metals					
Aluminum	mg/L	0.005	0.005	0.005	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.14	0.12	0.11	0.098
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.017	0.016	0.018	0.019
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	130	130	120	120
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.0039	0.0028	0.0022	0.0026
Iron	mg/L	0.1	0.1	0.15	0.14
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	27	27	27	27
Manganese	mg/L	**0.1**	**0.1**	**0.096**	**0.08**
Molybdenum	mg/L	0.00083	0.00076	0.00083	0.00057
Nickel	mg/L	0.0013	0.001	0.001	0.0011
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	3.6	3.1	3	2.8
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	4.8	5.1	5	5
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**160**	**120**	**100**	**80**
Strontium	mg/L	0.29	0.3	0.31	0.29
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0031	0.0029	0.0027	0.0022
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.01	0.0061	0.005	0.0098

Appendix S. (Continued)

Sample Location		WT-TW2-13				
Sample Date Sample ID		03-Sep-13 20130903	10-Sep-13 20130910	17-Sep-13 20130917	03-Oct-13 20131003	17-Oct-13 20131017
General Chemistry						
Alkalinity, Bicarbonate (as CaCO3)	mg/L	300	300	300	300	300
Alkalinity, Carbonate (as CaCO3)	mg/L	2.5	1.9	1.7	2.3	3.3
Alkalinity, Total (as CaCO3)	mg/L	300	300	300	300	300
Ammonia (as N)	mg/L	0.05	0.05	0.063	0.12	0.09
Anion Sum	meq/L	10.9	10.7	10.5	10.2	9.89
Cation Sum	meq/L	11	11.2	10.6	9.6	9.68
Chloride	mg/L	110	95	88	78	69
Dissolved Organic Carbon (DOC)	mg/L	1.8	1.7	1.8	1.6	1.7
Electrical Conductivity, Lab	µmhos/cm	1100	1000	1000	990	940
Hardness (as CaCO3)	mg/L	**410**	**430**	**410**	**380**	**390**
Ion Balance	%	0.51	2.1	0.35	3.28	1.05
Langelier Index (at 20 C)	none	1.01	0.922	0.849	0.95	1.12
Langelier Index (at 4 C)	none	0.763	0.675	0.601	0.702	0.874
Nitrate (as N)	mg/L	0.98	1.2	1.4	1.7	1.7
Nitrate + Nitrite (as N)	mg/L	-	-	-	-	-
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01	0.01
pH	S.U.	7.94	7.84	7.78	7.9	8.06
Saturation pH (at 20 C)	none	6.93	6.92	6.93	6.95	6.94
Saturation pH (at 4 C)	none	7.18	7.16	7.18	7.2	7.19
Sulfate	mg/L	86	91	91	88	83
Total Dissolved Solids (Calculated)	mg/L	**603**	**588**	**580**	**550**	**540**
UV%Transmittance	%	89	89	89	89	90
Metals						
Aluminum	mg/L	0.005	0.005	0.005	0.005	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001	0.001
Barium	mg/L	0.099	0.095	0.088	0.083	0.088
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.019	0.016	0.023	0.016	0.026
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	120	120	120	110	110
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.0025	0.003	0.0032	0.0026	0.0032
Iron	mg/L	0.19	0.22	0.24	0.26	0.29
Lead	mg/L	0.0005	0.0005	0.00068	0.0005	0.0005
Magnesium	mg/L	27	29	29	26	27
Manganese	mg/L	**0.078**	**0.078**	**0.074**	**0.064**	**0.065**
Molybdenum	mg/L	0.00075	0.00074	0.00096	0.00065	0.00076
Nickel	mg/L	0.001	0.001	0.001	0.001	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1	0.1
Potassium	mg/L	2.9	2.9	2.8	2.6	2.7
Selenium	mg/L	0.002	0.002	0.002	0.002	0.002
Silicon	mg/L	5.2	5.4	5.4	5	5.2
Silver	mg/L	0.0001	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**63**	**58**	**52**	**43**	**40**
Strontium	mg/L	0.32	0.33	0.32	0.31	0.33
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0022	0.0025	0.0025	0.0023	0.0022
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.005	0.0067	0.0059	0.005	0.005

Appendix S. (Continued)

Sample Location		WT-MW-OW1A-11			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	310	300	300	310
Alkalinity, Carbonate (as CaCO3)	mg/L	2.4	2.9	2	3.2
Alkalinity, Total (as CaCO3)	mg/L	310	300	300	310
Ammonia (as N)	mg/L	0.053	0.05	0.05	0.05
Anion Sum	meq/L	8.93	8.67	8.7	9.17
Cation Sum	meq/L	9.15	8.61	9.06	9.29
Chloride	mg/L	28	24	28	37
Dissolved Organic Carbon (DOC)	mg/L	0.87	0.97	0.92	0.83
Electrical Conductivity, Lab	µmhos/cm	820	800	810	860
Hardness (as CaCO3)	mg/L	**430**	**410**	**430**	**430**
Ion Balance	%	1.2	0.34	2.06	0.64
Langelier Index (at 20 C)	none	1.02	1.08	0.945	1.14
Langelier Index (at 4 C)	none	0.77	0.83	0.697	0.896
Nitrate (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrate + Nitrite (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.92	8.01	7.85	8.04
Saturation pH (at 20 C)	none	6.9	6.93	6.91	6.89
Saturation pH (at 4 C)	none	7.15	7.18	7.16	7.14
Sulfate	mg/L	89	91	88	88
Total Dissolved Solids (Calculated)	mg/L	490	466	480	500
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.014	0.005	0.012	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.0014	0.0014	0.0013	0.0013
Barium	mg/L	0.31	0.29	0.31	0.32
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.017	0.018	0.018	0.014
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	120	110	120	120
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.001	0.001	0.001	0.001
Iron	mg/L	**1.6**	**1.6**	**1.6**	**1.7**
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	33	31	32	33
Manganese	mg/L	**0.11**	**0.11**	**0.12**	**0.13**
Molybdenum	mg/L	0.00062	0.00059	0.00055	0.00067
Nickel	mg/L	0.001	0.001	0.001	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	2	1.9	2	2
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	6.8	6.4	6.5	6.3
Silver	mg/L	0.0001	0.0001	0.0001	0.00012
Sodium	mg/L	12	8.5	1	13
Strontium	mg/L	0.43	0.4	0.45	0.46
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.00042	0.00045	0.00043	0.00047
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.005	0.005	0.005	0.005

Appendix S. (Continued)

Sample Location		WT-MW-OW1B-11			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	320	290	240	260
Alkalinity, Carbonate (as CaCO3)	mg/L	2.3	2.9	1.9	3
Alkalinity, Total (as CaCO3)	mg/L	320	300	240	270
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05
Anion Sum	meq/L	10.7	7.91	6.16	7.98
Cation Sum	meq/L	11	7.82	6.33	8.02
Chloride	mg/L	47	5	8	27
Dissolved Organic Carbon (DOC)	mg/L	2.1	2.1	1.5	1.8
Electrical Conductivity, Lab	µmhos/cm	1000	740	590	770
Hardness (as CaCO3)	mg/L	**460**	**370**	**300**	**380**
Ion Balance	%	1.44	0.55	1.37	0.28
Langelier Index (at 20 C)	none	1.02	1.06	0.805	1.1
Langelier Index (at 4 C)	none	0.77	0.814	0.557	0.851
Nitrate (as N)	mg/L	**12**	10	4.7	10
Nitrate + Nitrite (as N)	mg/L	**12**	10	4.9	10
Nitrite (as N)	mg/L	0.15	0.19	0.2	0.14
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.89	8.02	7.93	8.08
Saturation pH (at 20 C)	none	6.87	6.96	7.13	6.98
Saturation pH (at 4 C)	none	7.12	7.2	7.37	7.23
Sulfate	mg/L	94	51	37	55
Total Dissolved Solids (Calculated)	mg/L	**610**	432	340	440
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.012	0.016	0.014	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.099	0.066	0.063	0.082
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.03	0.033	0.025	0.022
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	130	110	84	110
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.00054	0.00052	0.0005	0.00052
Copper	mg/L	0.0029	0.0035	0.003	0.0034
Iron	mg/L	0.1	0.1	0.1	0.1
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	33	26	21	26
Manganese	mg/L	**0.14**	**0.11**	**0.093**	**0.12**
Molybdenum	mg/L	0.00079	0.00071	0.00098	0.00069
Nickel	mg/L	0.0026	0.002	0.0018	0.0012
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	3.3	2.6	2.3	2.6
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	4.8	4.4	4	4
Silver	mg/L	0.0001	0.0001	0.0001	0.00011
Sodium	mg/L	**40**	7.7	7.7	6.1
Strontium	mg/L	0.31	0.22	0.19	0.27
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.009	0.0069	0.0049	0.006
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.0066	0.0052	0.0063	0.0073

Appendix S. (Continued)

Sample Location		WT-MW-OW3B-09			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	370	290	280	270
Alkalinity, Carbonate (as CaCO3)	mg/L	2	2.6	1.6	2.7
Alkalinity, Total (as CaCO3)	mg/L	370	290	280	270
Ammonia (as N)	mg/L	0.19	0.069	0.076	0.09
Anion Sum	meq/L	14	9.14	9.55	8.93
Cation Sum	meq/L	14.7	9.07	9.47	9.55
Chloride	mg/L	150	17	17	18
Dissolved Organic Carbon (DOC)	mg/L	1.4	1.5	1.6	1.4
Electrical Conductivity, Lab	µmhos/cm	1400	830	850	820
Hardness (as CaCO3)	mg/L	**610**	**430**	**450**	**460**
Ion Balance	%	2.39	0.39	0.45	3.39
Langelier Index (at 20 C)	none	1.04	1.06	0.862	1.09
Langelier Index (at 4 C)	none	0.79	0.809	0.614	0.844
Nitrate (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrate + Nitrite (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.76	7.98	7.79	8.03
Saturation pH (at 20 C)	none	6.72	6.92	6.93	6.94
Saturation pH (at 4 C)	none	6.97	7.17	7.18	7.19
Sulfate	mg/L	120	130	170	150
Total Dissolved Solids (Calculated)	mg/L	**780**	**506**	**540**	**510**
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.011	0.005	0.013	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.1	0.065	0.063	0.054
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.021	0.017	0.038	0.018
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	170	120	130	130
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.001	0.001	0.001	0.001
Iron	mg/L	**1.3**	**0.93**	**0.96**	**0.85**
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	45	32	33	35
Manganese	mg/L	**0.17**	**0.12**	**0.13**	**0.12**
Molybdenum	mg/L	0.00085	0.00066	0.00063	0.0005
Nickel	mg/L	0.001	0.001	0.001	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	4	3.2	3	2.6
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	7	7.3	7.4	7.6
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**55**	6.6	6.1	6.8
Strontium	mg/L	0.58	0.4	0.45	0.46
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0013	0.0011	0.0011	0.0007
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.0062	0.005	0.005	0.005

Appendix S. (Continued)

Sample Location		WT-MW-OW3A-09			
Sample Date		22-Aug-13	03-Sep-13	16-Sep-13	17-Oct-13
Sample ID		2	4	6	7
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	320	310	310	290
Alkalinity, Carbonate (as CaCO3)	mg/L	2.2	2.9	2.2	2.8
Alkalinity, Total (as CaCO3)	mg/L	320	310	310	290
Ammonia (as N)	mg/L	0.06	0.079	0.05	0.069
Anion Sum	meq/L	10.2	9.23	9.01	8.14
Cation Sum	meq/L	10.2	9.4	9.61	8.6
Chloride	mg/L	65	40	33	26
Dissolved Organic Carbon (DOC)	mg/L	0.95	0.82	0.83	1.1
Electrical Conductivity, Lab	µmhos/cm	950	870	840	760
Hardness (as CaCO3)	mg/L	**460**	**430**	**440**	**400**
Ion Balance	%	0.26	0.88	3.21	2.76
Langelier Index (at 20 C)	none	0.99	1.1	0.984	1.05
Langelier Index (at 4 C)	none	0.742	0.854	0.736	0.806
Nitrate (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrate + Nitrite (as N)	mg/L	0.1	0.1	0.1	0.1
Nitrite (as N)	mg/L	0.01	0.01	0.01	0.01
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.86	8	7.87	8.01
Saturation pH (at 20 C)	none	6.87	6.9	6.89	6.95
Saturation pH (at 4 C)	none	7.12	7.15	7.13	7.2
Sulfate	mg/L	90	89	88	74
Total Dissolved Solids (Calculated)	mg/L	**550**	499	500	440
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.011	0.005	0.005	0.012
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.16	0.14	0.15	0.12
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.016	0.017	0.016	0.014
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	130	120	120	110
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.001	0.001	0.001	0.001
Iron	mg/L	**1**	**0.98**	**1**	**1**
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	36	33	33	31
Manganese	mg/L	**0.17**	**0.15**	**0.17**	**0.16**
Molybdenum	mg/L	0.00086	0.00092	0.001	0.00095
Nickel	mg/L	0.001	0.001	0.001	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	2.4	2.3	2.3	2.1
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	5.6	5.4	5.7	5.3
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	20	16	16	12
Strontium	mg/L	0.44	0.4	0.42	0.39
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0017	0.0016	0.0018	0.0016
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.005	0.005	0.005	0.0054

Appendix S. (Continued)

Sample Location		WT-MW-OW2-11			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	240	300	310	290
Alkalinity, Carbonate (as CaCO3)	mg/L	1.9	3	2	3.1
Alkalinity, Total (as CaCO3)	mg/L	240	310	320	300
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05
Anion Sum	meq/L	8.39	11.4	11.5	9.5
Cation Sum	meq/L	8.74	12.2	12.1	10.2
Chloride	mg/L	100	150	130	76
Dissolved Organic Carbon (DOC)	mg/L	2.7	2.9	3.4	2.9
Electrical Conductivity, Lab	µmhos/cm	850	1200	1100	930
Hardness (as CaCO3)	mg/L	**300**	**400**	**410**	**380**
Ion Balance	%	2.01	3.43	2.35	3.74
Langelier Index (at 20 C)	none	0.796	1.07	0.916	1.11
Langelier Index (at 4 C)	none	0.548	0.826	0.669	0.86
Nitrate (as N)	mg/L	1.9	1.7	2.6	3.4
Nitrate + Nitrite (as N)	mg/L	1.9	1.7	2.7	3.4
Nitrite (as N)	mg/L	0.01	0.01	0.026	0.028
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.93	8.02	7.83	8.05
Saturation pH (at 20 C)	none	7.13	6.94	6.91	6.95
Saturation pH (at 4 C)	none	7.38	7.19	7.16	7.19
Sulfate	mg/L	28	42	68	55
Total Dissolved Solids (Calculated)	mg/L	460	**632**	**640**	**530**
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.013	0.014	0.011	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.085	0.096	0.091	0.067
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.019	0.025	0.027	0.018
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	87	120	120	110
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.0068	0.008	0.0087	0.0088
Iron	mg/L	0.1	0.1	0.1	0.1
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	20	27	27	24
Manganese	mg/L	0.011	0.01	0.01	0.0074
Molybdenum	mg/L	0.0015	0.00095	0.00081	0.00057
Nickel	mg/L	0.0013	0.0015	0.0015	0.001
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	2.7	3.1	3	3.1
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	3.2	3.4	3.8	4
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**61**	**94**	**87**	**58**
Strontium	mg/L	0.16	0.22	0.23	0.2
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0014	0.0019	0.0018	0.0014
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.0065	0.0072	0.0098	0.0079

Appendix S. (Continued)

Sample Location		WT-MW-OW3-11			
Sample Date		**22-Aug-13**	**03-Sep-13**	**16-Sep-13**	**17-Oct-13**
Sample ID		**2**	**4**	**6**	**7**
General Chemistry					
Alkalinity, Bicarbonate (as CaCO3)	mg/L	310	330	320	290
Alkalinity, Carbonate (as CaCO3)	mg/L	2.2	2.7	1.8	3.4
Alkalinity, Total (as CaCO3)	mg/L	320	330	320	290
Ammonia (as N)	mg/L	0.05	0.05	0.05	0.05
Anion Sum	meq/L	11.6	13.3	11.7	7.91
Cation Sum	meq/L	11.9	13.3	12	8.25
Chloride	mg/L	110	130	76	8
Dissolved Organic Carbon (DOC)	mg/L	2.2	2.6	2.5	2.5
Electrical Conductivity, Lab	µmhos/cm	1100	1300	1100	750
Hardness (as CaCO3)	mg/L	**430**	**480**	**490**	**380**
Ion Balance	%	1.18	0.27	1.23	2.1
Langelier Index (at 20 C)	none	0.965	1.09	0.941	1.15
Langelier Index (at 4 C)	none	0.717	0.842	0.693	0.898
Nitrate (as N)	mg/L	4.8	**18**	**17**	10
Nitrate + Nitrite (as N)	mg/L	4.9	**18**	**17**	10
Nitrite (as N)	mg/L	0.11	0.089	0.11	0.17
Orthophosphate(as P)	mg/L	0.01	0.01	0.01	0.01
pH	S.U.	7.87	7.95	7.78	8.1
Saturation pH (at 20 C)	none	6.91	6.86	6.84	6.95
Saturation pH (at 4 C)	none	7.15	7.11	7.08	7.2
Sulfate	mg/L	87	90	96	56
Total Dissolved Solids (Calculated)	mg/L	**650**	**763**	**680**	450
UV%Transmittance	%	-	-	-	-
Metals					
Aluminum	mg/L	0.016	0.0096	0.005	0.005
Antimony	mg/L	0.0005	0.0005	0.0005	0.0005
Arsenic	mg/L	0.001	0.001	0.001	0.001
Barium	mg/L	0.099	0.11	0.1	0.067
Beryllium	mg/L	0.0005	0.0005	0.0005	0.0005
Boron	mg/L	0.024	0.026	0.028	0.028
Cadmium	mg/L	0.0001	0.0001	0.0001	0.0001
Calcium	mg/L	120	140	150	110
Chromium (Total)	mg/L	0.005	0.005	0.005	0.005
Cobalt	mg/L	0.0005	0.0005	0.0005	0.0005
Copper	mg/L	0.0028	0.0033	0.0039	0.0039
Iron	mg/L	0.1	0.1	0.1	0.1
Lead	mg/L	0.0005	0.0005	0.0005	0.0005
Magnesium	mg/L	29	32	31	26
Manganese	mg/L	**0.11**	**0.13**	**0.13**	**0.096**
Molybdenum	mg/L	0.00066	0.0005	0.00055	0.0005
Nickel	mg/L	0.0011	0.002	0.0024	0.0012
Phosphorus	mg/L	0.1	0.1	0.1	0.1
Potassium	mg/L	4.5	4.8	4.6	3.7
Selenium	mg/L	0.002	0.002	0.002	0.002
Silicon	mg/L	4.4	4.5	4.6	4.4
Silver	mg/L	0.0001	0.0001	0.0001	0.0001
Sodium	mg/L	**74**	**83**	**48**	12
Strontium	mg/L	0.28	0.31	0.32	0.23
Thallium	mg/L	0.00005	0.00005	0.00005	0.00005
Titanium	mg/L	0.005	0.005	0.005	0.005
Uranium	mg/L	0.0086	0.0091	0.0097	0.0079
Vanadium	mg/L	0.0005	0.0005	0.0005	0.0005
Zinc	mg/L	0.0069	0.0059	0.01	0.005

Appendix T. Turbidity Data from Handheld Device

Date	Turbidity (FNU)
03/09/2013 9:12	0.14
06/09/2013 8:56	0.58
06/09/2013 15:13	0.2
10/09/2013 9:00	0.4
17/09/2013 12:00	0.11
19/09/2013 11:05	0.85
20/09/2013 11:40	0.45
24/09/2013 9:47	0.31
26/09/2013 12:47	1.04
27/09/2013 13:32	0.25
30/09/2013 9:40	0.31
01/10/2013 13:40	0.63
02/10/2013 18:00	0.12
03/10/2013 11:00	0.14
04/10/2013 9:58	0.2
08/10/2013 10:15	0.35
09/10/2013 11:36	0.12
10/10/2013 13:22	0.13
11/10/2013 12:58	0.36
15/10/2013 13:15	0.22
16/10/2013 13:05	0.37

Appendix U. Stable Water Isotope Data

Oxygen-18 (^{18}O) and Deuterium (^{2}H) comprise a small amount of our water, alongside the more stable Oxygen-16 (^{16}O) and Hydrogen-1. Different amounts of these isotopes can be indicators of different things, such as elevation, latitude, season, the humidity in a vapour source region, and identifying periods of glaciation. Isotope abundance is measured as a ratio of the isotope to the common nuclide, such as ^{18}O compared to ^{16}O. The abundance ration in a sample is provided in relation to a reference gas with a known isotope composition. The amount of ^{18}O can then be determined using Equation 14,

$$\delta^{18}O_{sample} = \frac{(^{18}O/^{16}O)_{sample} - (^{18}O/^{16}O)_{reference}}{(^{18}O/^{16}O)_{reference}}$$

When represented in as per million quantity,

$$\delta^{18}O_{sample} = \left(\frac{(^{18}O/^{16}O)_{sample}}{(^{18}O/^{16}O)_{reference}} - 1 \right) \cdot 1000\,‰ \text{ VSMOW}$$

where δ is the standard symbol for an isotopic measurement, VSMOW is the Vienna Standard Mean Ocean Water, and ‰ is the per-million notation (Clark & Aravena, 2005).

In this case, the reference gas is VSMOW, so the resulting answer is provided as a ‰ different from VSMOW. The δX ‰ value has great meaning. A positive δX ‰ value indicates that the sample has more of the measured isotope than the reference gas; a negative δX ‰ value would mean that the sample has less than the reference. Additional, an isotopic difference can be calculated between two samples. The terms enriched or depleted are used to describe if samples have a larger or smaller δX ‰ value, which can be an indicator of many things (Clark & Aravena, 2005).

The hydrologic cycle governs isotope behaviour, including the processes of evaporation, condensation, and eventual precipitation. Within the groundwater sector, isotopic composition can be very helpful. The relative amounts of ^{18}O can help distinguish between different water sources, determine mixing between multiple sources, and quantify evaporative loss. Two governing principals allow for the predictability in the behaviour of $\delta^{18}O$ and $\delta^{2}H$. First, they correlate with a mean annual temperature and second, their relationship correlates on a global and local scale.

When water evaporates from a large water body, such as an ocean, isotopes are selectively partitioned. Lighter isotopes will evaporate more than the heavy isotope, eventually forming clouds that move inland. When temperature drops, condensation occurs and precipitation forms; the heavy ^{18}O and ^{2}H isotopes are preferentially distilled as rainout from the vapour. Over time, the vapour becomes depleted in ^{18}O and ^{2}H and continues farther inland, resulting in progressively more negative, depleted precipitation. This is termed the Rayleigh–type distillation. When it becomes colder, precipitation is more isotopically–depleted (Clark & Aravena, 2005).

The correlation between ^{18}O and ^{2}H forms the basis for the global meteoric water line (GMWL), fitting a line with the equation:

$$\delta^{2}H = 8\ \delta^{18}O + 10\ ‰\ SMOW$$

The GMWL is an average of many local regional meteoric water lines. The globally-averaged line differs from local lines in both slope and $\delta^{2}H$ intercept because of climate and geographic reasons. The line allows for a datum by which to compare the isotopic composition of any samples collected. Data from Simcoe Isotopic Station used to generate the local meteoric water line LMWL equation that is applicable to southern Ontario:

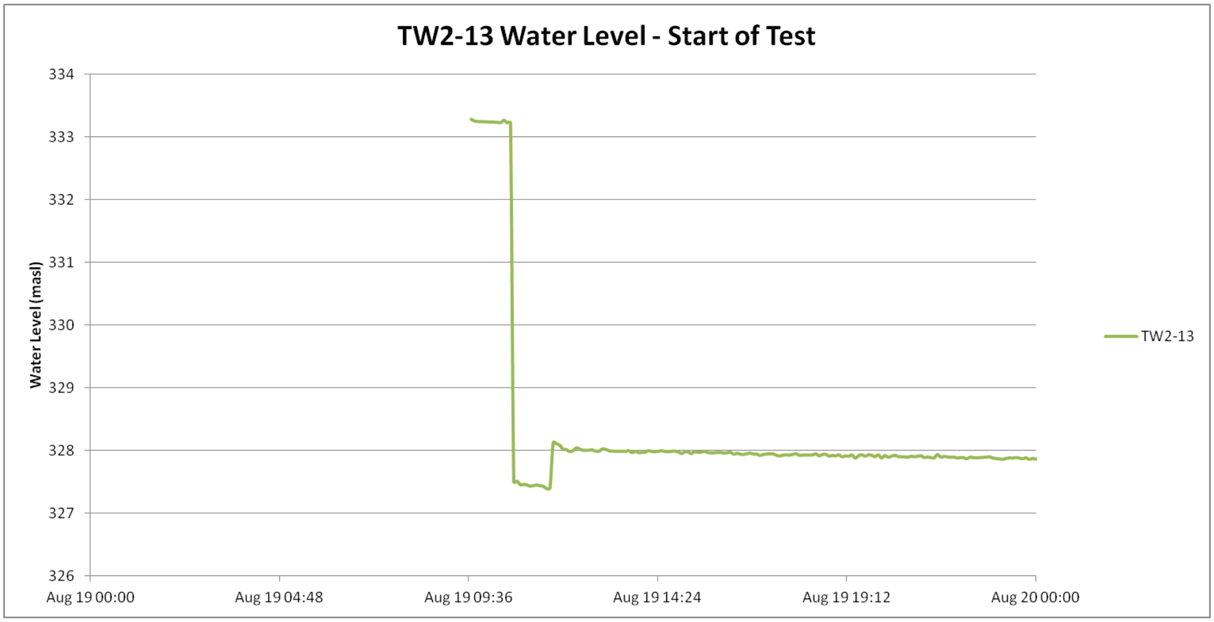
$$\delta^{2}H = 8.13\ \delta^{18}O + 10.8\ ‰$$

available via “Simcoe Ontario Local Meteoric Water Line,” 2013.

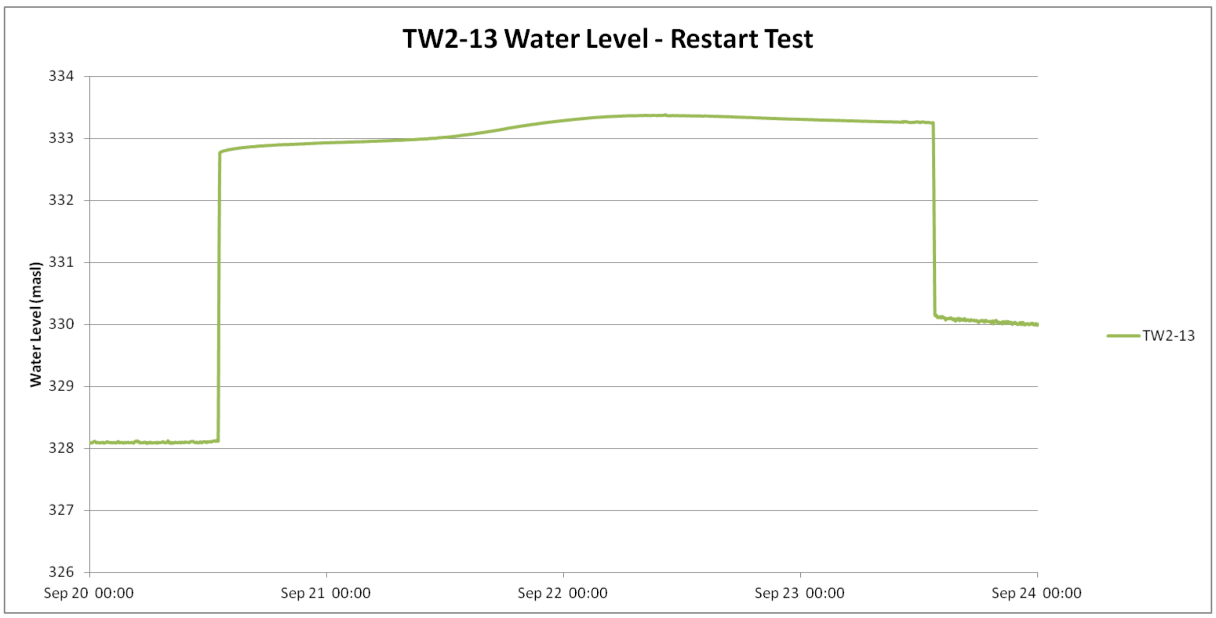
Sample Location	**Sample**	**Date**	**δ18O (‰)**	**δ2H (‰)**
Alder Creek	1	14-Aug-13	-9.64	-66.36
	2	22-Aug-13	-10.27	-68.45
	3	26-Aug-13	-10.31	-68.79
	4	3-Sep-13	-9.68	-65.20
	6	16-Sep-13	-10.36	-68.72
	7	17-Oct-13	-9.77	-64.13
UW-CMT1-2	1	14-Aug-13	-9.58	-64.61
	2	22-Aug-13	-9.90	-66.08
	4	3-Sep-13	-9.94	-66.31
	5	10-Sep-13	-10.01	-66.78
	6	16-Sep-13	-10.01	-67.68
	7	17-Oct-13	-9.33	-61.81
UWCMT1-6	1	14-Aug-13	-10.50	-70.32
	2	22-Aug-13	-10.22	-67.03
	4	3-Sep-13	-11.05	-73.09
	5	10-Sep-13	-10.77	-71.60
	6	16-Sep-13	-10.78	-71.37
	7	17-Oct-13	-10.88	-73.27
UW-CMT2A-2	1	14-Aug-13	-9.52	-64.11
	2	22-Aug-13	-9.49	-63.29
	4	3-Sep-13	-10.63	-70.03
	6	16-Sep-13	-10.71	-70.38
	7	17-Oct-13	-10.53	-70.16
UW-CMT2A-6	1	14-Aug-13	-9.76	-64.93
	2	22-Aug-13	-9.97	-65.72
	4	3-Sep-13	-11.24	-74.81
	6	16-Sep-13	-10.45	-68.77
	7	17-Oct-13	-10.22	-67.67
UW-CMT2B-2	1	14-Aug-13	-9.53	-64.67
	2	22-Aug-13	-10.19	-68.53
	4	3-Sep-13	-11.03	-73.13
	6	16-Sep-13	-11.17	-74.27
	7	17-Oct-13	-10.82	-71.83
UW-CMT2B-6	1	14-Aug-13	-10.01	-67.86
	2	22-Aug-13	-10.76	-70.53
	4	3-Sep-13	-10.59	-69.41
	6	16-Sep-13	-10.59	-70.18
	7	17-Oct-13	-10.59	-70.46
UW-CMT3-2	2	22-Aug-13	-9.57	-64.47
	4	3-Sep-13	-9.83	-65.43
	6	16-Sep-13	-9.98	-66.57
	7	17-Oct-13	-9.76	-65.02
UW-CMT3-6	2	22-Aug-13	-10.27	-69.09
	4	3-Sep-13	-10.51	-69.70
	6	16-Sep-13	-10.23	-67.29
	7	17-Oct-13	-11.18	-75.62

Appendix V. Continuous Water Level Data Figures for Pumping Test Well, TW2-13

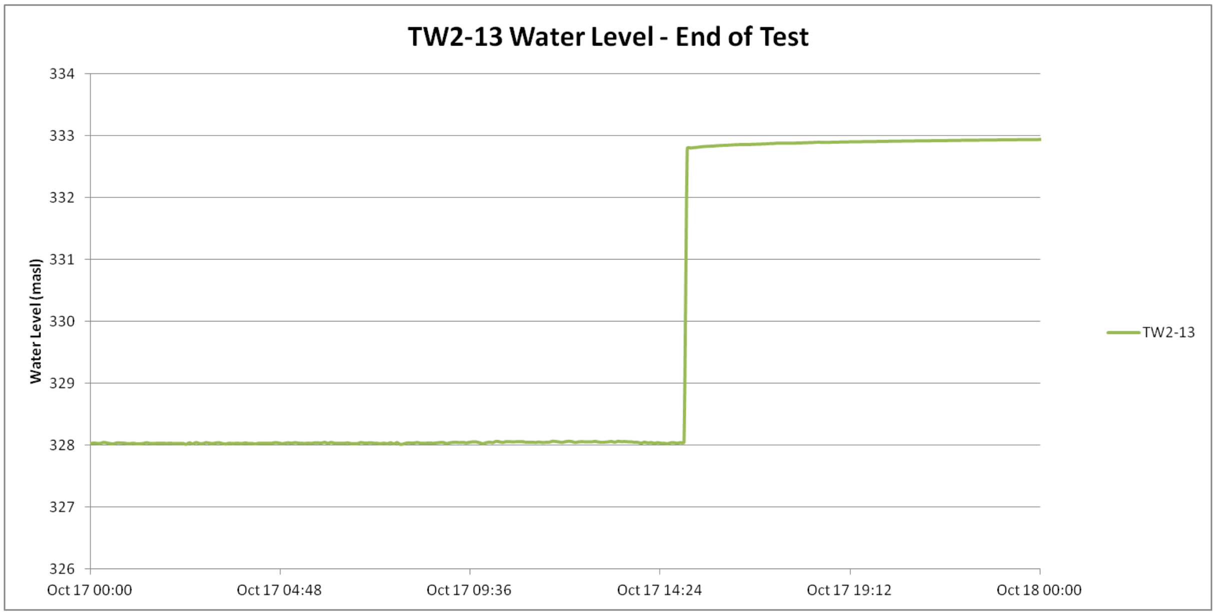
Start of the pumping test, August 19, 2013



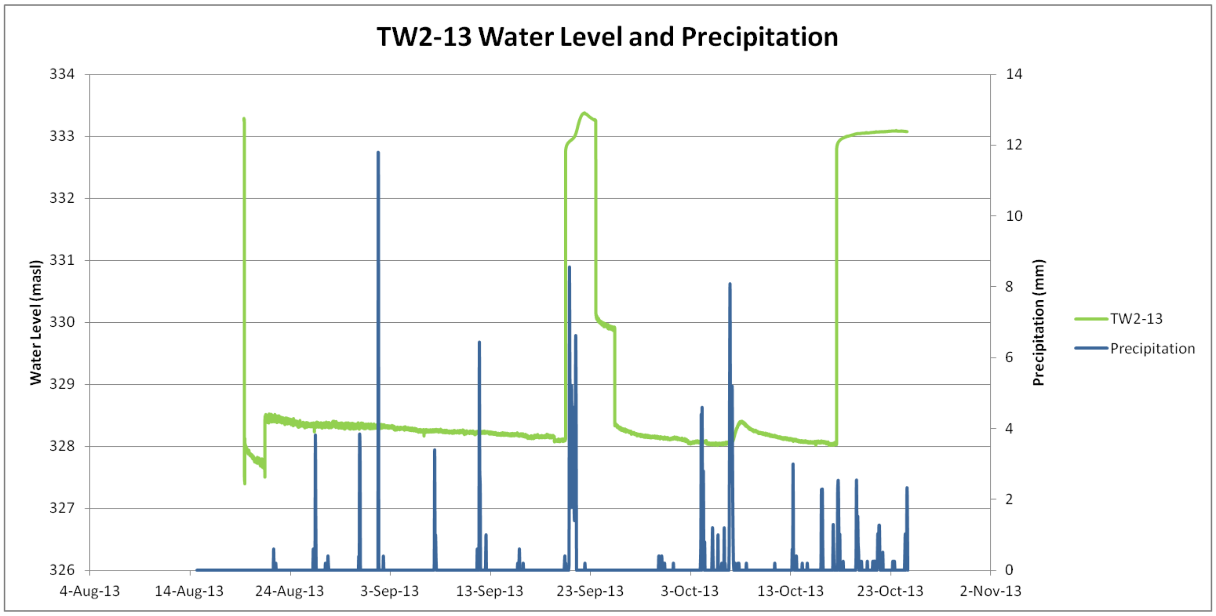
Mid-test shut off period, September 20 to September 23, 2013



End of the pumping test, October 17, 2013

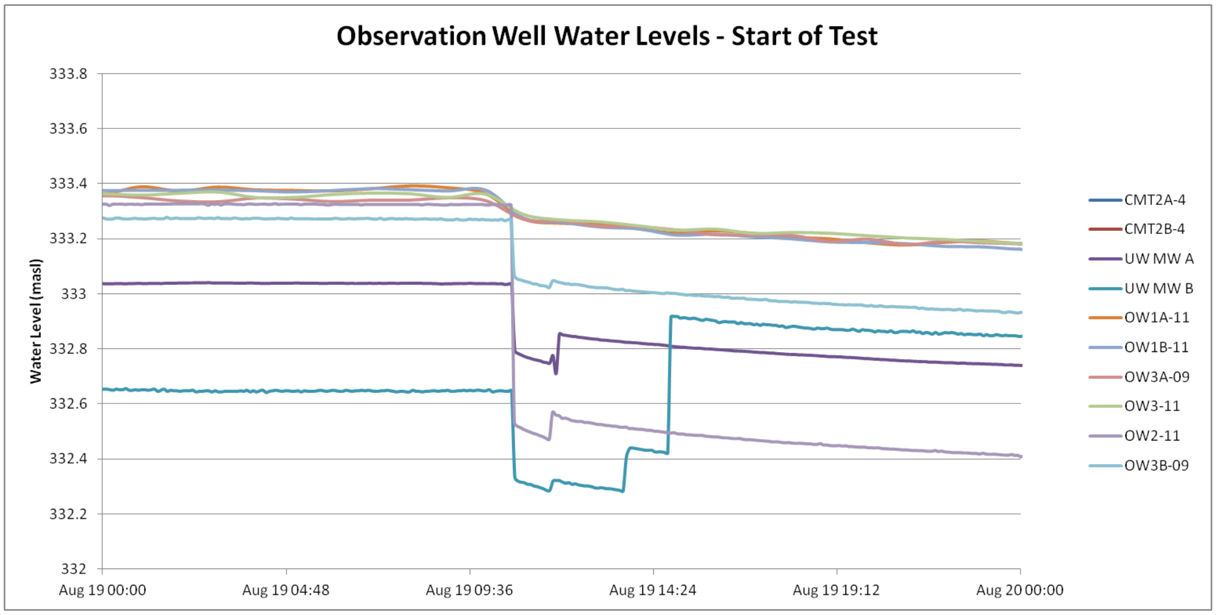


Throughout the duration of the test, with precipitation data

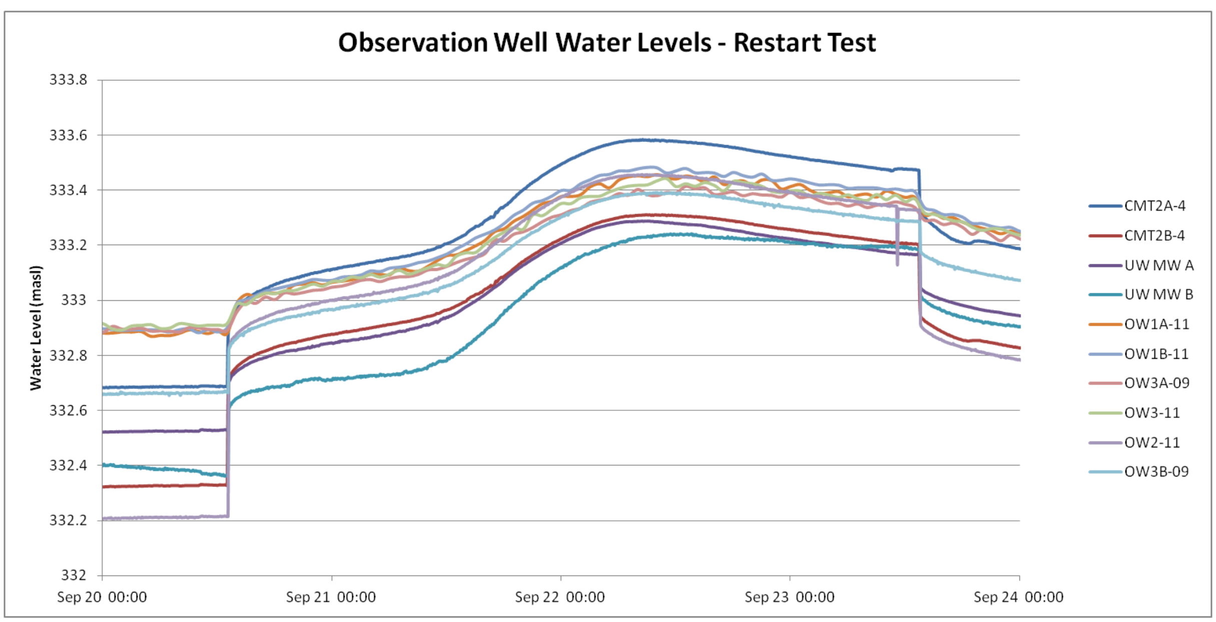


Appendix W. Continuous Water Level Data Figures for Observation Wells

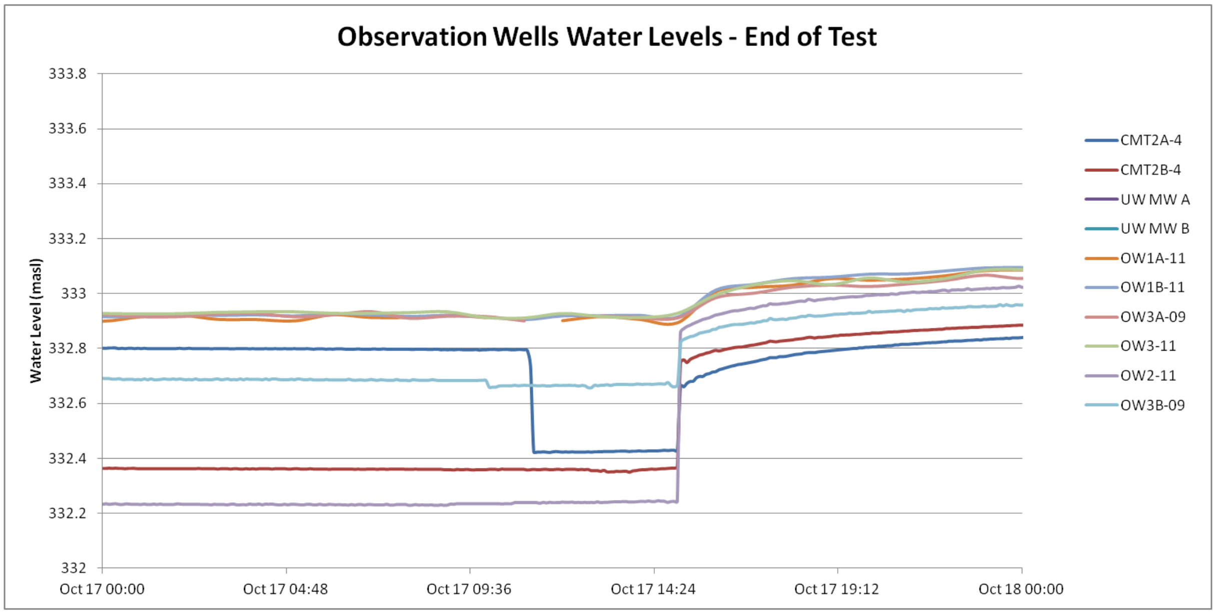
CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, at the start of the pumping test, August 19, 2013.



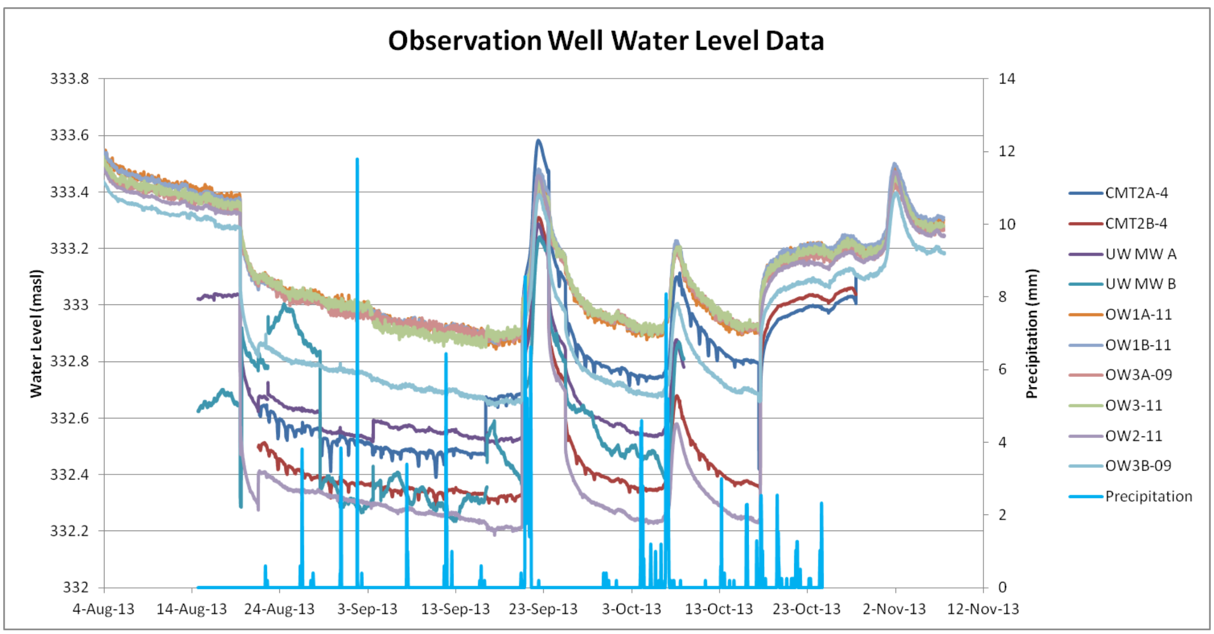
CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, during mid-test shut off period, September 20 to September 23, 2013.



CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, at the end of the pumping test, October 17, 2013.

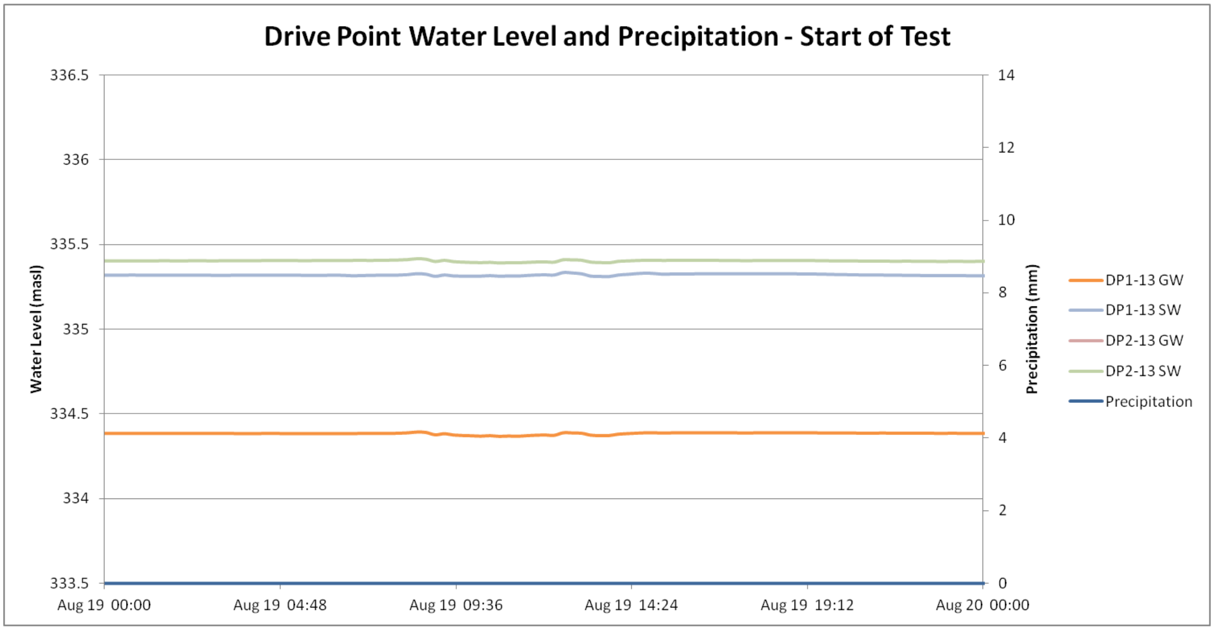


CMT2A-4, CMT2B-4, UW MWA, UW MWB, OW1A-11, OW1B-11, OW3A-09, OW3-11, OW2-11, and OW3B-09, and precipitation data throughout the pumping test.

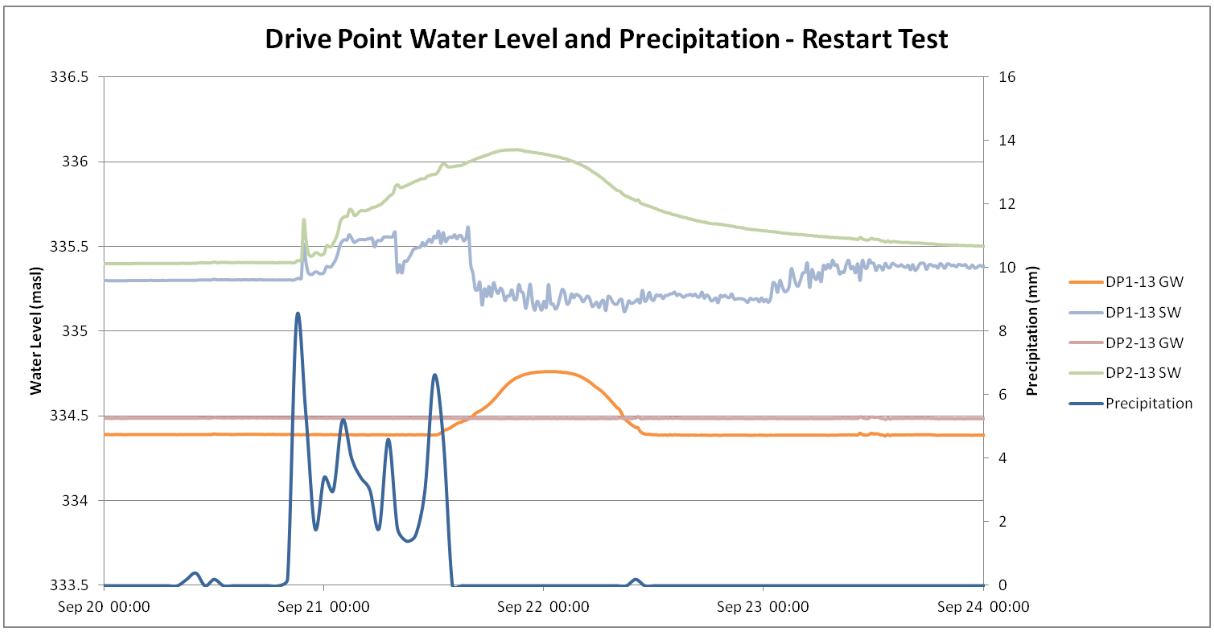


Appendix X. Continuous Water Level Data Figures for Shallow Groundwater and Surface Water in Drive Points

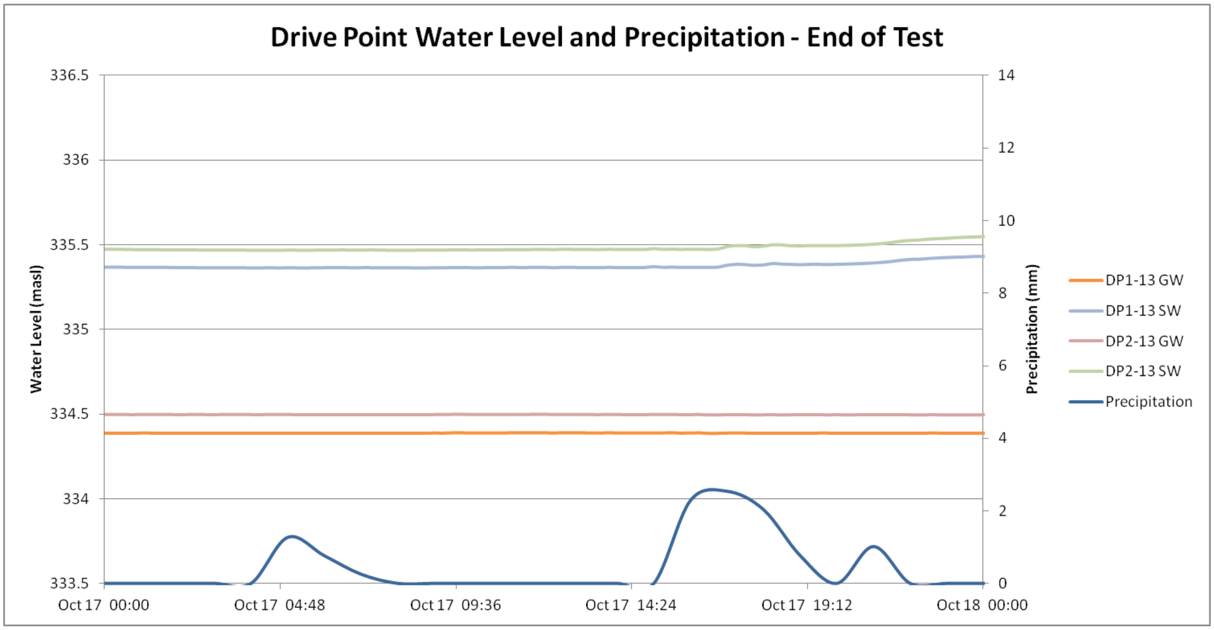
Drive points and precipitation data at the start of the pumping test, August 19, 2013.



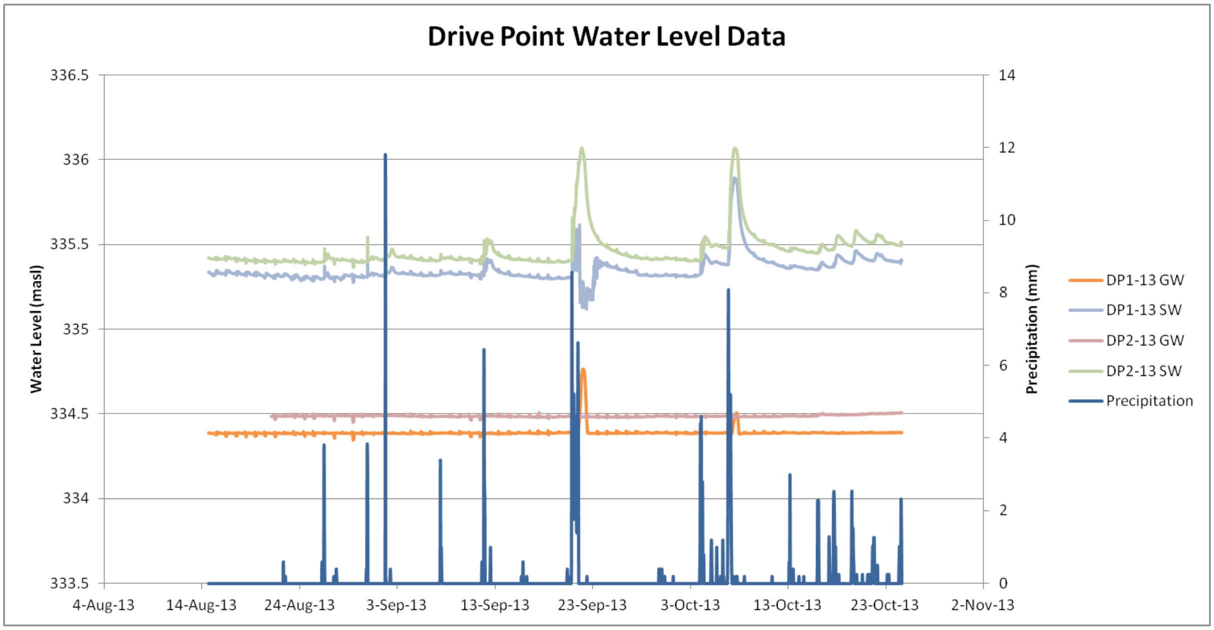
Drive points and precipitation data during the mid-test shut off period, September 20 to September 23, 2013.



Drive points and precipitation data at the end of the pumping test, October 17, 2013.



Drive points and precipitation data throughout the pumping test.



Appendix Y. Pumping Test Analysis Reports generated from different AquiferTest Analyses

Although the Theis method is governed by many constricting assumption, this is the fundamental method developed and a good starting point for a new analysis. Theis assumes that the aquifer is homogeneous, infinite, flat-lying, and isotropic, as well as being confined with uniform thickness. It is also assumed that the well is fully penetrating, water is released instantaneously from storage, there is no borehole storage, flow is radial, the well is undergoing constant discharge, and Darcy's law is valid. The Theis equation is based on the equation describing the drawdown *d(r,t)* shows a similar form to the classical heat equation in a radial coordinate system. Therefore, drawdown can be solved similarly to the heat equation. Based on these considerations, drawdown, s (m) is defined by the following equation

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

where Q is the pumping rate (m^3/s), T is the transmissivity (m^2/s) and W(u) is the well function. W(u) and u are obtained via curve fitting and have no physical meaning. U is defined as

$$u = \frac{r^2 S}{4\,t\,T}$$

where r is the distance between the pumping and monitoring well (m), *t* the time and *S* the storativity. Theis analysis is completed by plotting drawdown over time on a log-log graph. This data can be overlain on the dimensionless Theis type curve, represented as the W(u) function versus1/u. By superimposing the data plotted over the best fitting type curve, matching (time, drawdown) and (1/u, W(u)) points can be found. This allows for the calculation of S and T using the equations above (Freeze & Cherry, 1979).

The Theis Recovery method functions only slightly differently from Theis. Instead of drawdown being plotted against time, water level rise is used. This increase is water level is termed residual drawdown, defined using

$$s' = \frac{Q}{4\,\pi T} W(u) - W(u')$$

$$u' = \frac{r^2 S\prime}{4\, t\prime\, T}$$

where s' represents residual drawdown, *S'* is the storativity value during recovery, *t'* is the elapsed times from the end of pumping. This reversed curve can once again be superimposed against the type curve in order to determine its corresponding dimensionless parameters and solve for storativity and transmissivity. The same assumptions apply from Theis (Freeze & Cherry, 1979).

Neuman's method is a solution for pumping tests performed in unconfined aquifers. The drawdown response for unconfined aquifers differs from Theis, with three distinct segments: a steep segment at early time, with water being released instantaneously from aquifer storage, followed by a flat segment, indicating water being released from storage farther away after a time-lag, with a final steep segment becoming steeper signifying the additional source as the primary water supplier. Neuman also assumed that the aquifer is anisotropic, with hydraulic conductivities different vertically and horizontally. Drawdown in an unconfined aquifer is typified using the following equation

$$s' = \frac{Q}{4\,\pi T} W(u_{\mathrm{A}}, u_B, \beta)$$

where $W(u_A, u_B, \beta)$ is the unconfined well function, with u_A and u_B representing the early and late time type curves, respectively. These type curves are represented as

$$u_A = \frac{r^2 S}{4\, t\, T} \text{ and } u_B = \frac{r^2 S}{4\, t\, T}$$

with β corresponding to

$$\beta = \frac{r^2 K_V}{b^2 K_h}$$

where K_v and K_h are the vertical and horizontal components to hydraulic conductivity (m/s), respectively, and b is the thickness of the water table (m) (Schlumberger Water Services, 2013).

The Boulton method is another option for determining parameters from pump test data in unconfined aquifers, under either isotropic or anisotropic conditions and for both fully and partially penetrating wells. The Boulton type curve utilizes Theis once again. The late stage of drawdown and time data available is fitted to a Theis curve to obtain parameter estimates for transmissivity, specific yield, and storage. Then, the early stage data is fitted to another Theis curve. The Boulton type curve parameters are defined as

$$s_D = \frac{2\,\pi T(H-b)}{Q}$$

$$t_D = \frac{T\,t}{r^2 S}$$

where H is the average head along the saturated thickness and b is the thickness of the saturated zone, all in meters (Schlumberger Water Services, 2013).

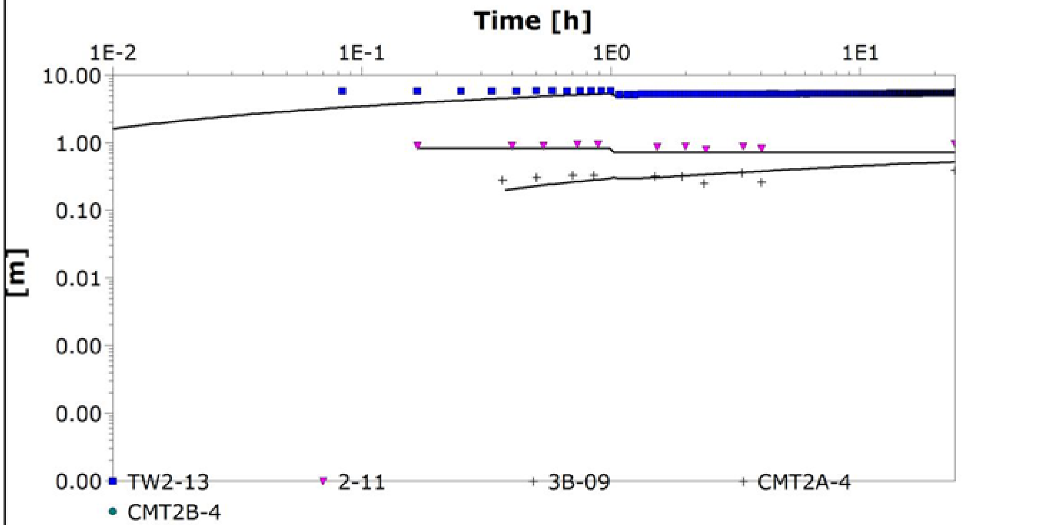
The final pump test method utilized is Theis with Jacob Correction. This method assumes that the water table exists within an unconfined aquifer, which is calculated by adjusting the value for the thickness of the aquifer as elevation head changes. Transmissivity will therefore change, decreasing with increasing drawdown. Physically, this means that flow will be both radial and vertical resulting in the anisotropic assumption being applied. Measured drawdown data is corrected using the Jacob modification to allow for the pumping test to be interpreted as though it is confined. The Jacob modification assumes that there is no delay in yield and that drawdown is small relative to the total saturated thickness of the aquifer. Generally, delayed yield will be evident at the start of a pumping test but will diminish by the late time stage; as a rule, this method should only be applied to late time data for this reason. The correction of this data is as follows:

$$s_{corr} = s - (s^2/2D)$$

where s_{corr} is the corrected drawdown, s is the measured drawdown, and D is the original aquifer thickness, all in meters (Schlumberger Water Services, 2013).

Theis Method

Contact Info **Address** **Company Name** **City, State/Province**	**Pumping Test Analysis Report**	
	Project: Alder Creek	
	Number:	
	Client: RMOW	
Location: Mannheim	Pumping Test: TW2-13 Test	Pumping Well: TW2-13
Test Conducted by: Cailin Hillier		Test Date: 19/08/2013
Analysis Performed by:	Theis	Analysis Date: 07/03/2014
Aquifer Thickness: 40.00 m	Discharge: variable, average rate 10.508 [l/s]	



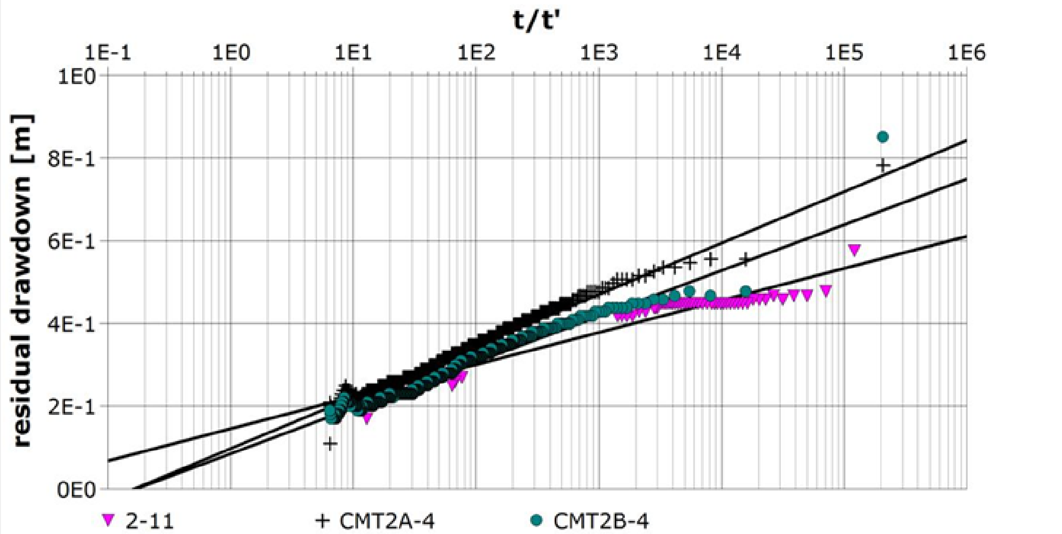
Calculation using Theis

Observation Well	Transmissivity [m²/s]	Hydraulic Conductivity [m/s]	Storage coefficient	P	Radial Distance to PW [m]
TW2-13	1.45×10^{-3}	3.63×10^{-5}	5.73×10^{-1}	1.00×10^{2}	0.1
2-11	2.51×10^{-2}	6.27×10^{-4}	1.00×10^{-7}	1.00×10^{2}	2.7
3B-09	1.21×10^{-2}	3.02×10^{-4}	8.76×10^{-2}	1.00×10^{2}	2.62
CMT2A-4	1.97×10^{-2}	4.93×10^{-4}	1.70×10^{-2}	1.00×10^{2}	5.82
CMT2B-4	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{2}	5.65
Average	1.19×10^{-2}	2.97×10^{-4}	1.36×10^{-1}	1.00×10^{2}	

Recovery Theis Method

Contact Info **Address** **Company Name** **City, State/Province**	**Pumping Test Analysis Report**
	Project: Alder Creek
	Number:
	Client: RMOW

Location: Mannheim	Pumping Test: TW2-13 Test	Pumping Well: TW2-13
Test Conducted by: Cailin Hillier		Test Date: 19/08/2013
Analysis Performed by:	Recovery Theis	Analysis Date: 03/03/2014
Aquifer Thickness: 40.00 m	Discharge: variable, average rate 10.508 [l/s]	

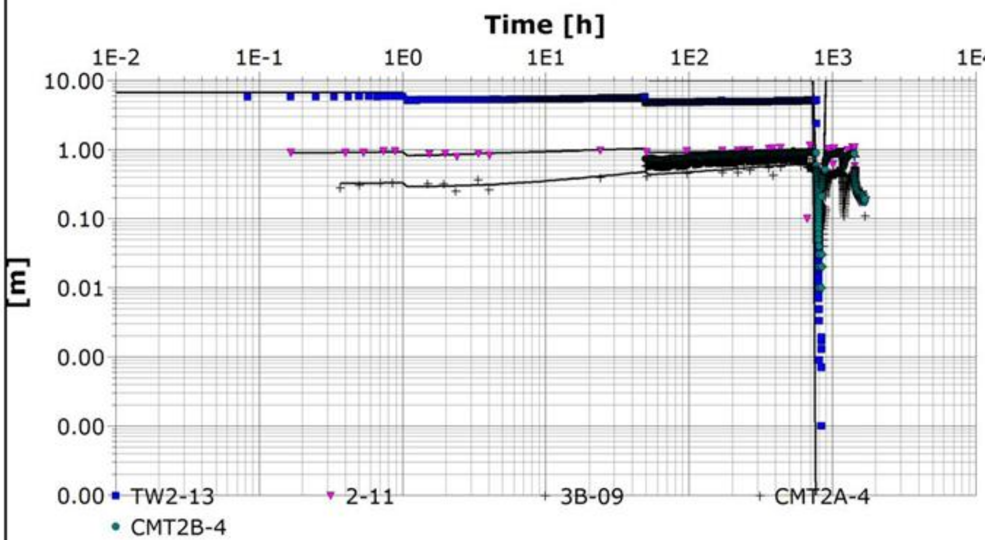


Calculation using THEIS & JACOB

Observation Well	Transmissivity [m²/s]	Hydraulic Conductivity [m/s]	Radial Distance to PW [m]	
TW2-13	4.99×10^{-3}	1.25×10^{-4}	0.1	
2-11	2.48×10^{-2}	6.20×10^{-4}	2.7	
3B-09	2.90×10^{-2}	7.24×10^{-4}	2.62	
CMT2A-4	1.55×10^{-2}	3.87×10^{-4}	5.82	
CMT2B-4	1.74×10^{-2}	4.35×10^{-4}	5.65	
Average	1.83×10^{-2}	4.58×10^{-4}		

Neuman Method

Contact Info Address Company Name City, State/Province		**Pumping Test Analysis Report**
		Project: Alder Creek
		Number:
		Client: RMOW
Location: Mannheim	Pumping Test: TW2-13 Test	Pumping Well: TW2-13
Test Conducted by: Cailin Hillier		Test Date: 19/08/2013
Analysis Performed by:	Neuman	Analysis Date: 07/03/2014
Aquifer Thickness: 40.00 m	Discharge: variable, average rate 10.508 [l/s]	



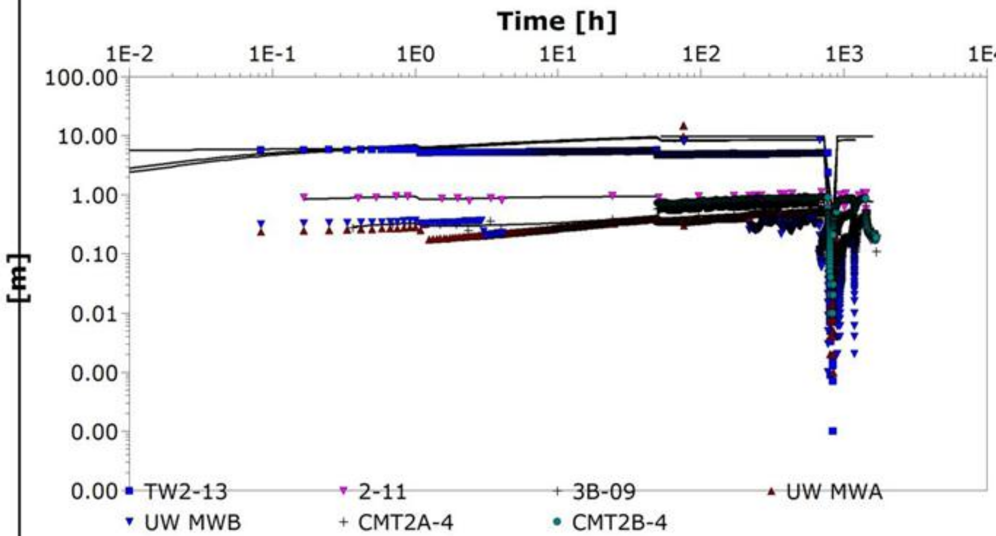
Calculation using Neuman

Observation Well	Transmissivity [m²/s]	Hydraulic Conductivity [m/s]	Specific Yield	Ratio K(v)/K(h)	Ratio Sy/S	P	Radial Distance to PW [m]
TW2-13	1.69×10^{-2}	4.22×10^{-4}	2.99×10^{-7}	3.70×10^{-2}	1.49×10^{4}	7.41×10^{2}	0.1
2-11	1.68×10^{-2}	4.20×10^{-4}	2.02×10^{-1}	9.39×10^{-1}	9.88×10^{4}	5.18×10^{4}	2.7
3B-09	1.03×10^{-2}	2.57×10^{-4}	5.00×10^{-1}	7.28×10^{-1}	5.00×10^{3}	5.46×10^{5}	2.62
CMT2A-4	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.00×10^{2}	5.82
CMT2B-4	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.00×10^{2}	5.65
Average	9.20×10^{-3}	2.30×10^{-4}	1.40×10^{-1}	3.45×10^{-1}	2.38×10^{4}	1.20×10^{5}	

Boulton Method

Contact Info Address Company Name City, State/Province	**Pumping Test Analysis Report**
	Project: Alder Creek
	Number:
	Client: RMOW

Location: Mannheim	Pumping Test: TW2-13 Test	Pumping Well: TW2-13
Test Conducted by: Cailin Hillier		Test Date: 19/08/2013
Analysis Performed by:	Boulton	Analysis Date: 10/03/2014
Aquifer Thickness: 40.00 m	Discharge: variable, average rate 10.508 [l/s]	

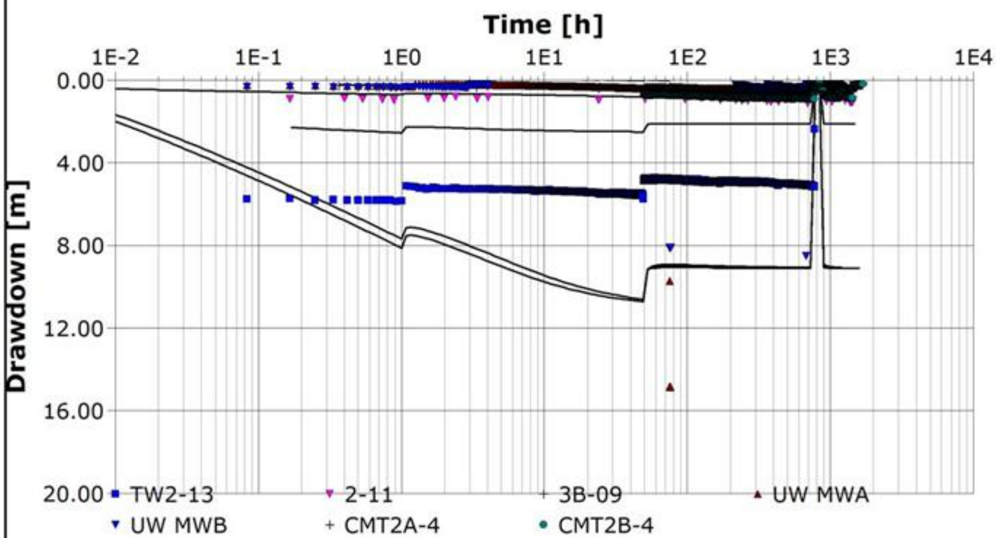


Calculation using Boulton

Observation Well	Transmissivity [m²/s]	Hydraulic Conductivity [m/s]	Specific Yield	Drainage factor	Ratio Sy/S	P	Radial Distance to PW [m]
TW2-13	1.17×10^{-2}	2.93×10^{-4}	9.90×10^{-1}	5.17×10^{-1}	1.00×10^{1}	1.27×10^{4}	0.1
2-11	2.10×10^{-2}	5.25×10^{-4}	4.31×10^{-3}	1.00×10^{-5}	3.03×10^{3}	1.39×10^{4}	2.7
3B-09	1.07×10^{-2}	2.67×10^{-4}	7.61×10^{-1}	2.57×10^{-4}	2.99×10^{1}	7.61×10^{5}	2.62
UW MWA	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.00×10^{2}	15.5
UW MWB	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.00×10^{2}	13.34
CMT2A-4	1.61×10^{-2}	4.03×10^{-4}	2.33×10^{-2}	1.00×10^{-5}	5.35×10^{1}	2.55×10^{5}	5.82
CMT2B-4	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{-2}	1.00×10^{2}	1.00×10^{2}	5.65
Average	8.93×10^{-3}	2.23×10^{-4}	2.54×10^{-1}	7.82×10^{-2}	4.89×10^{2}	1.49×10^{5}	

Theis with Jacob Correction Method

Contact Info Address Company Name City, State/Province	Pumping Test Analysis Report Project: Alder Creek Number: Client: RMOW	
Location: Mannheim	Pumping Test: TW2-13 Test	Pumping Well: TW2-13
Test Conducted by: Cailin Hillier		Test Date: 19/08/2013
Analysis Performed by:	Theis with Jacob Correction	Analysis Date: 10/03/2014
Aquifer Thickness: 40.00 m	Discharge: variable, average rate 10.508 [l/s]	



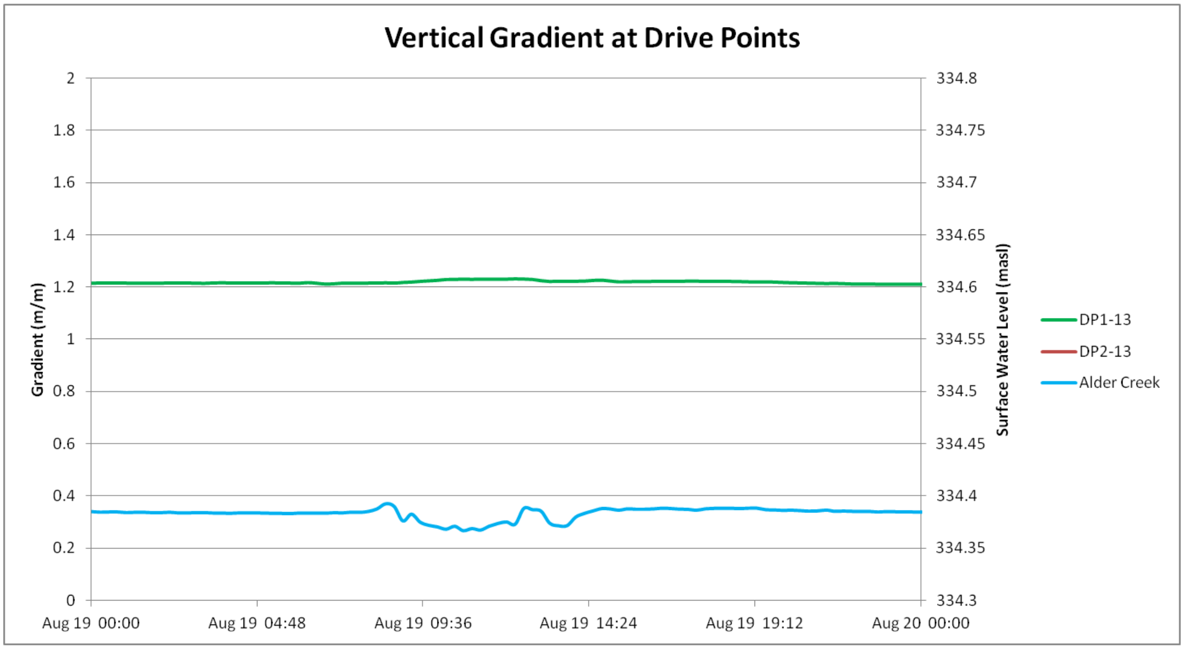
Calculation using Theis with Jacob Correction

Observation Well	Transmissivity [m²/s]	Hydraulic Conductivity [m/s]	Storage coefficient	P	Radial Distance to PW [m]
TW2-13	2.05×10^{-2}	5.12×10^{-4}	1.12×10^{-1}	3.66×10^{4}	0.1
2-11	8.91×10^{-3}	2.23×10^{-4}	1.00×10^{-7}	3.56×10^{4}	2.7
3B-09	1.67×10^{-2}	4.16×10^{-4}	3.51×10^{-1}	7.19×10^{4}	2.62
UW MWA	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{2}	15.5
UW MWB	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{2}	13.34
CMT2A-4	1.00×10^{-3}	2.50×10^{-5}	1.00×10^{-4}	1.00×10^{2}	5.82
CMT2B-4	2.20×10^{-2}	5.50×10^{-4}	1.00×10^{-4}	1.00×10^{2}	5.65
Average	1.01×10^{-2}	2.54×10^{-4}	6.62×10^{-2}	2.06×10^{4}	

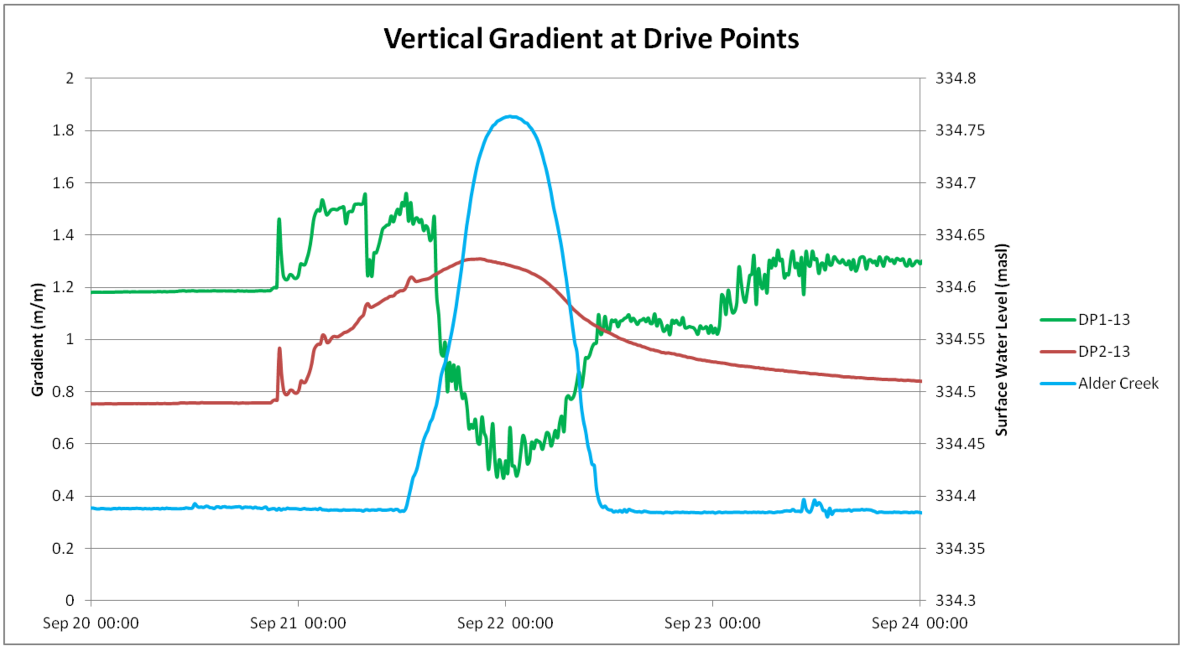
Appendix Z. Vertical Gradient Figures between Shallow Groundwater and Surface Water at Drive Points, with Surface Water Elevation Data

Note: a positive gradient indicates the surface water elevation is higher than groundwater

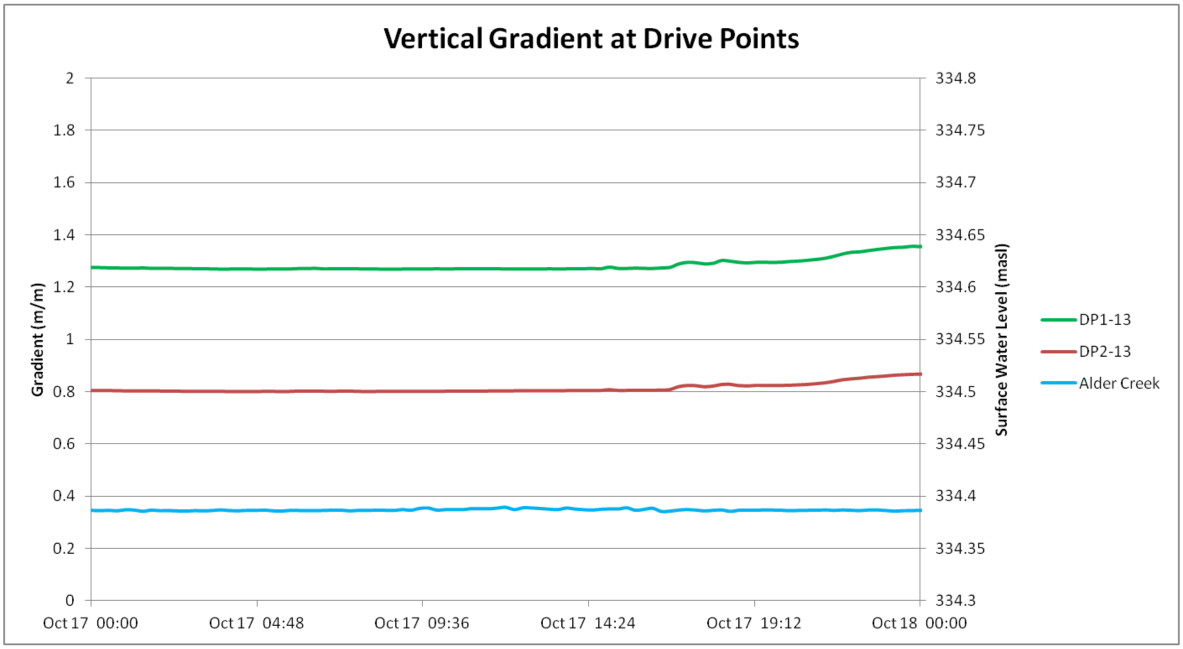
Start of the test, August 19, 2013



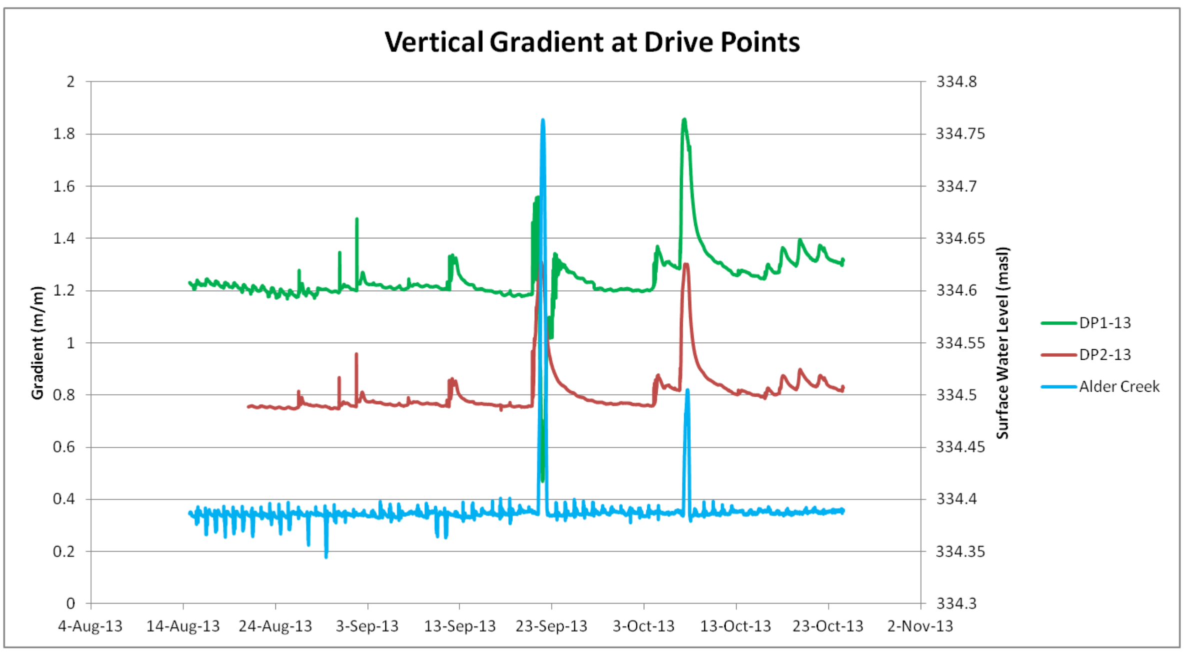
Mid-test shut off period from September 20, 2013 to September 23, 2013



End of the pumping test, October 17, 2013



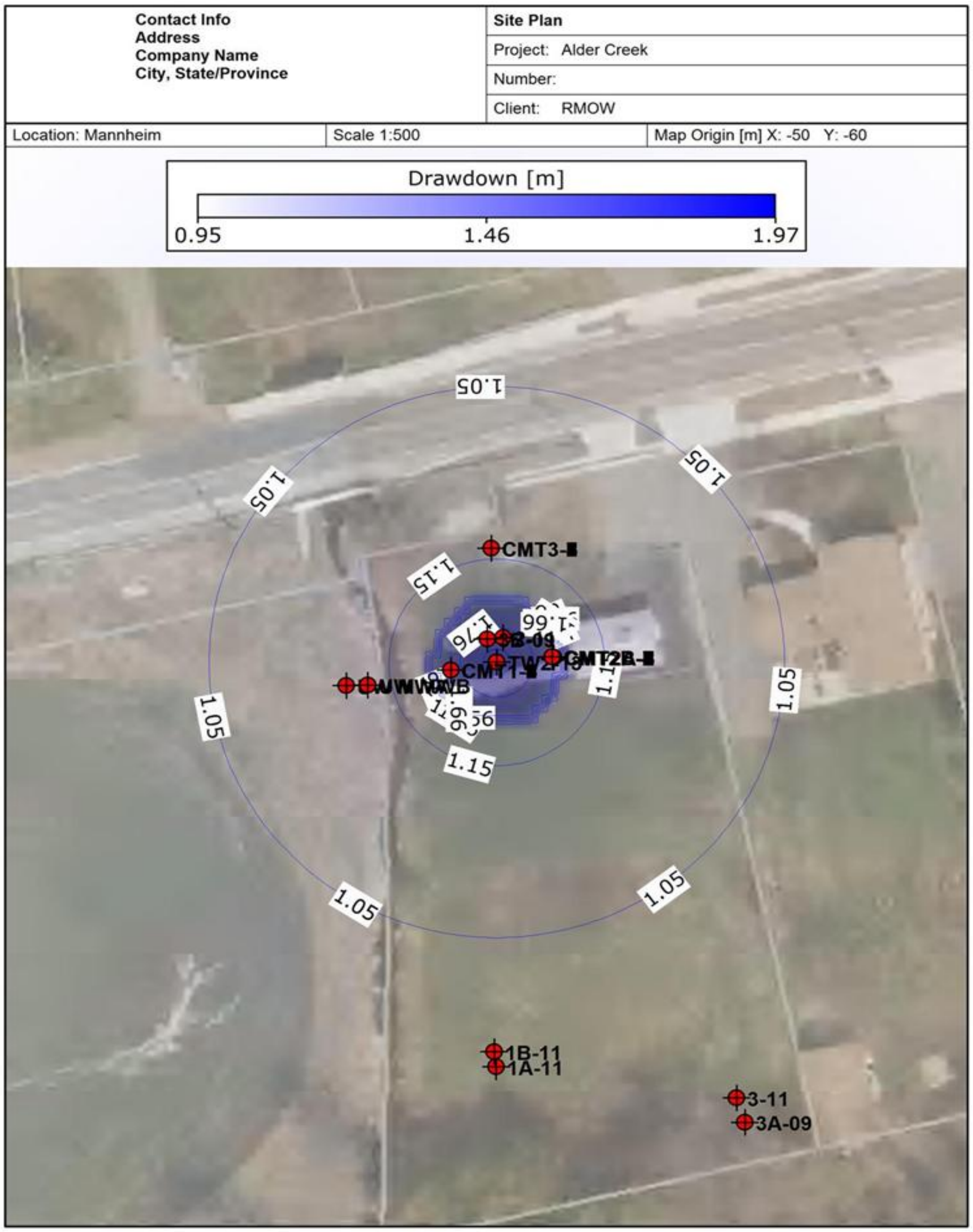
Data over the duration of the pumping test



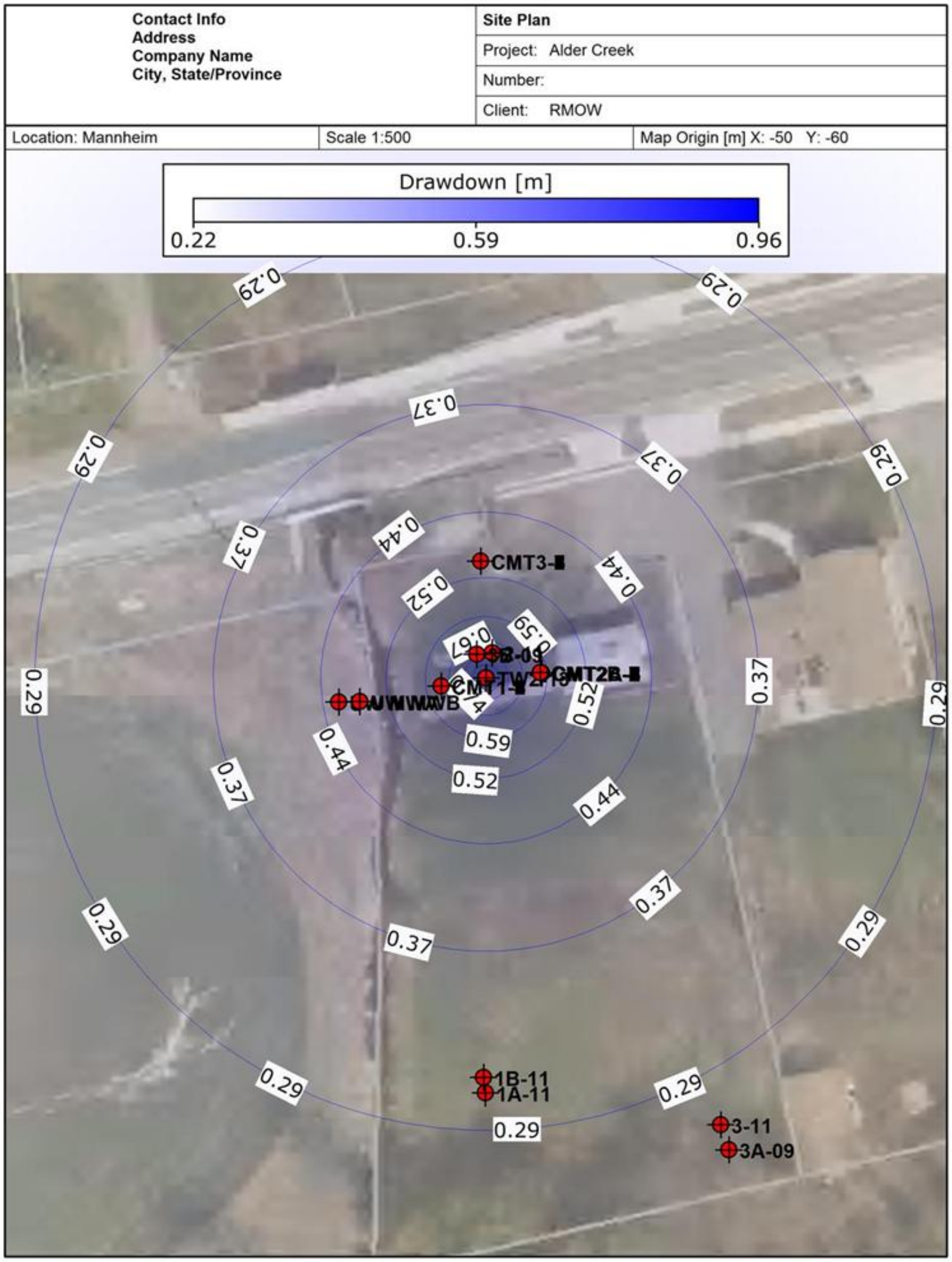
Appendix AA. Theoretical Drawdown Contours generated by AquiferTest

Note: contour lines are presented as meters of water drawn down; the georeferenced air photo used in these site maps was obtained from the Regional Municipality of Waterloo's GIS Locator Service (Regional Municipality of Waterloo, 2014).

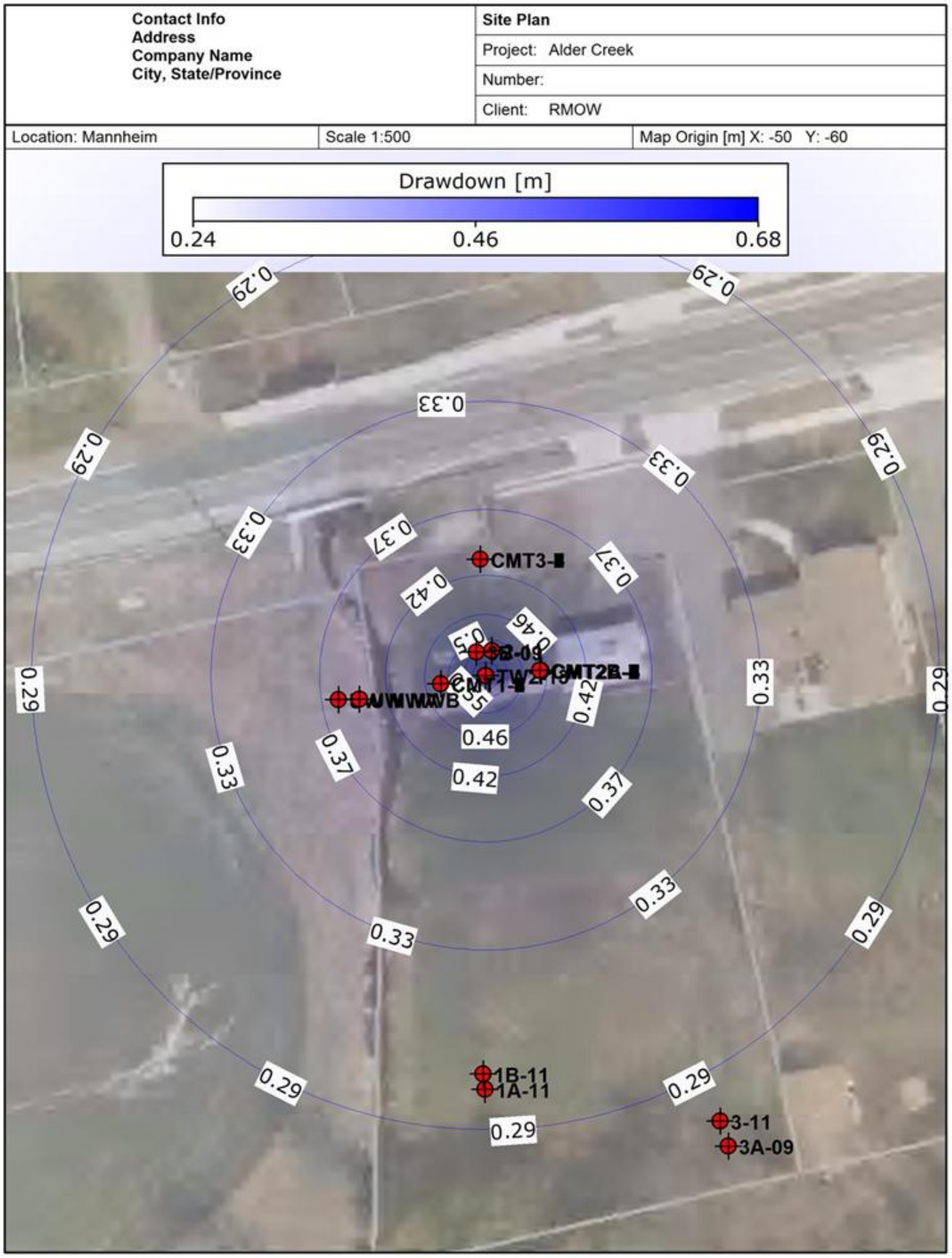
Neuman drawdown contours 1420 hours into pumping



Boulton contours 1420 hours into pumping



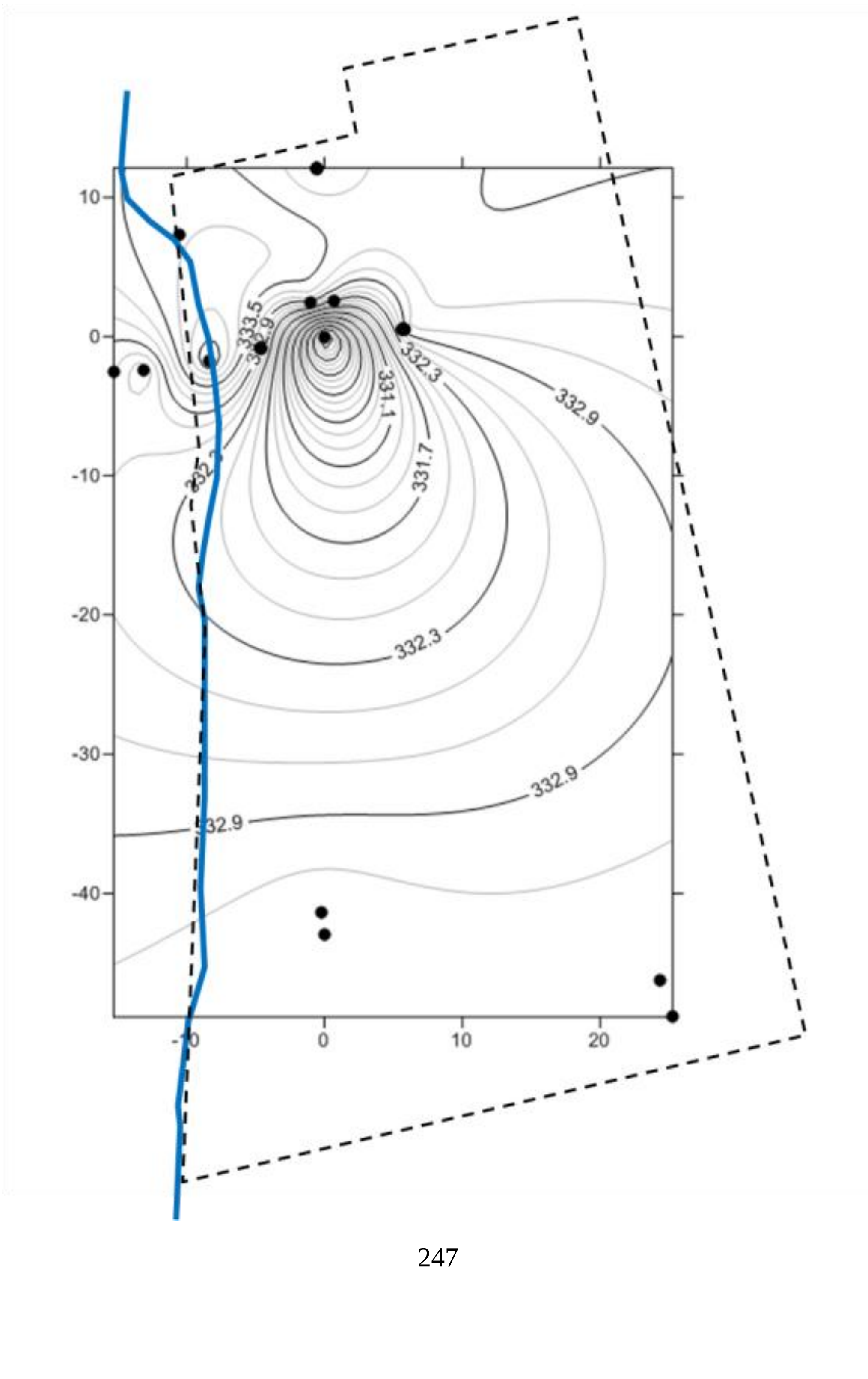
Theis with Jacob Correction contours 1420 hours into pumping



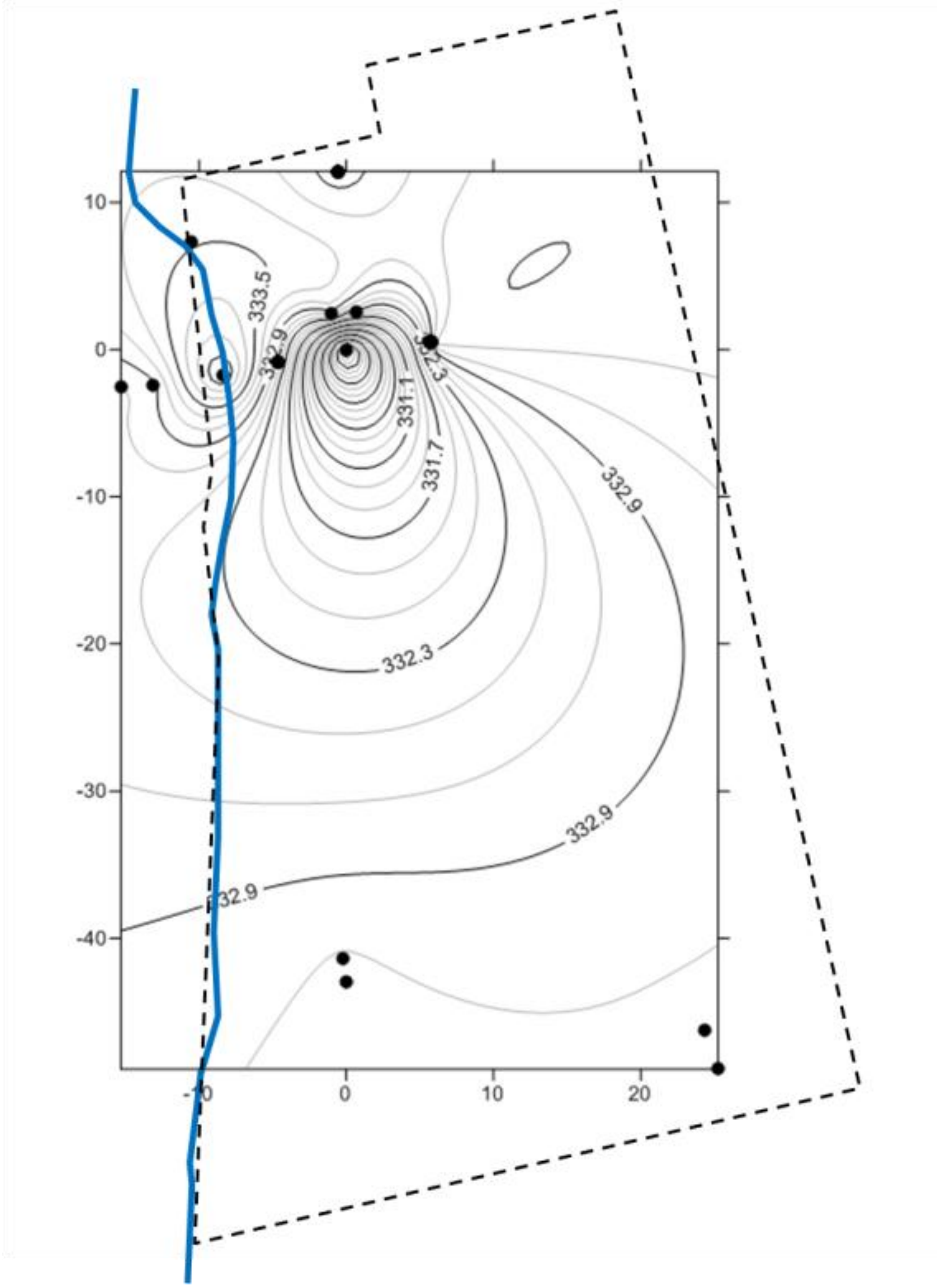
Appendix AB. Drawdown Contours generated via Kriging Water Level Data

Note: contour lines presented as meters above sea level; blue line is Alder Creek; dashed line is property boundary

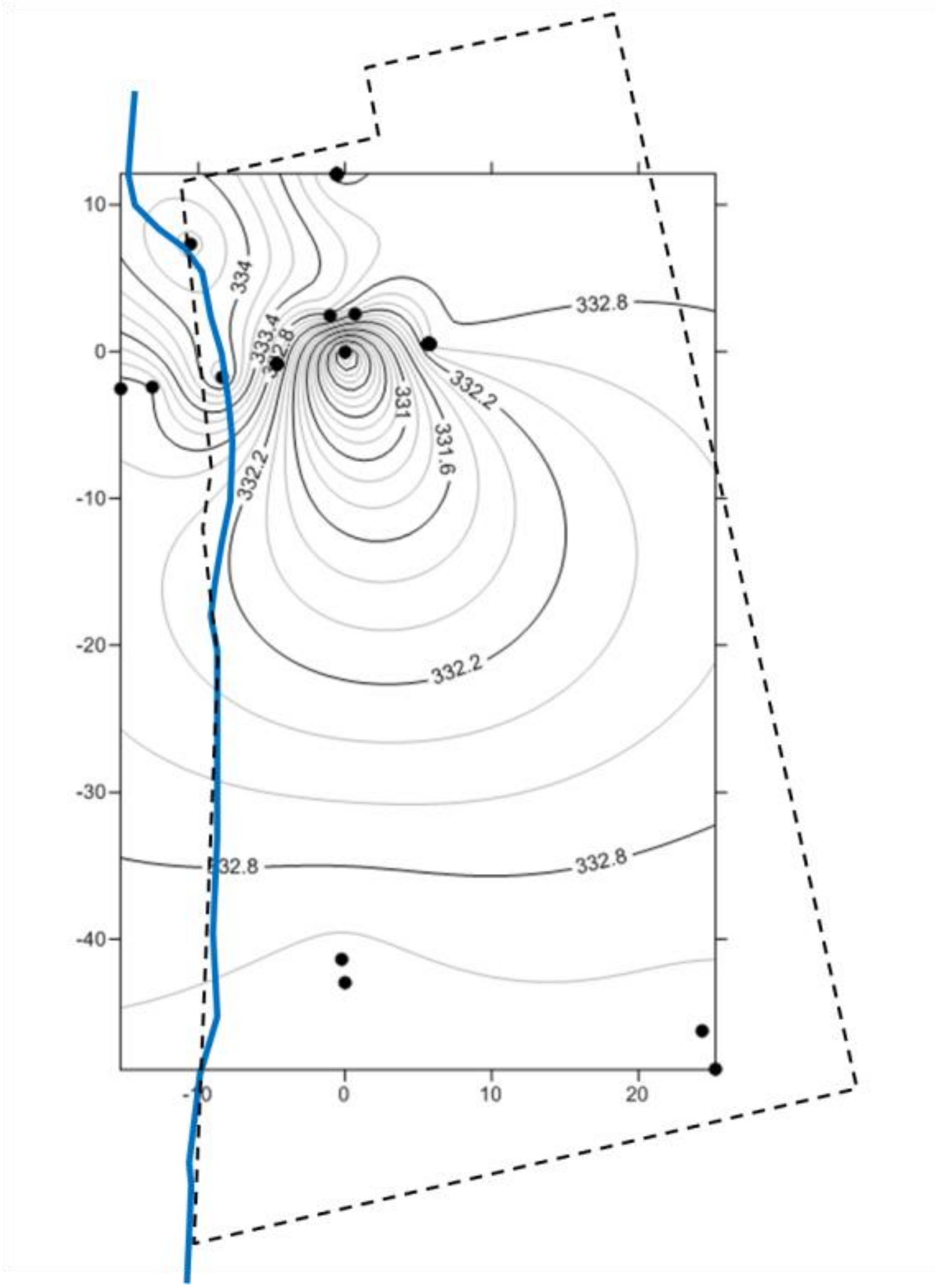
1 hour into test



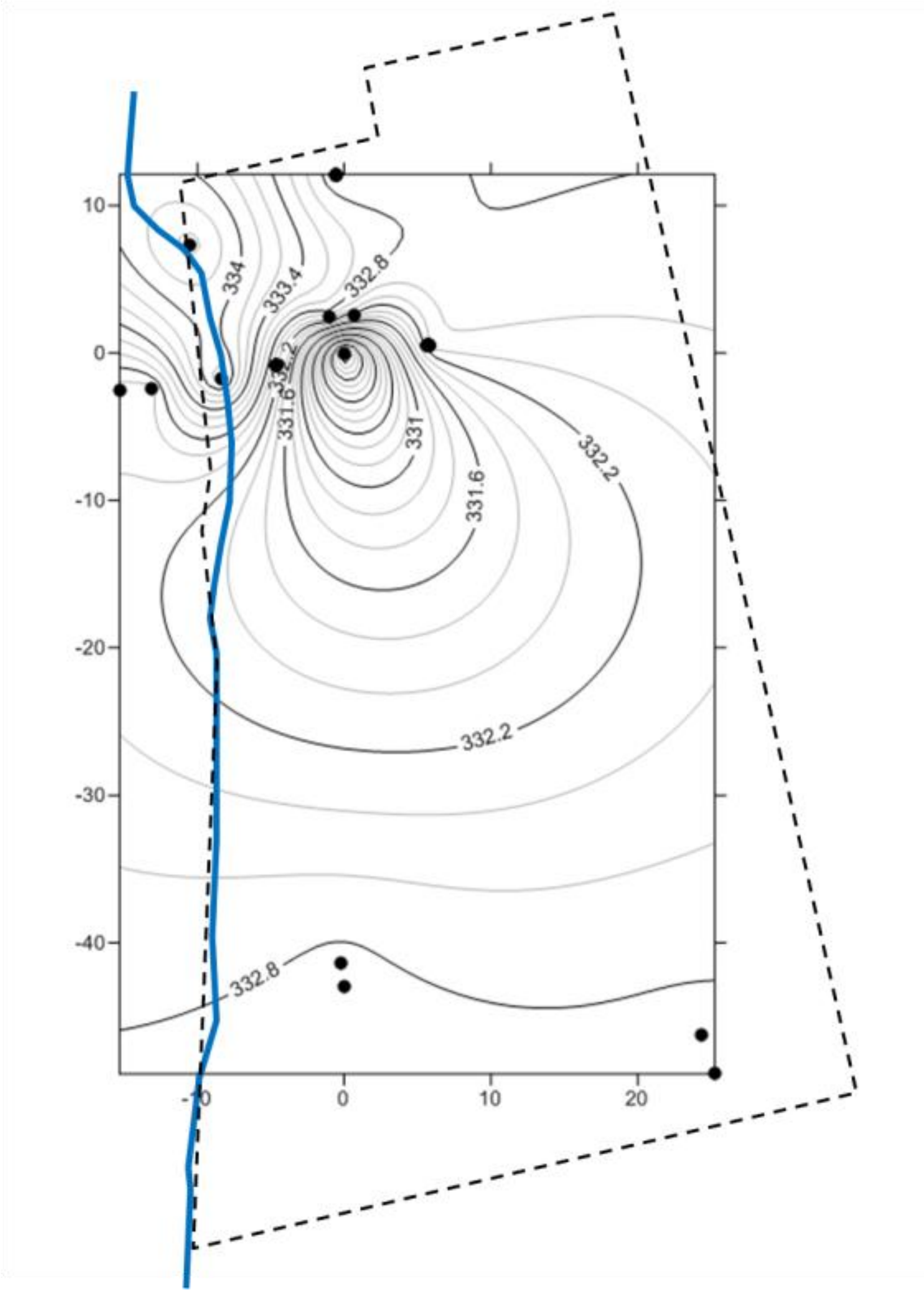
24 hours into test



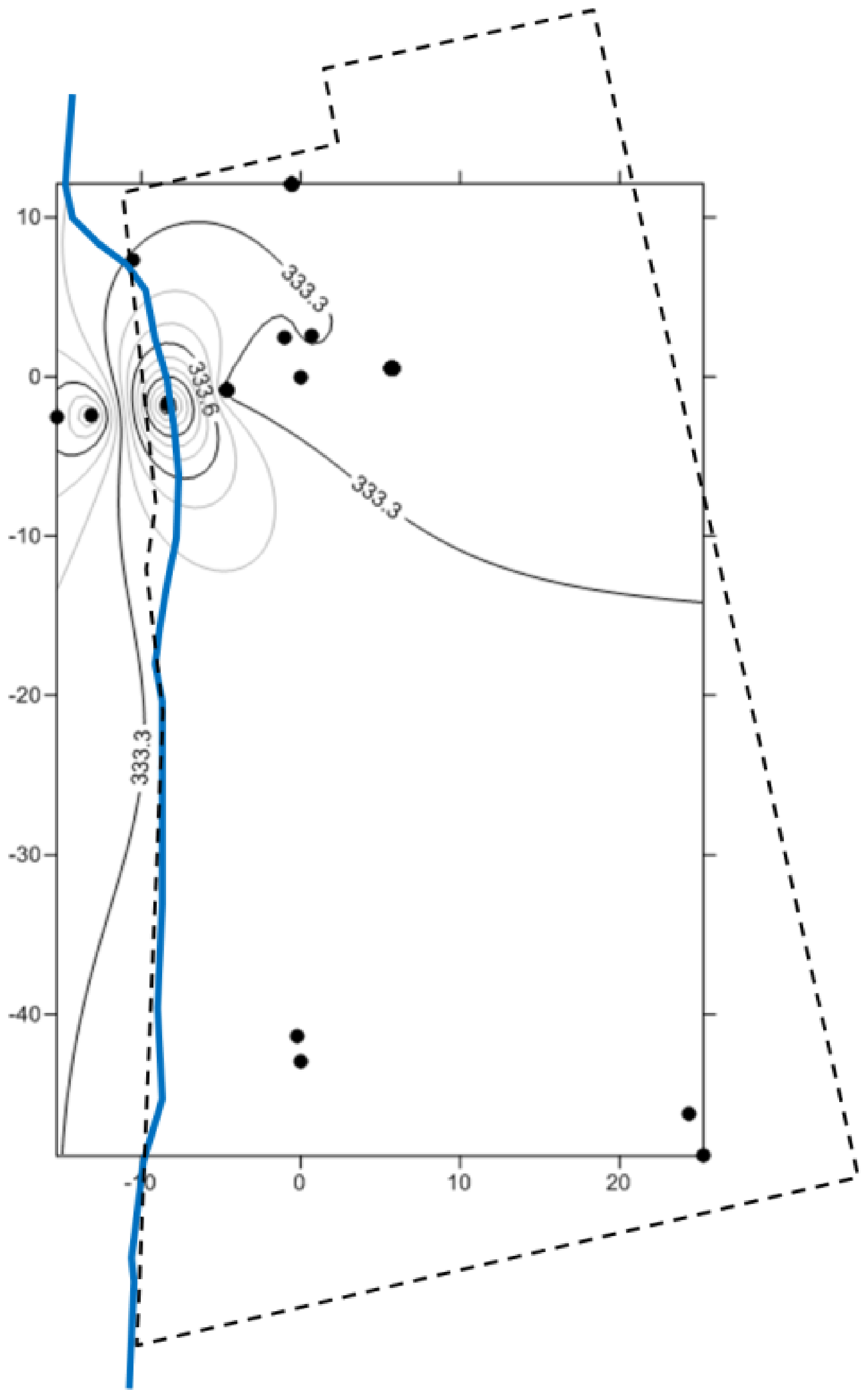
72 hours into test



1420 hours into test

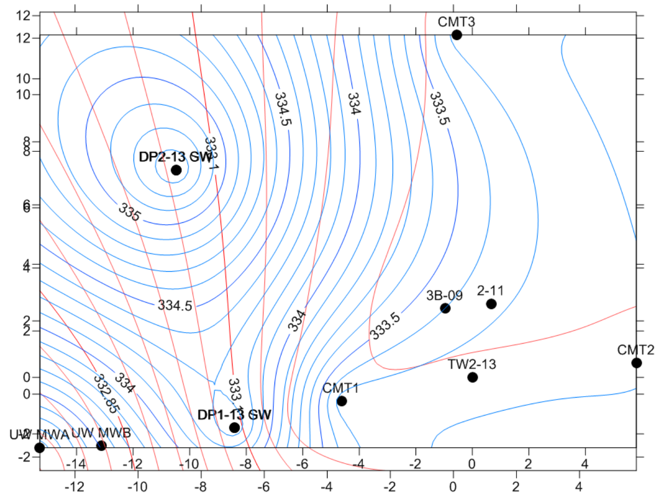


Recovery drawdown contours after test



Appendix AC. Deep and Shallow Groundwater Contours During the Pumping Test

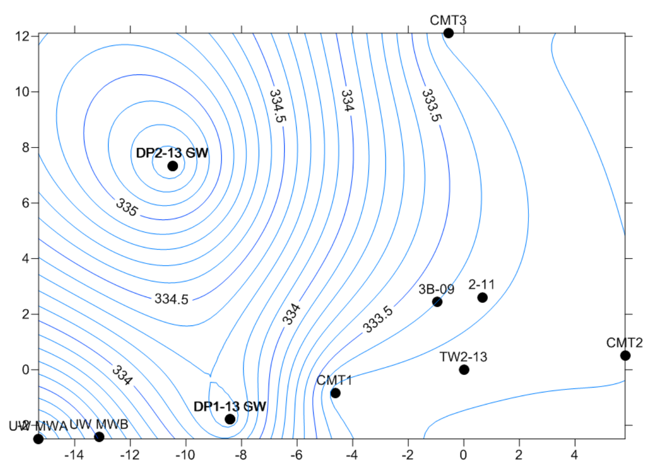
Static conditions prior to pumping



Shallow

Groundwater

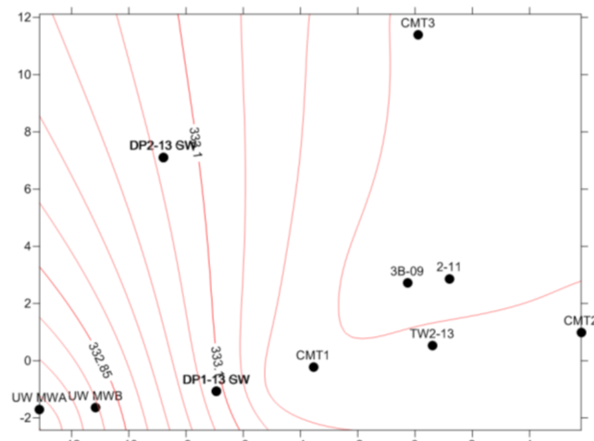
System



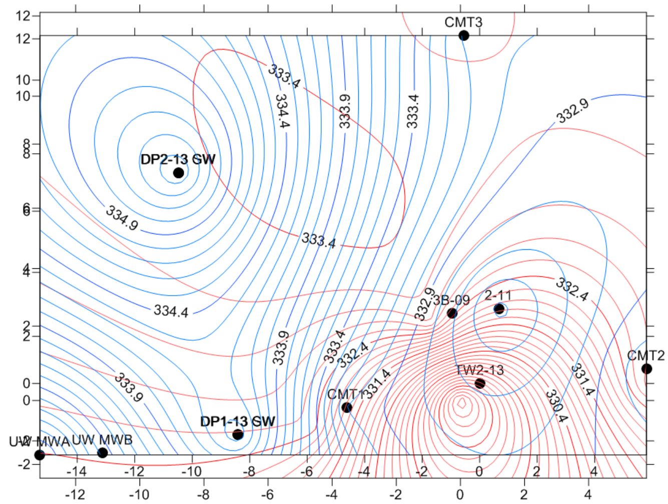
Deep

Groundwater

System



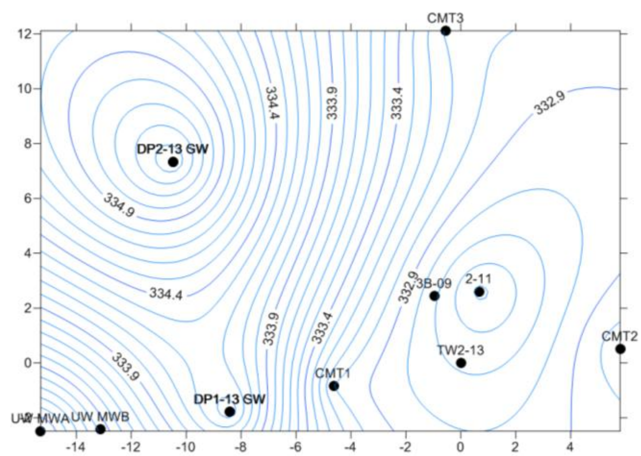
1-hour into pumping



Shallow

Groundwater

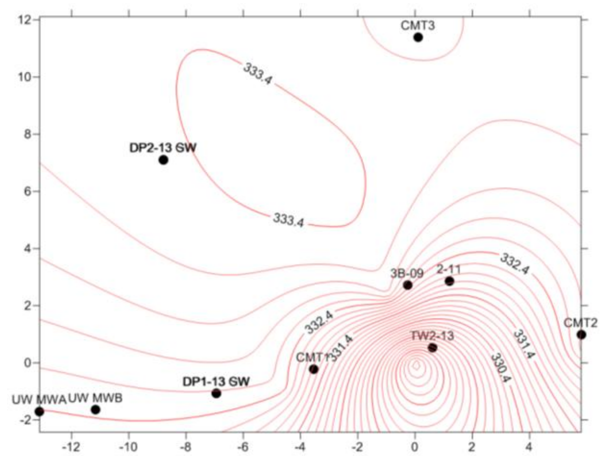
System



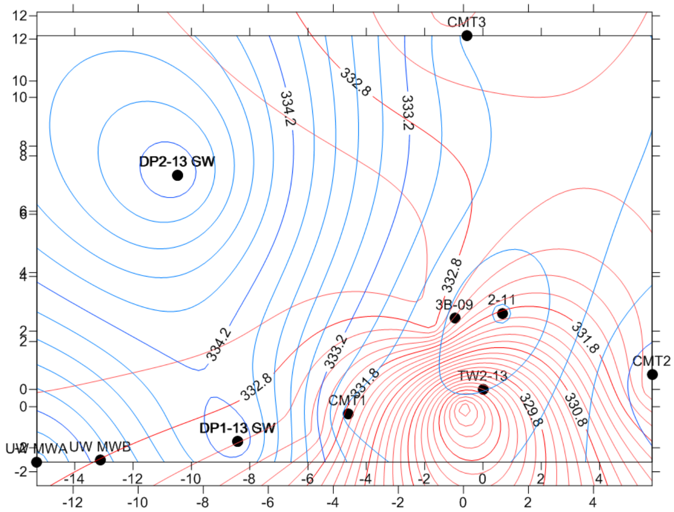
Deep

Groundwater

System



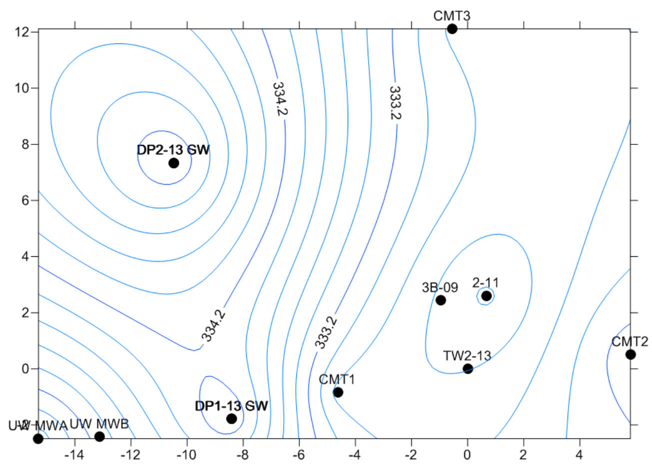
24-hours into pumping



Shallow

Groundwater

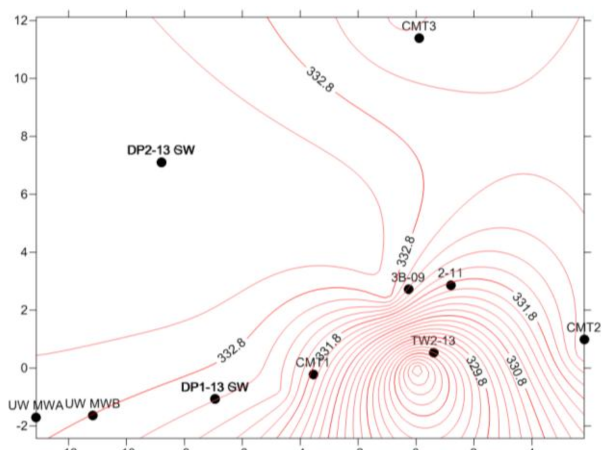
System



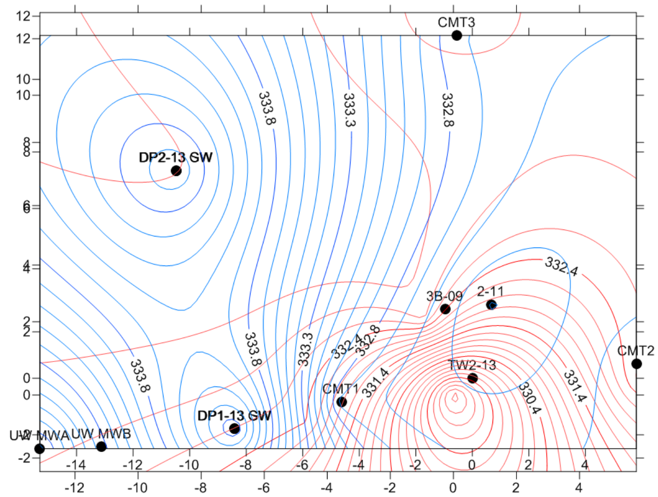
Deep

Groundwater

System



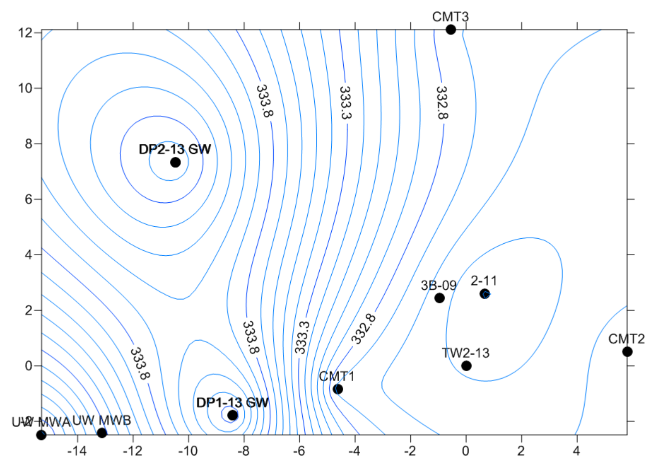
72-hours into pumping



Shallow

Groundwater

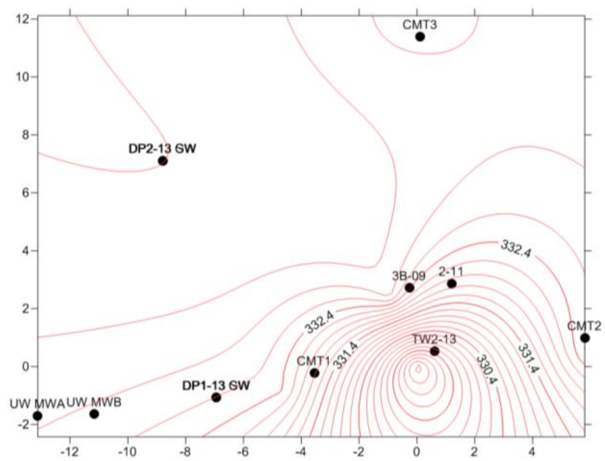
System



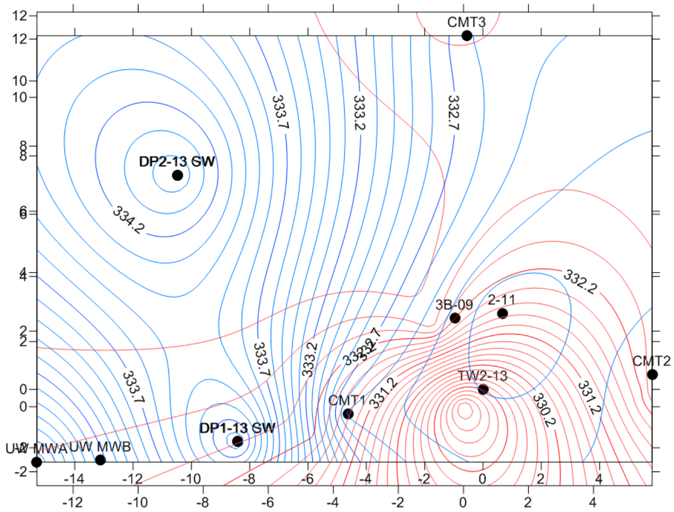
Deep

Groundwater

System



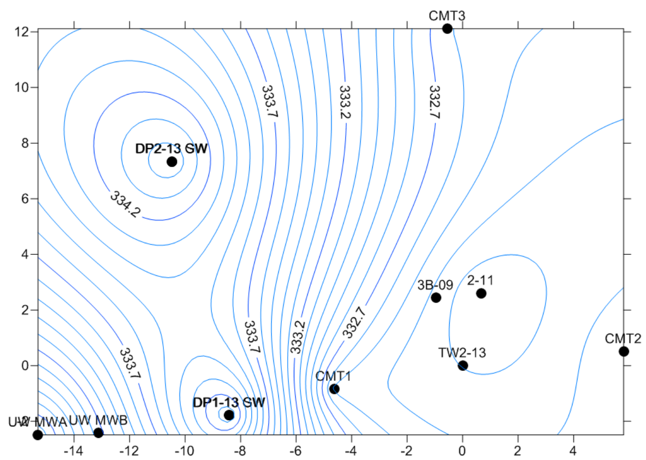
700-hour into pumping



Shallow

Groundwater

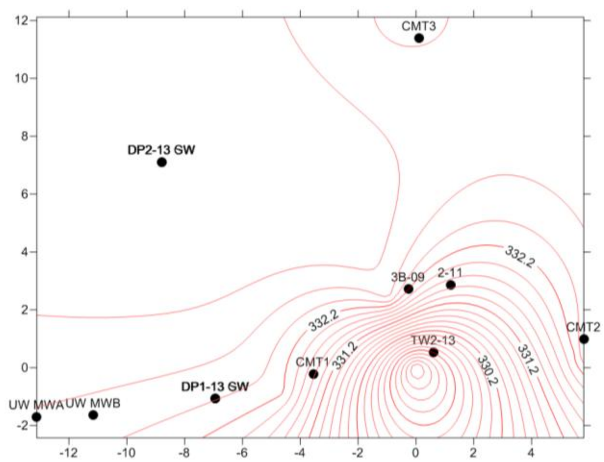
System



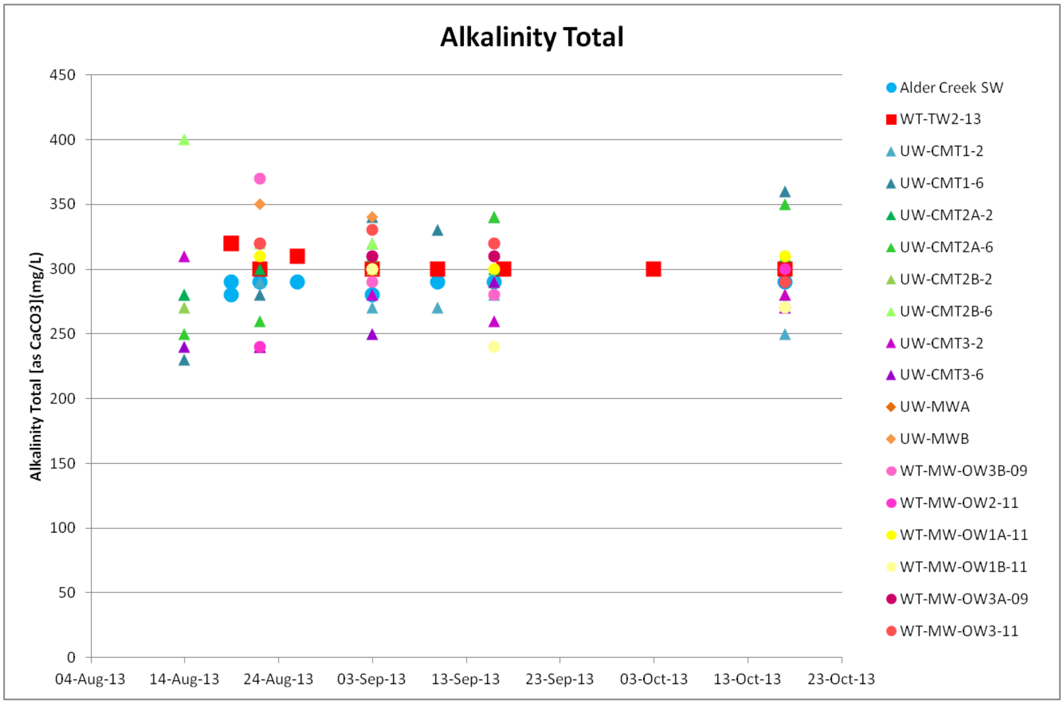
Deep

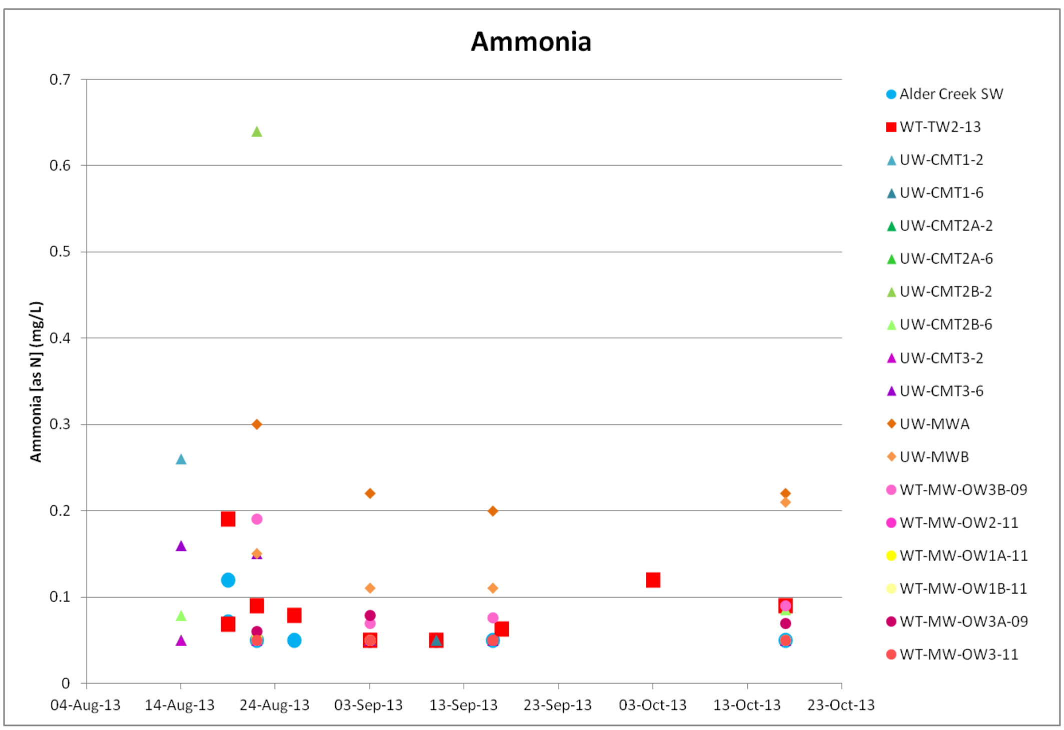
Groundwater

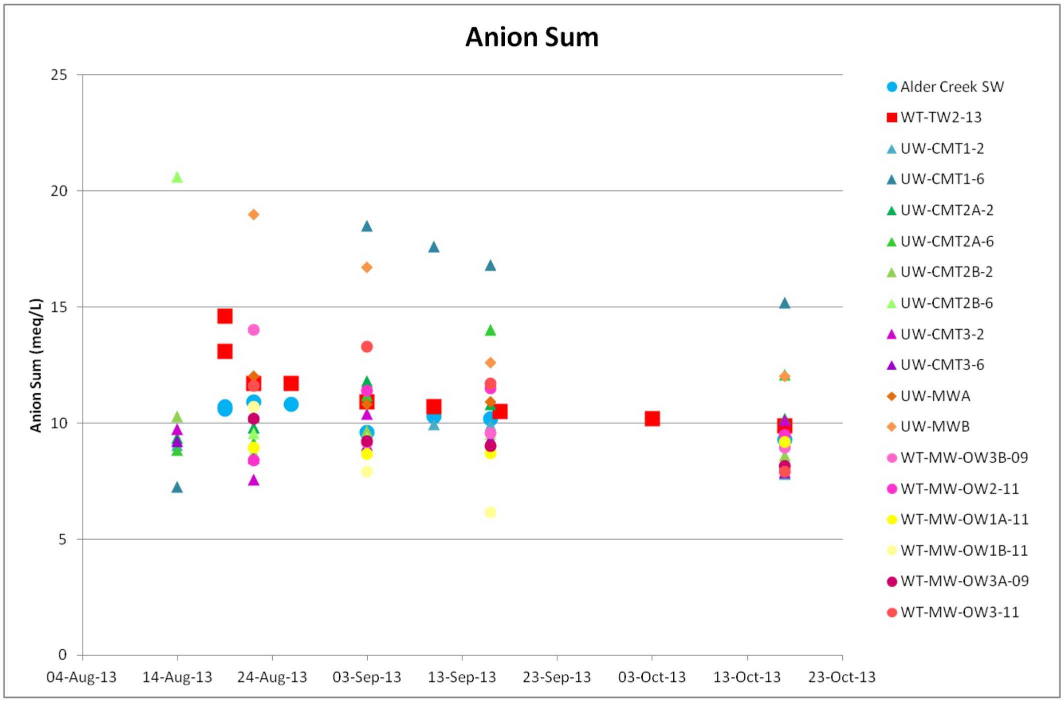
System

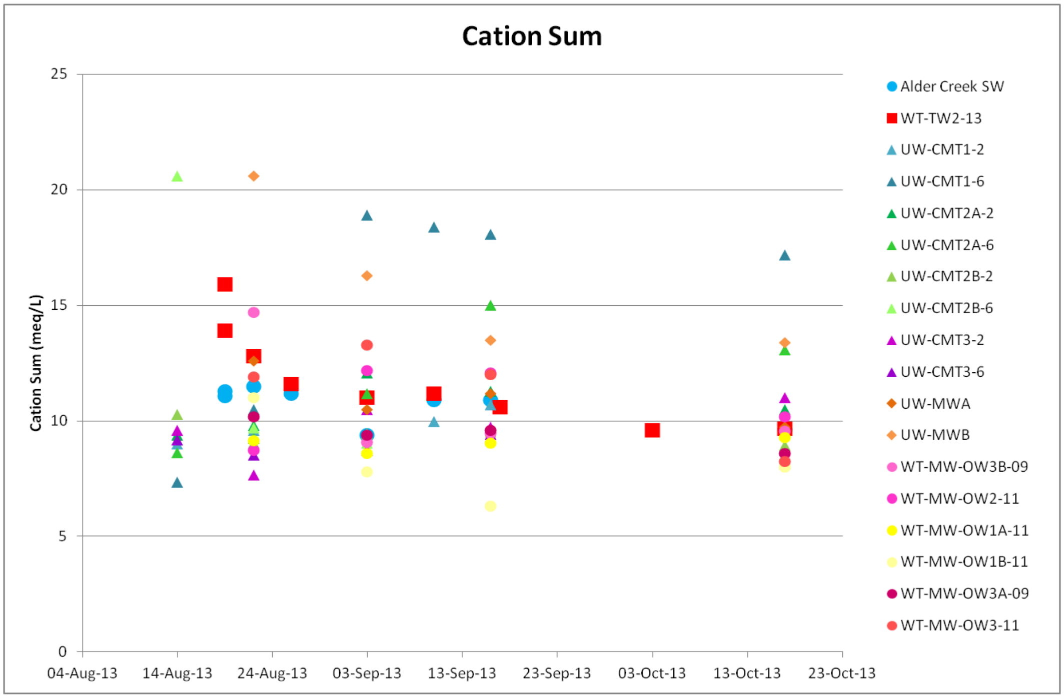


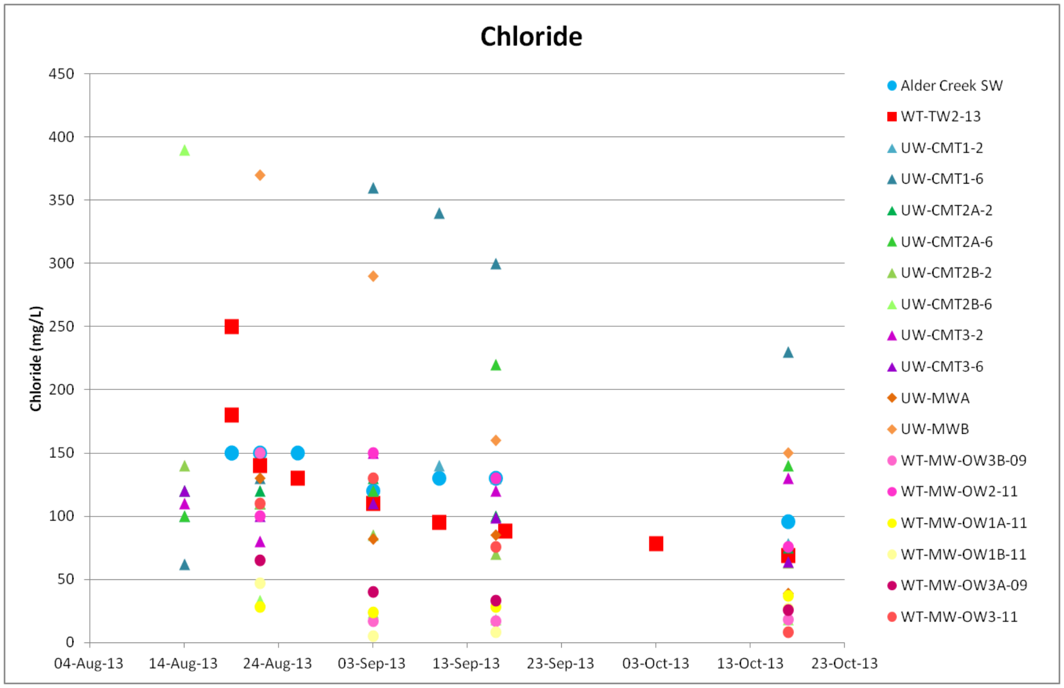
Appendix AD. All General Chemistry Data Figures for Groundwater and Surface Water Samples Collected during the Pumping Test

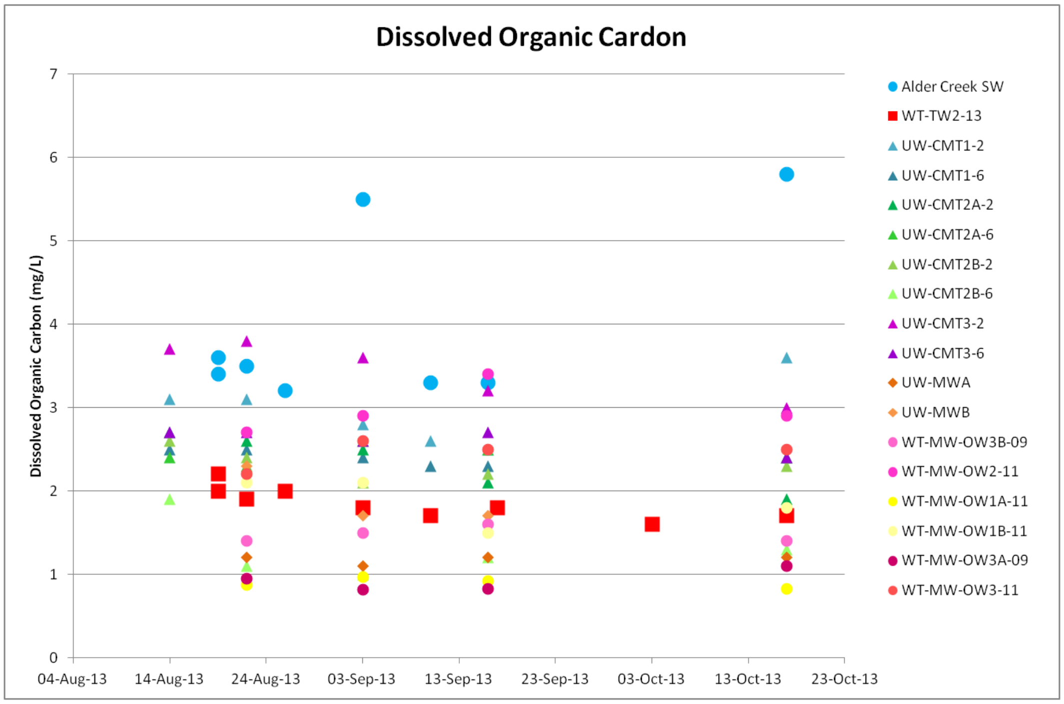


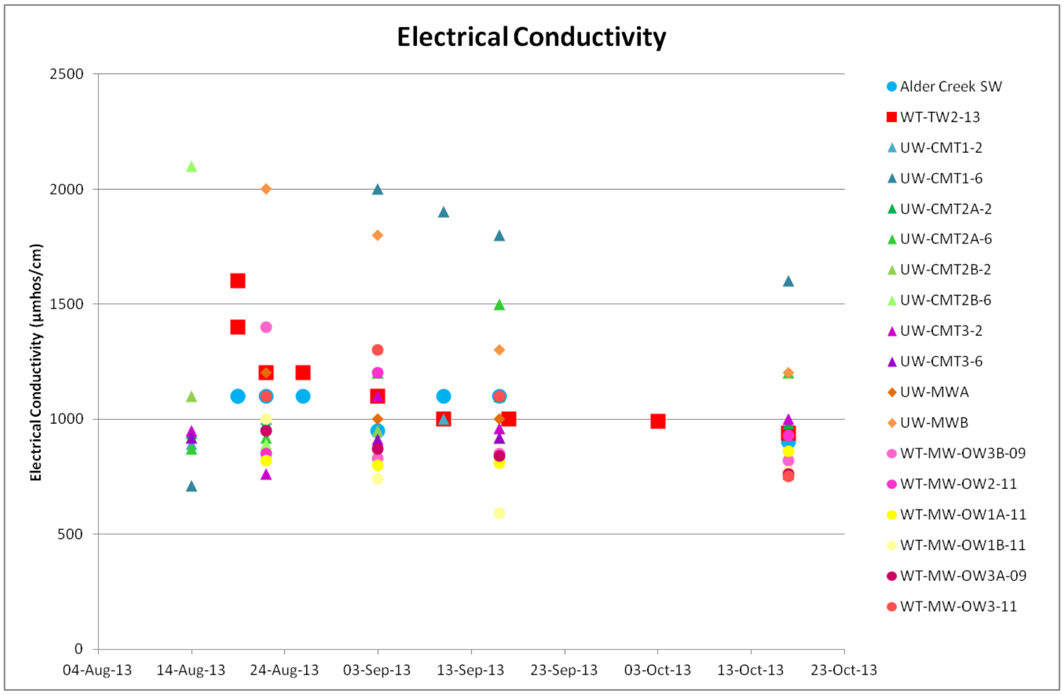


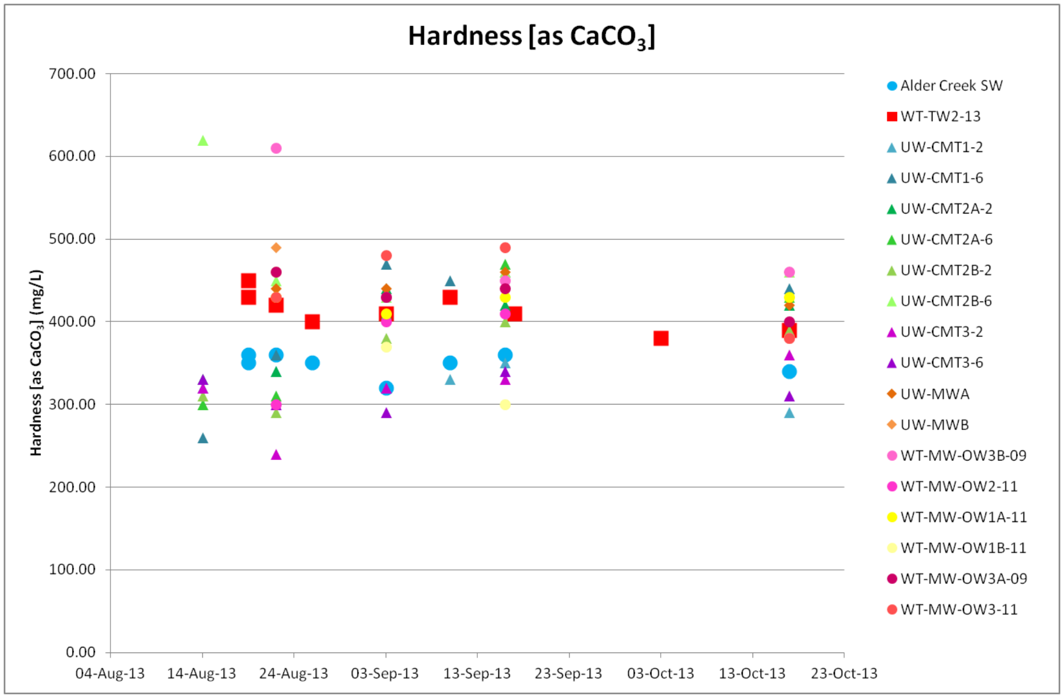

Anion Sum
Anion Sum (meq/L)
25
20
15
10
5
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

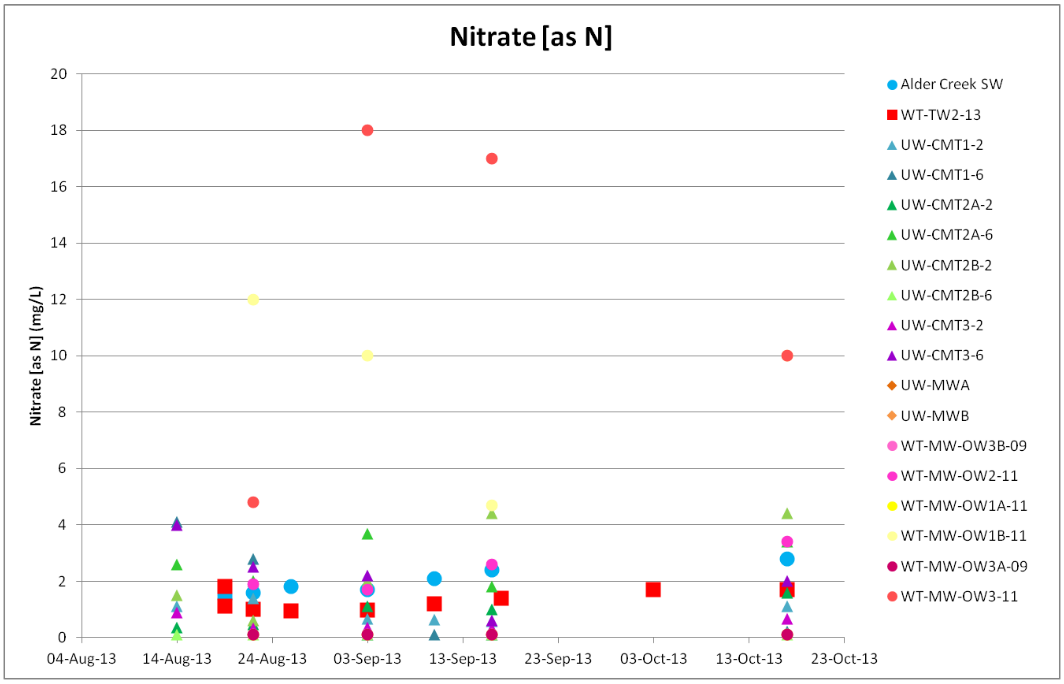

Cation Sum
Cation Sum (meq/L)
25
20
15
10
5
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

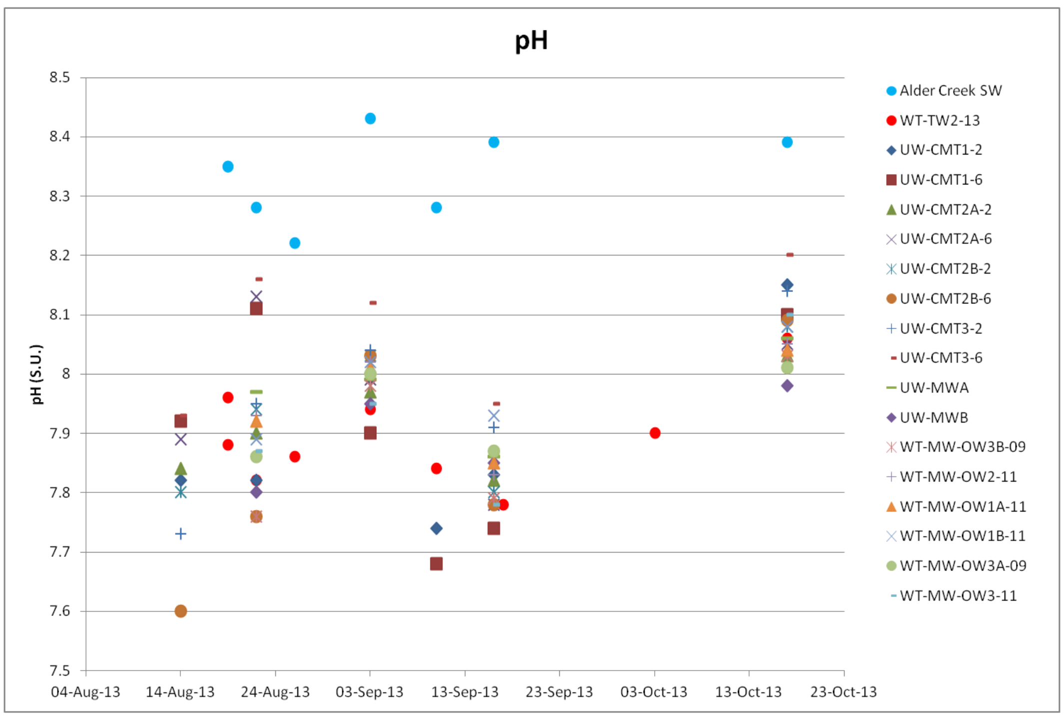

Chloride
Chloride (mg/L)
450
400
350
300
250
200
150
100
50
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

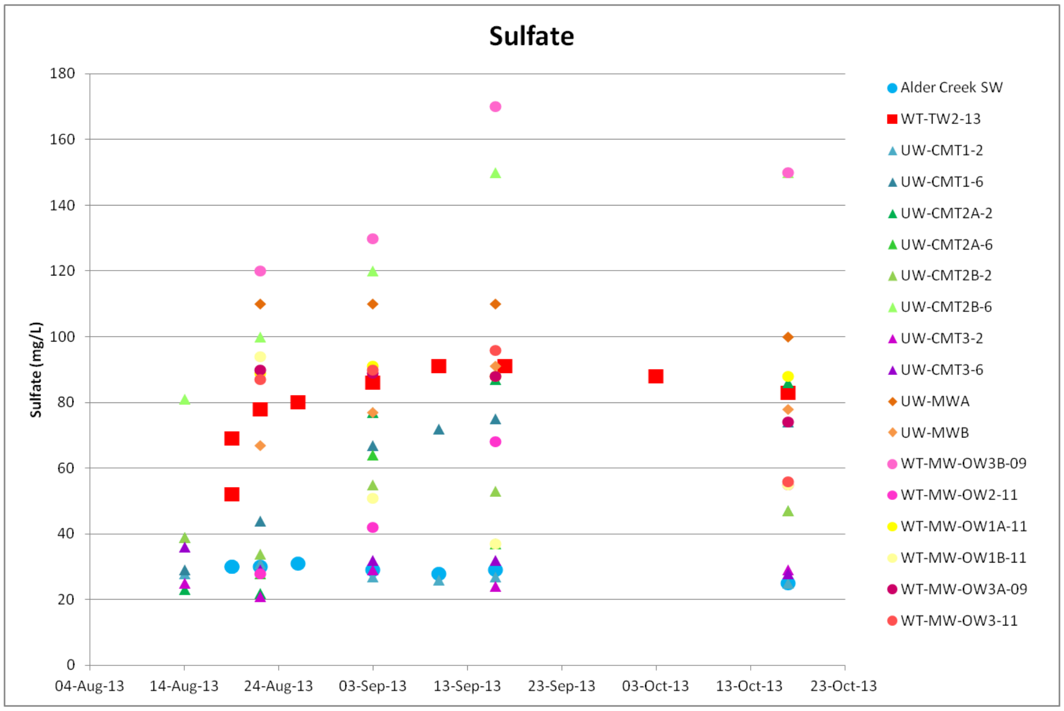

Dissolved Organic Cardon
Dissolved Organic Carbon (mg/L)
7
6
5
4
3
2
1
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

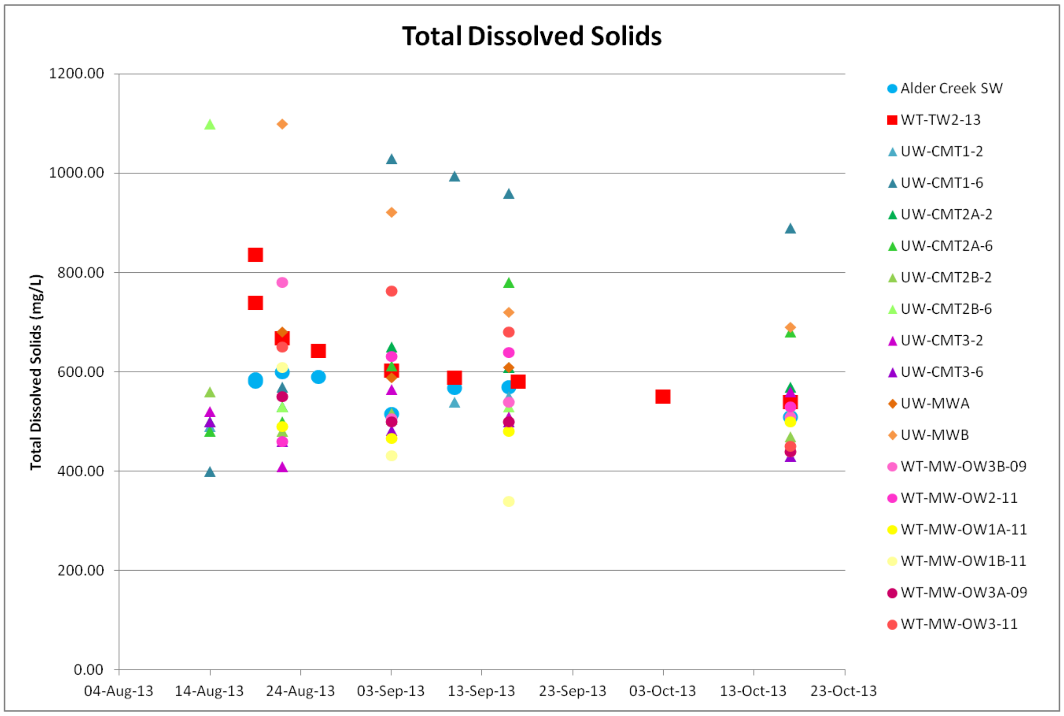

Electrical Conductivity
Electrical Conductivity (µmhos/cm)
2500
2000
1500
1000
500
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11


Hardness [as $CaCO_3$]
Hardness [as $CaCO_3$] (mg/L)
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

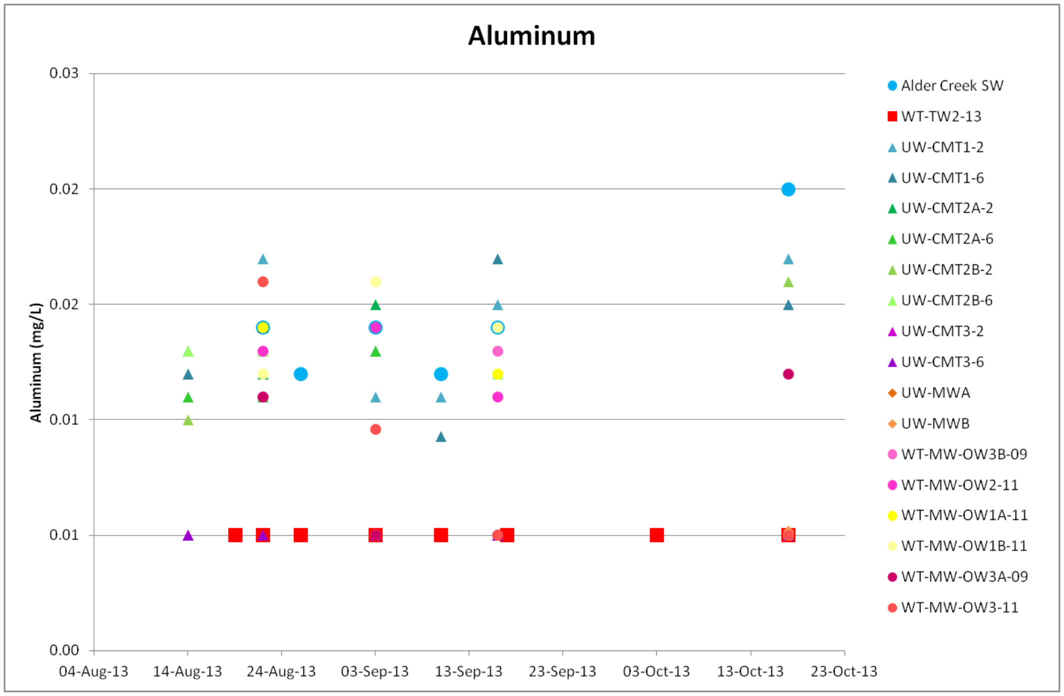

Nitrate [as N]
Nitrate [as N] (mg/L)
20
18
16
14
12
10
8
6
4
2
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

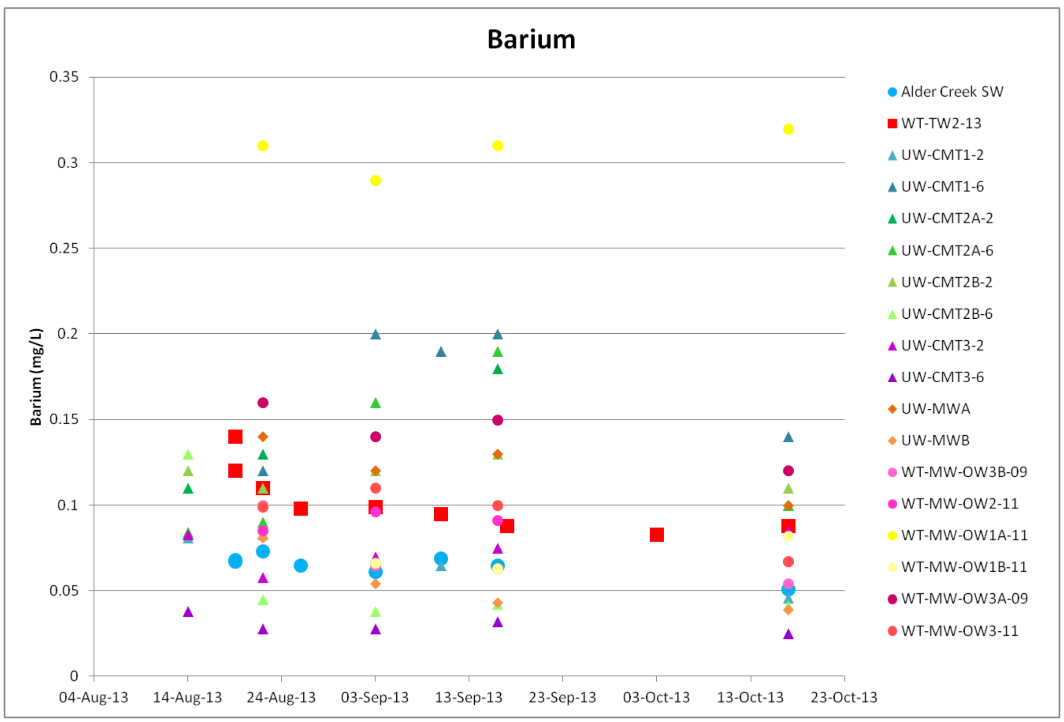

pH
pH (S.U.)
8.5
8.4
8.3
8.2
8.1
8
7.9
7.8
7.7
7.6
7.5
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

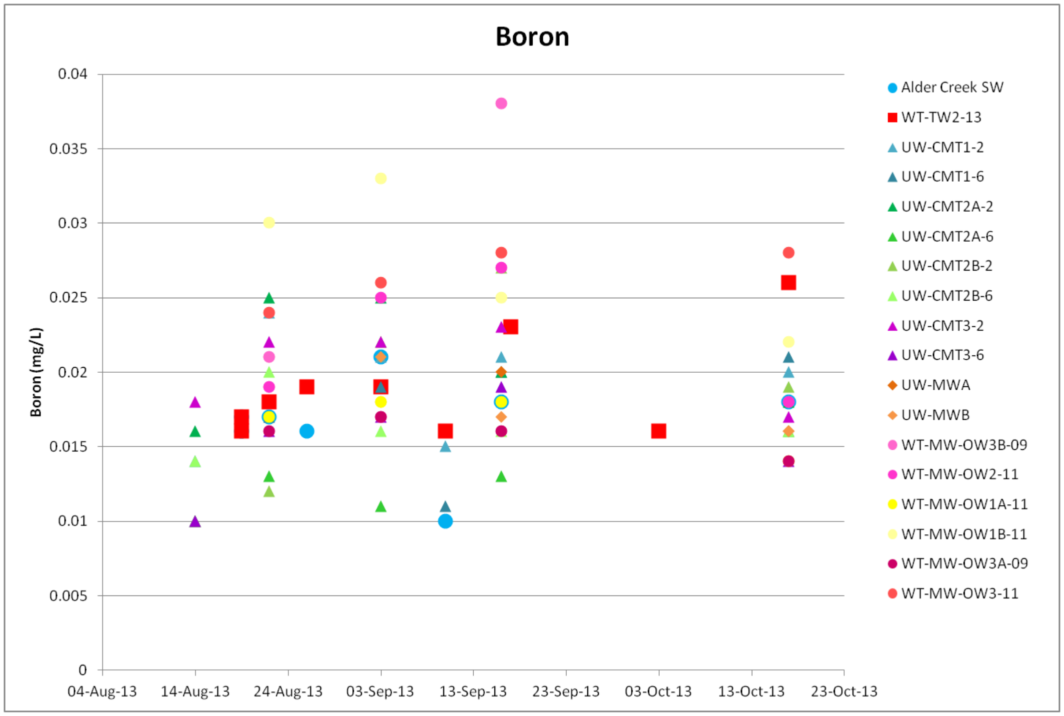

Sulfate
Sulfate (mg/L)
0
20
40
60
80
100
120
140
160
180
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11


Total Dissolved Solids
Total Dissolved Solids (mg/L)
0.00
200.00
400.00
600.00
800.00
1000.00
1200.00
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

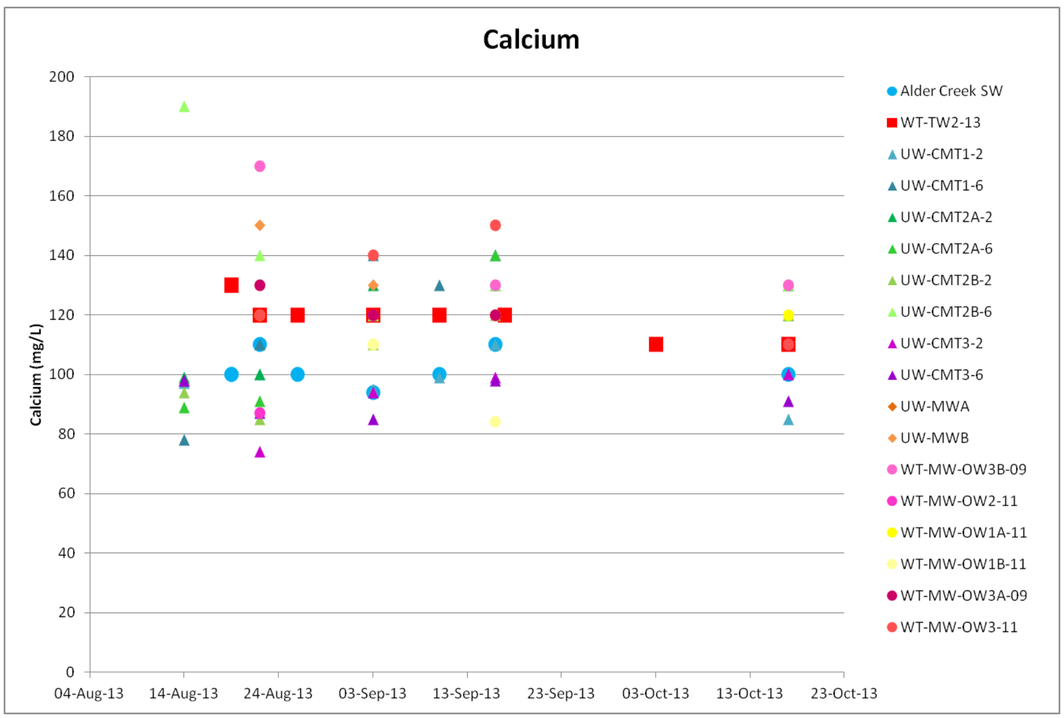
Appendix AE. Data Figures for Metals Studied from Groundwater and Surface Water Samples Collected during the Pumping Test



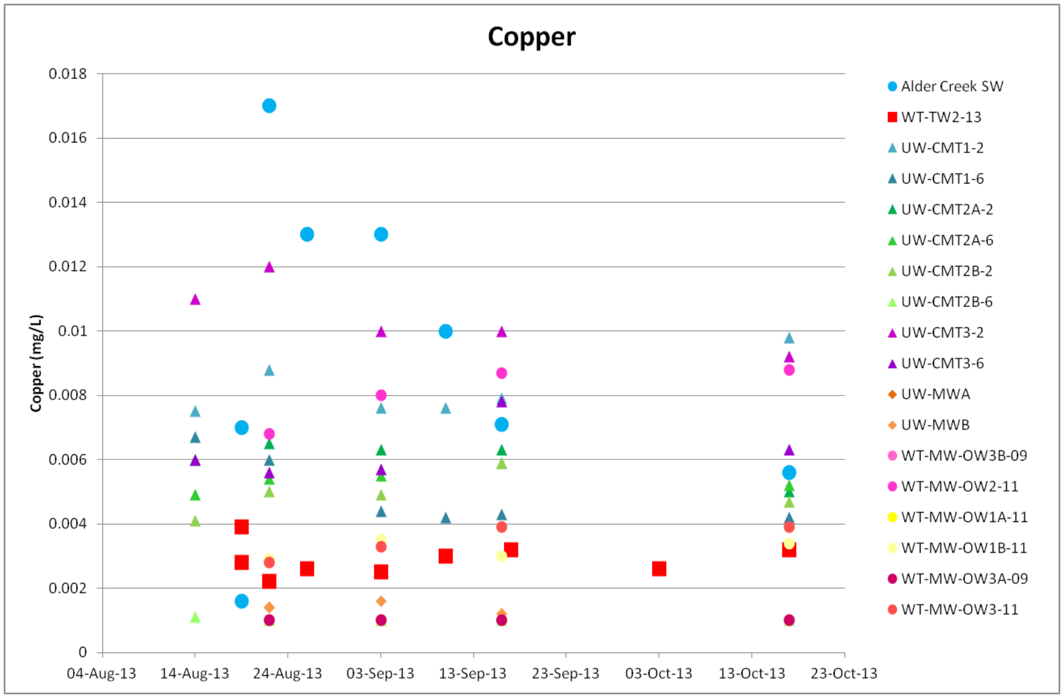


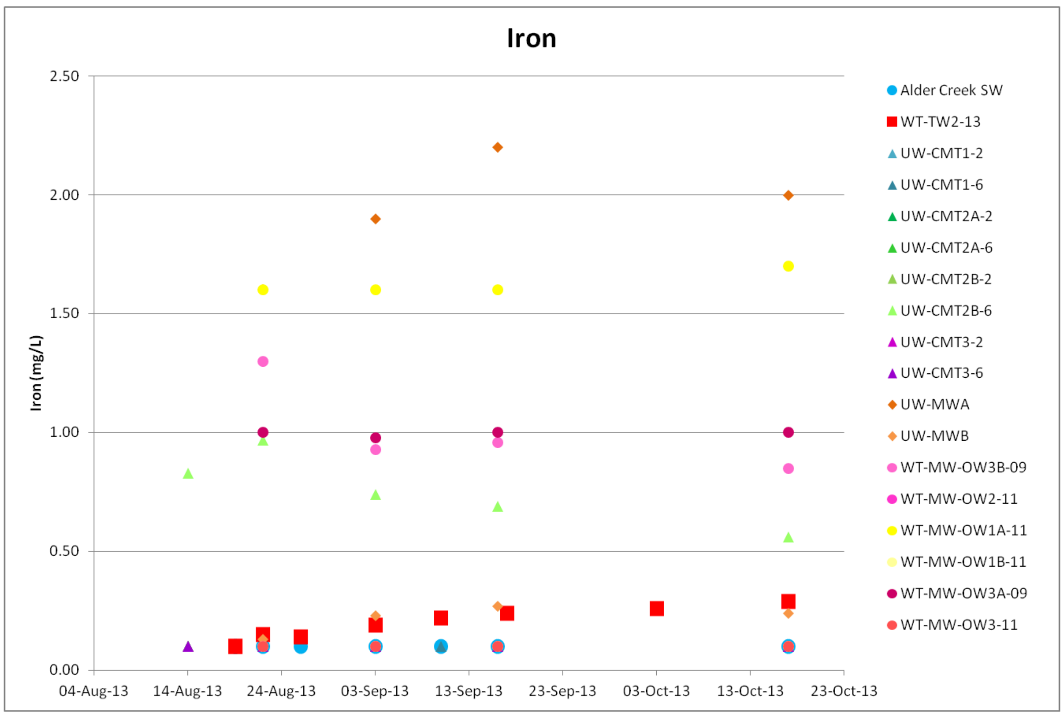


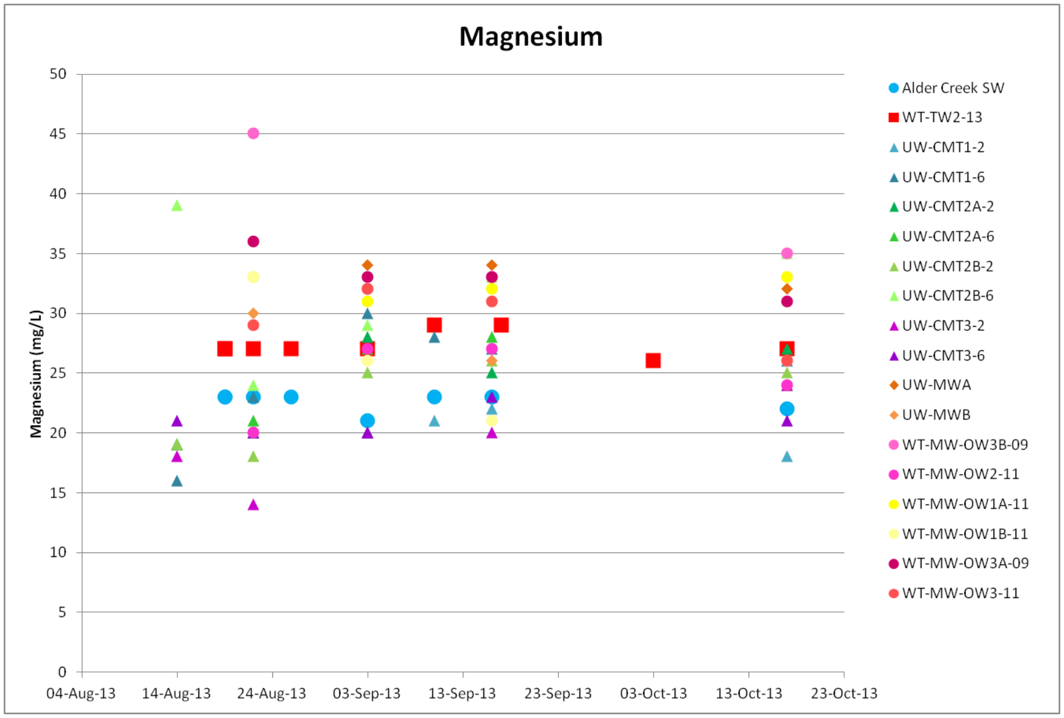
Boron
Boron (mg/L)
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

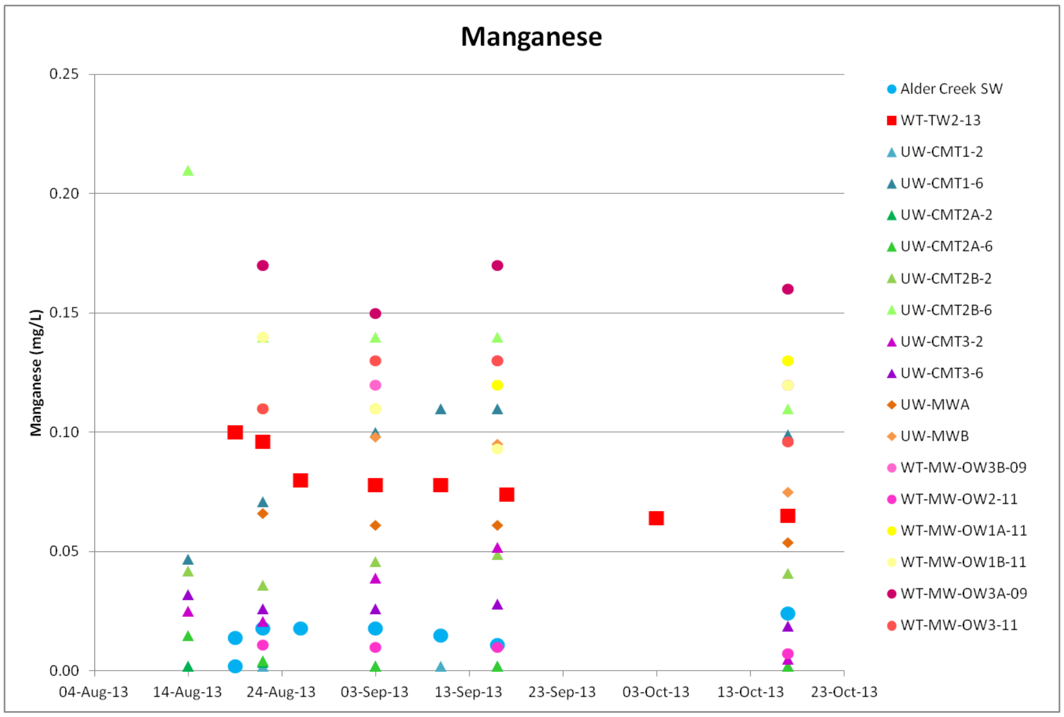


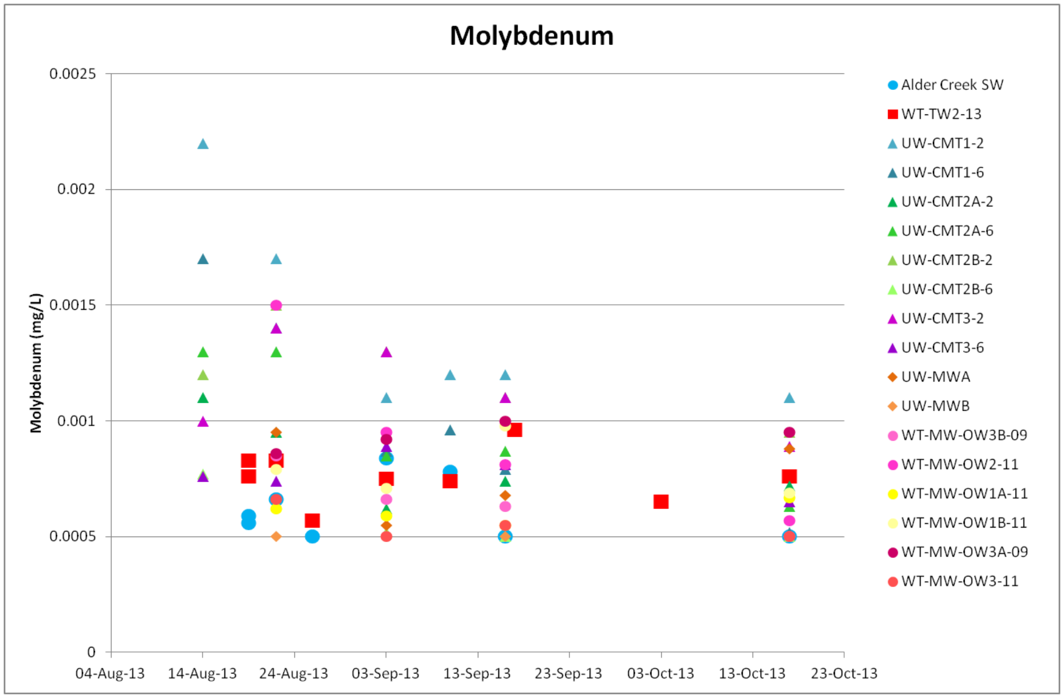
Calcium
Calcium (mg/L)
200
180
160
140
120
100
80
60
40
20
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

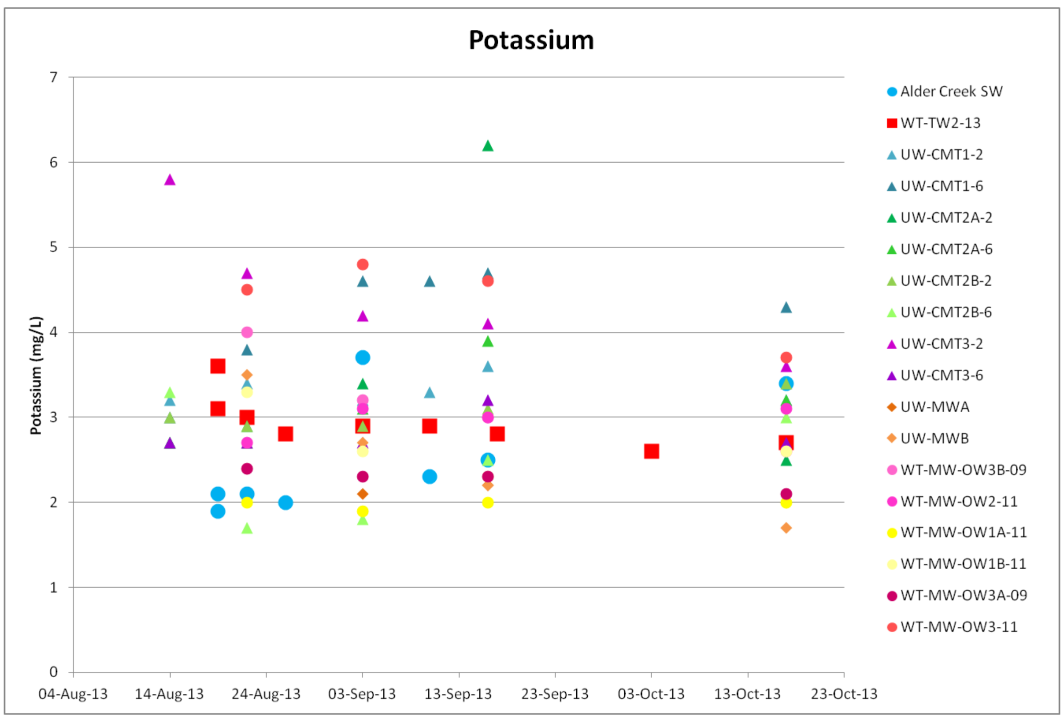

Copper
Copper (mg/L)
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

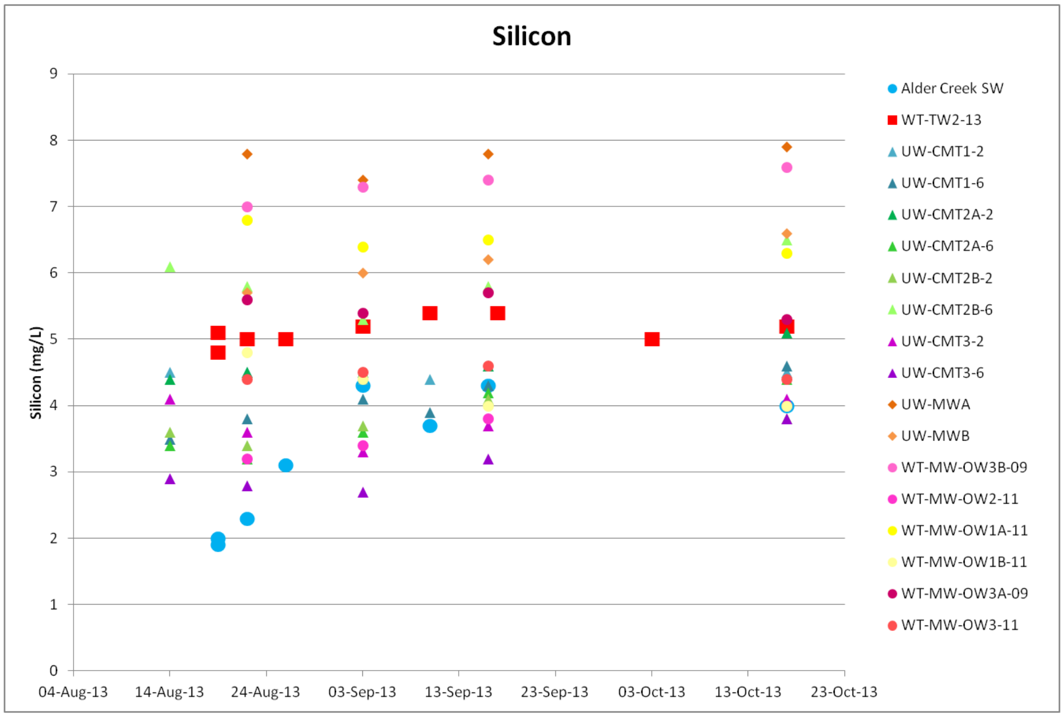

Iron
Iron (mg/L)
2.50
2.00
1.50
1.00
0.50
0.00
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

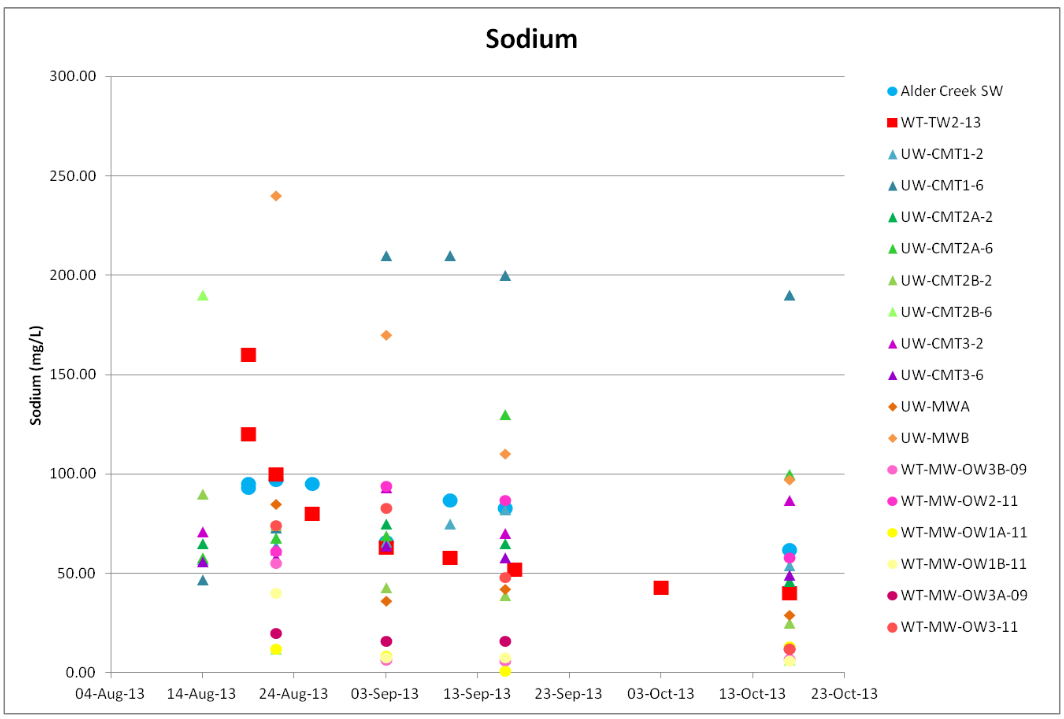

Magnesium
Magnesium (mg/L)
0
5
10
15
20
25
30
35
40
45
50
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

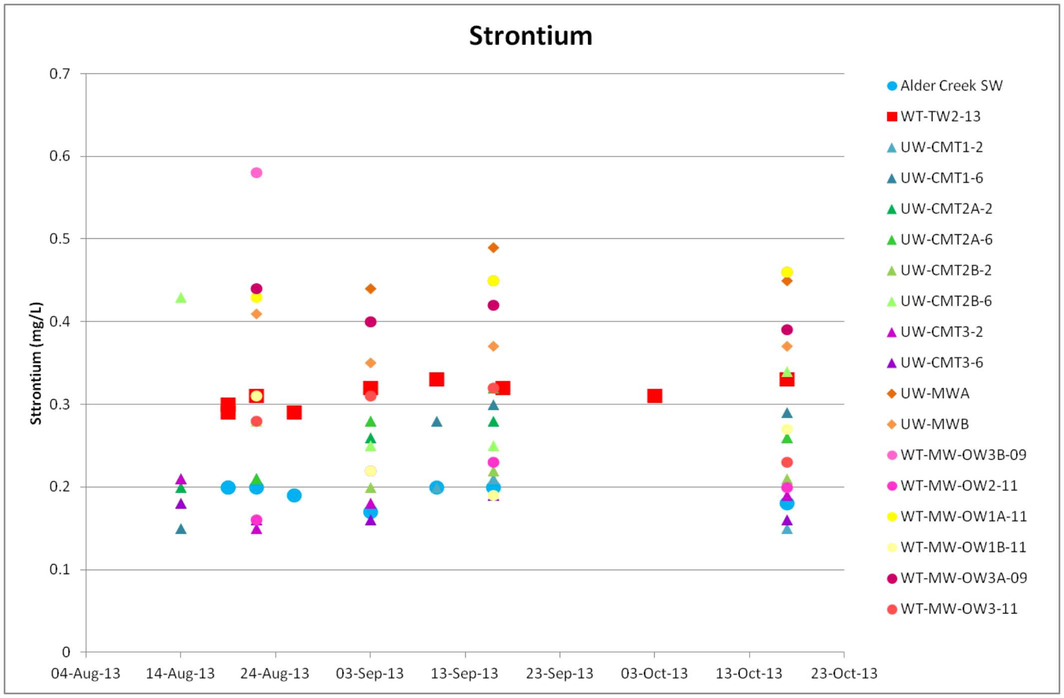

Manganese
Manganese (mg/L)
0.00
0.05
0.10
0.15
0.20
0.25
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

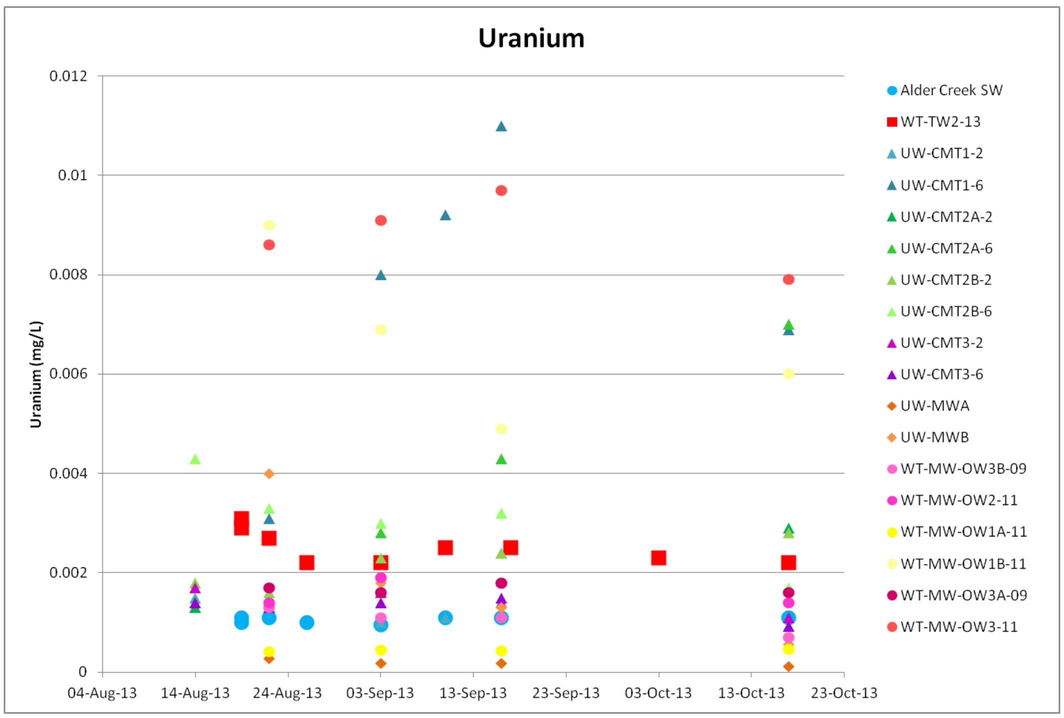

Molybdenum
Molybdenum (mg/L)
0.0025
0.002
0.0015
0.001
0.0005
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

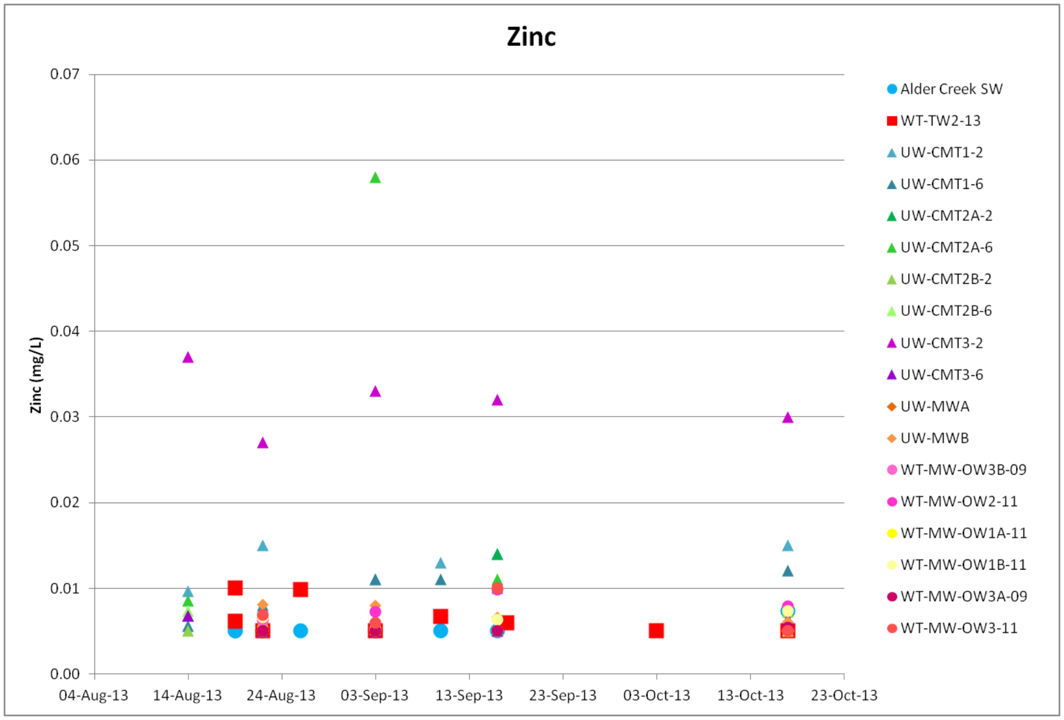

Potassium
Potassium (mg/L)
7
6
5
4
3
2
1
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11


Silicon
Silicon (mg/L)
0
1
2
3
4
5
6
7
8
9
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11


Sodium
Sodium (mg/L)
0.00
50.00
100.00
150.00
200.00
250.00
300.00
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11


Strontium
Sttrontium (mg/L)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

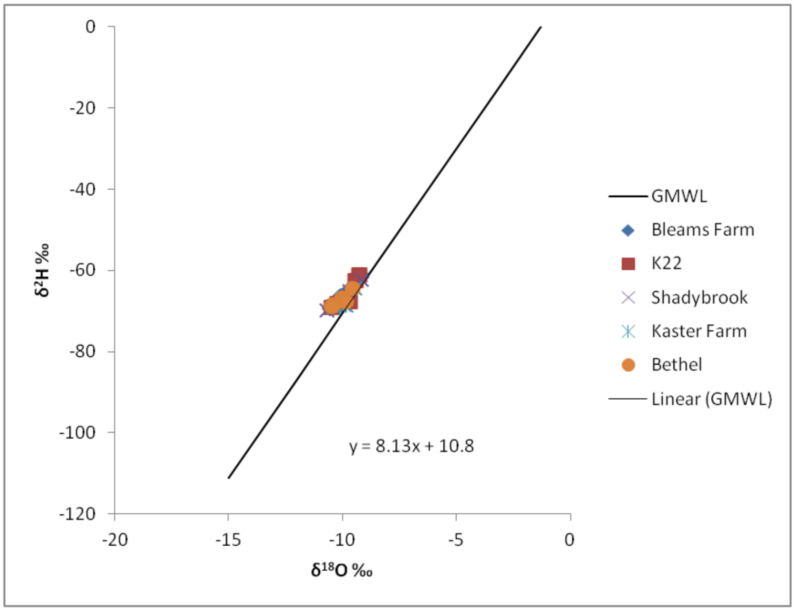

Uranium
Uranium (mg/L)
0.012
0.01
0.008
0.006
0.004
0.002
0
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11



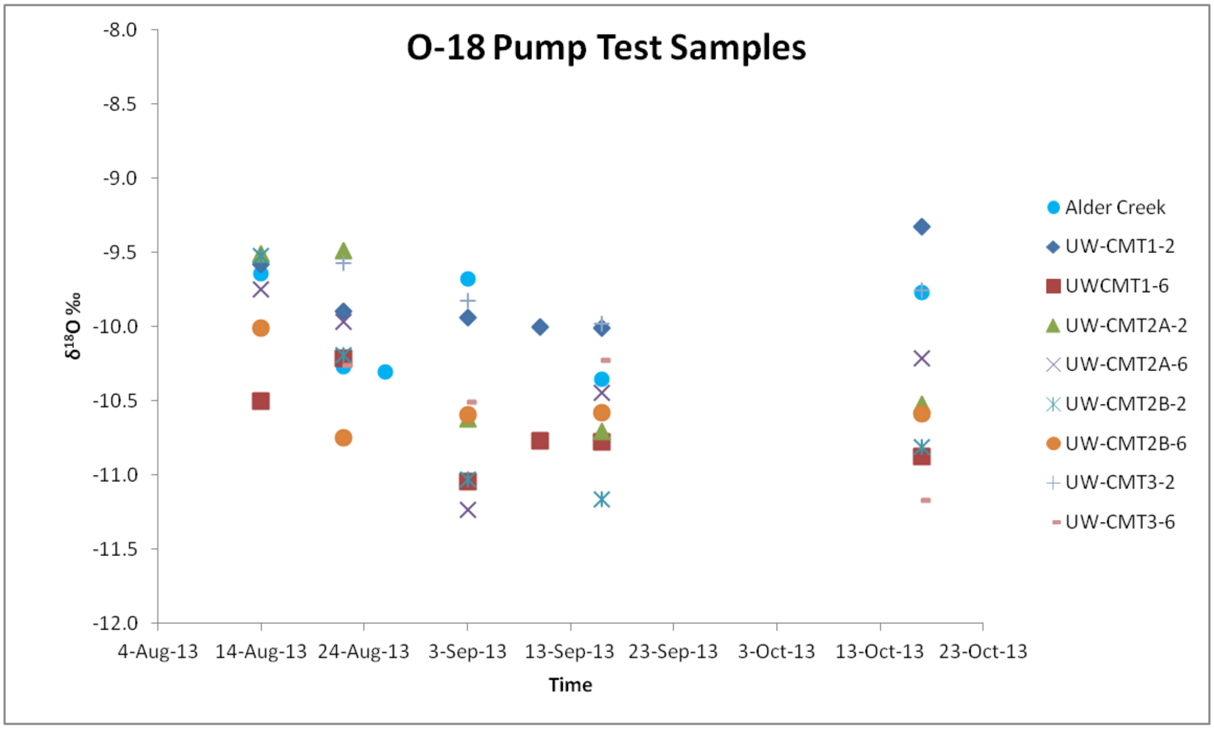
Zinc
Zinc (mg/L)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
04-Aug-13
14-Aug-13
24-Aug-13
03-Sep-13
13-Sep-13
23-Sep-13
03-Oct-13
13-Oct-13
23-Oct-13
Alder Creek SW
WT-TW2-13
UW-CMT1-2
UW-CMT1-6
UW-CMT2A-2
UW-CMT2A-6
UW-CMT2B-2
UW-CMT2B-6
UW-CMT3-2
UW-CMT3-6
UW-MWA
UW-MWB
WT-MW-OW3B-09
WT-MW-OW2-11
WT-MW-OW1A-11
WT-MW-OW1B-11
WT-MW-OW3A-09
WT-MW-OW3-11

Appendix AF. Stable Water Isotope Data Figures

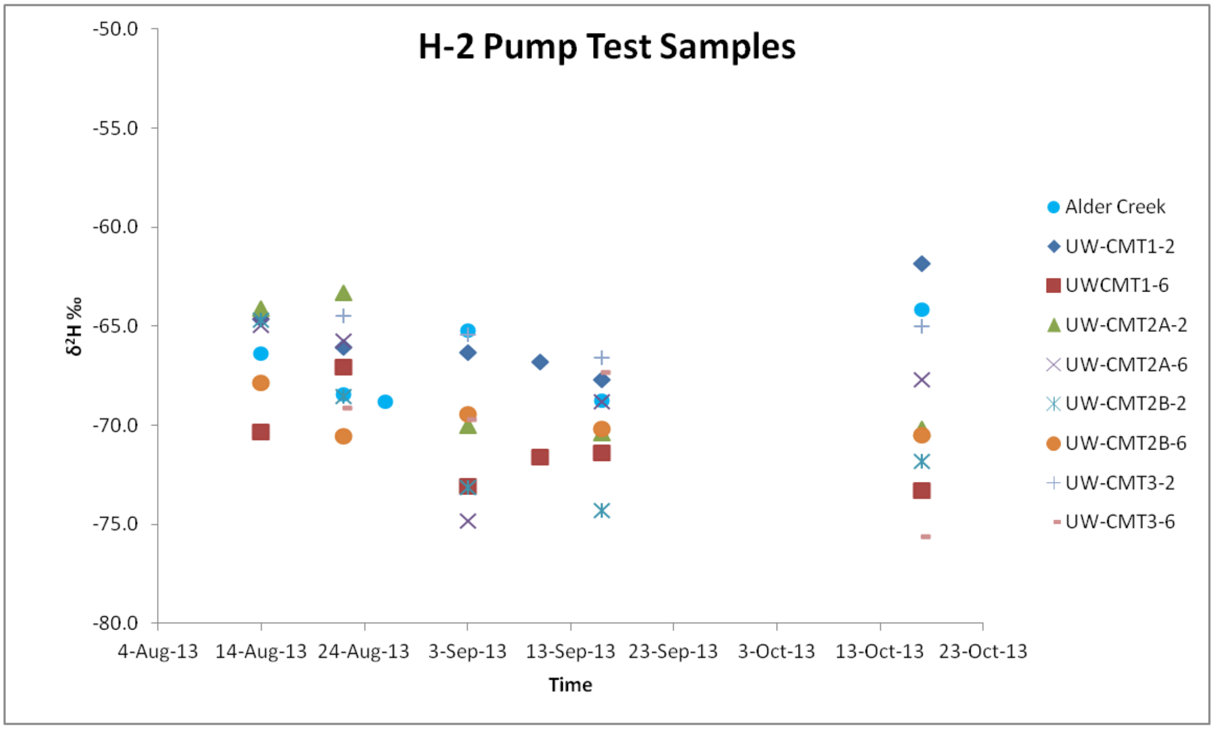
Local Meteoric Water Line, including samples collected over duration of sampling program.



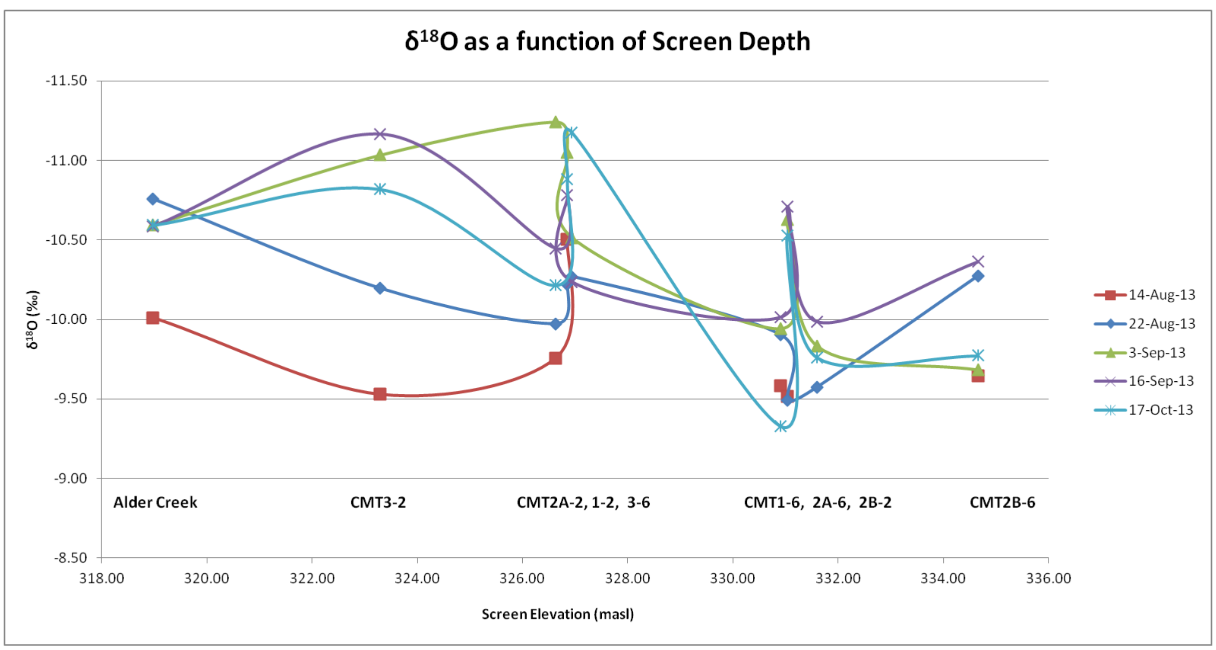
δ^{18}O content of samples collected over the duration of the pumping test.



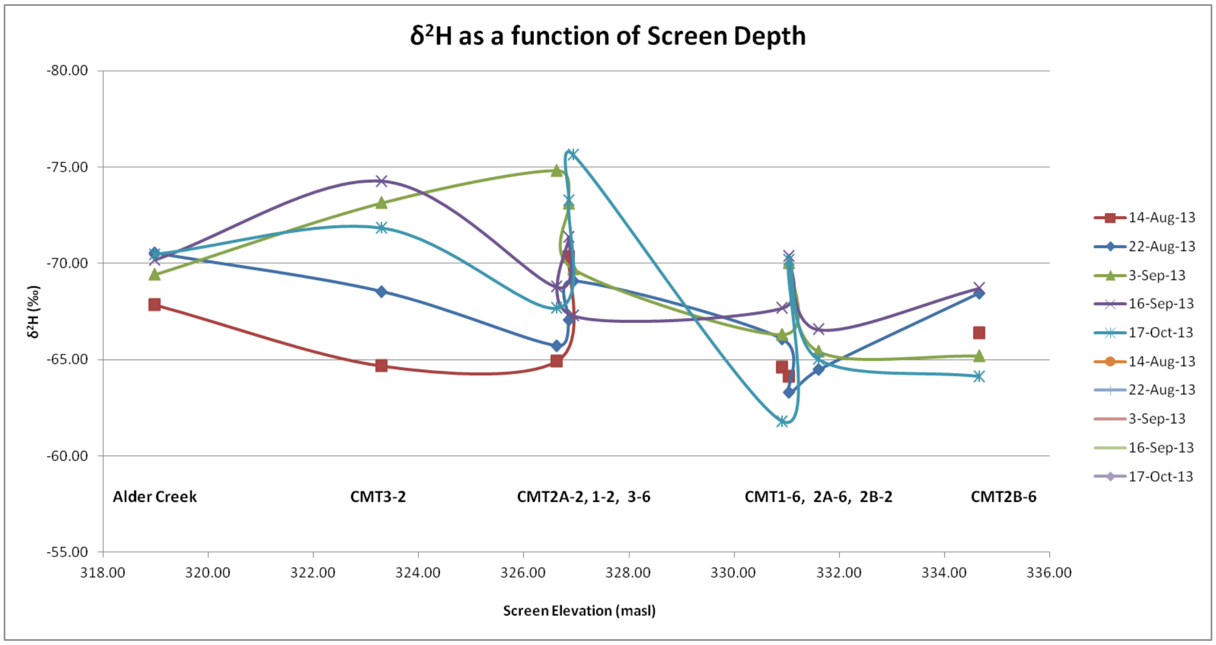
δ^2H content of samples collected over the duration of the pumping test.



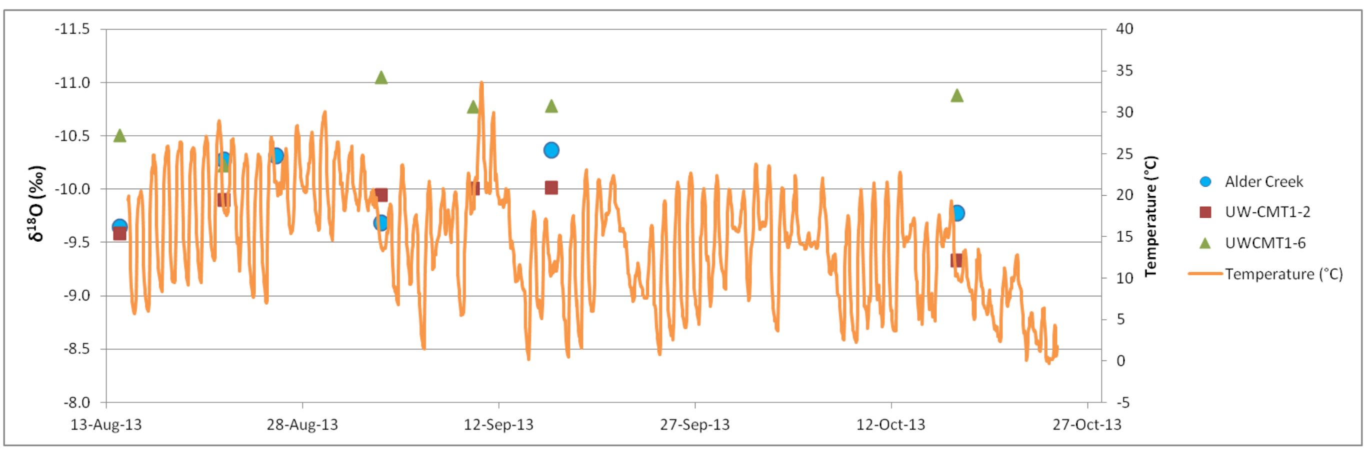
$\delta^{18}O$ content of samples collected as a function of depth.



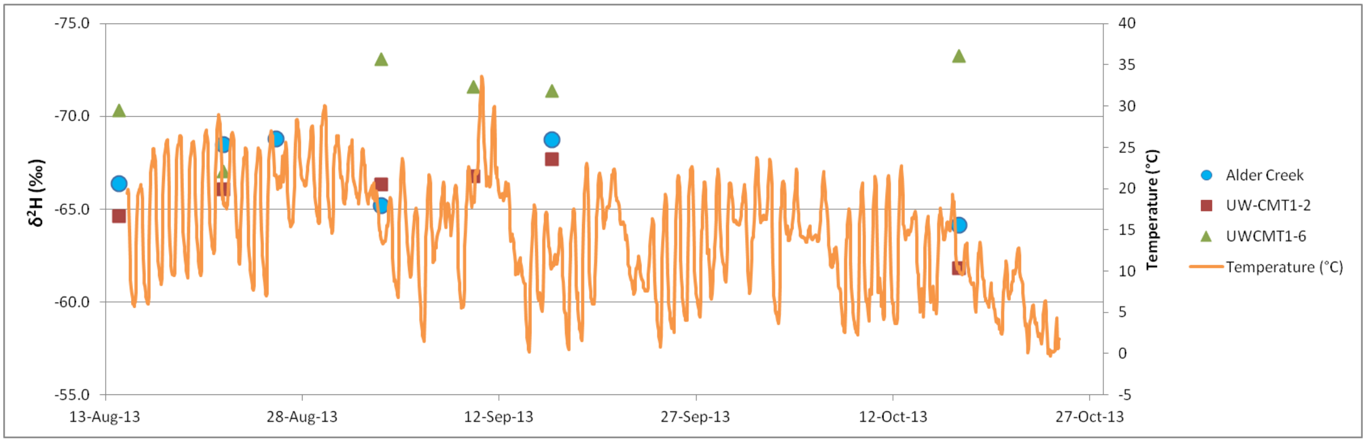
δ^2H content of samples collected as a function of depth.



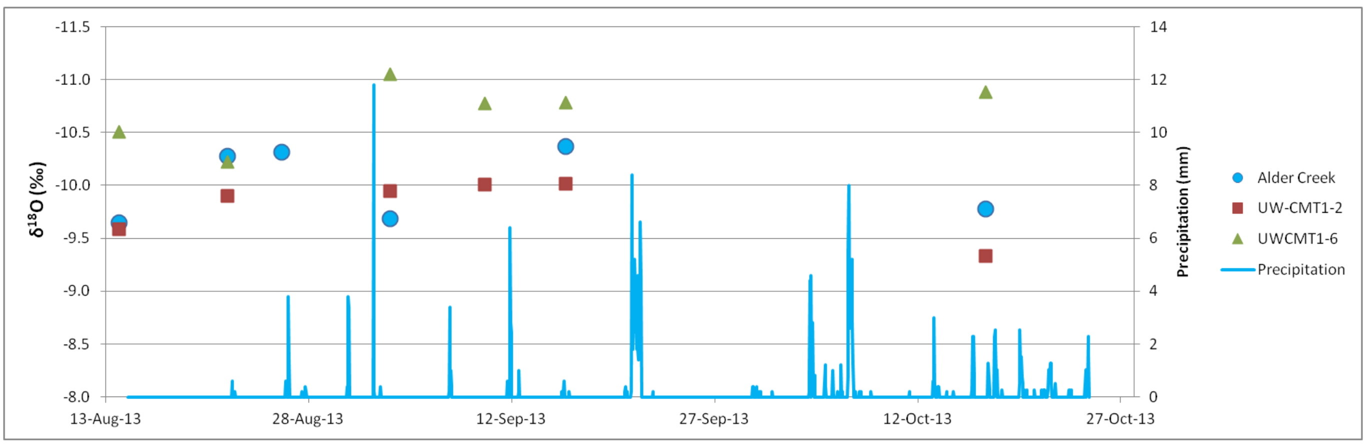
Alder Creek, CMT1-2, and CMT1-6 $\delta^{18}O$ data compared to air temperature throughout the test.



Alder Creek, CMT1-2, and CMT1-6 δ^2H data compared to air temperature throughout the test.

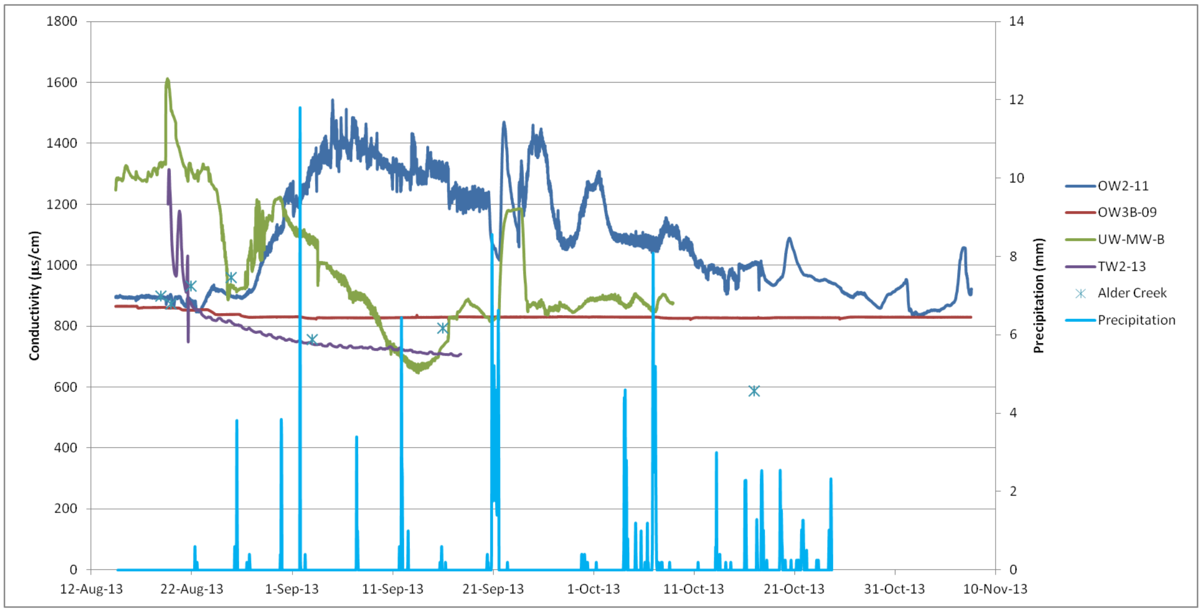


Alder Creek, CMT1-2, and CMT1-6 $\delta^{18}O$ data compared to precipitation events throughout the test.

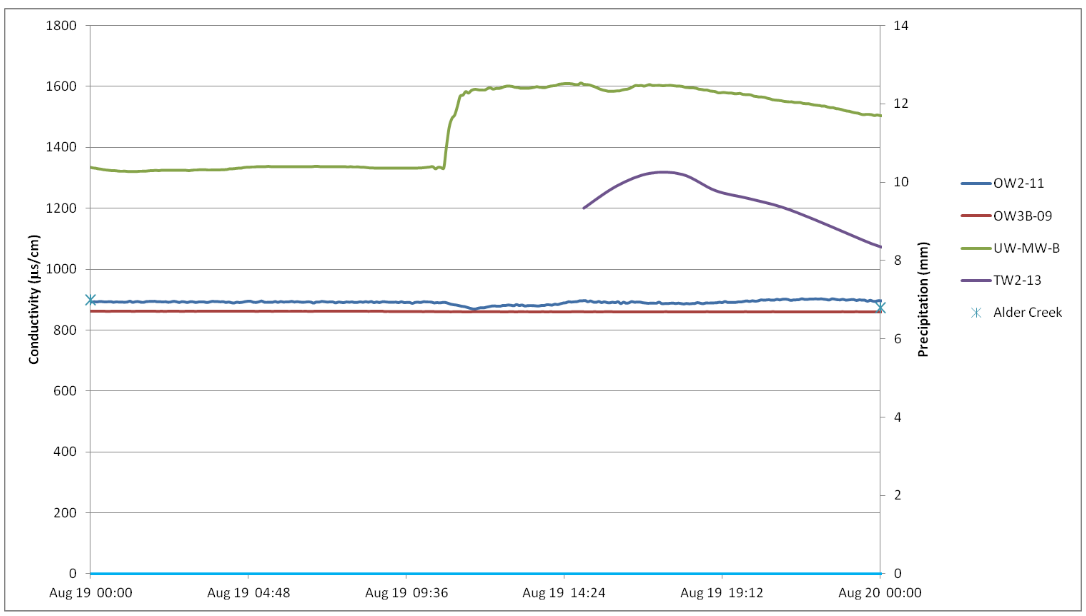


Appendix AG. Continuous Conductivity Data Figures collected in wells OW2-11, OW3B-09, UW MWB, and TW2-13, with precipitation data

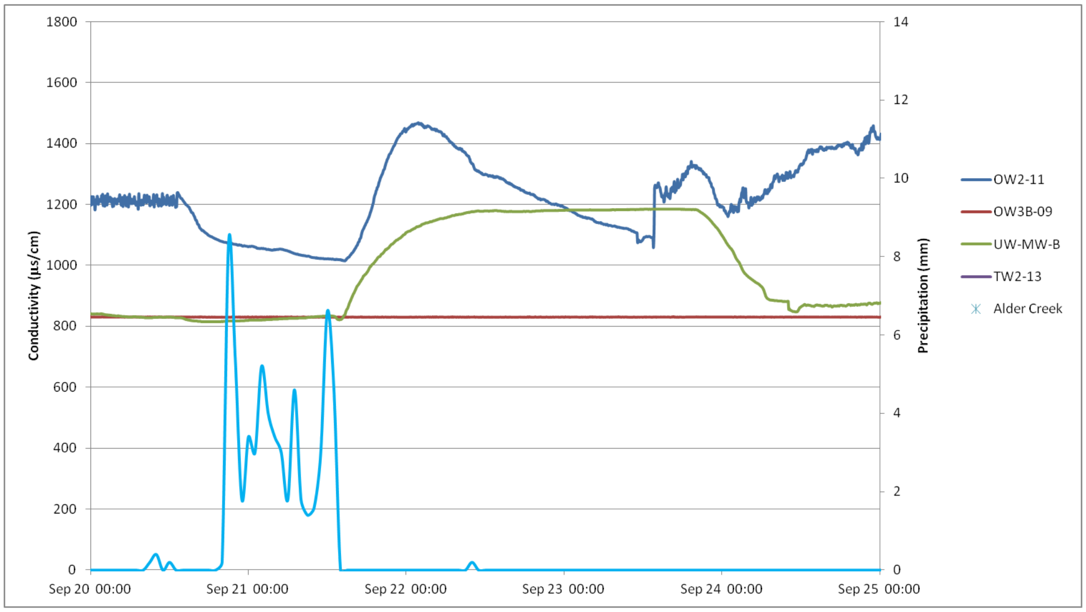
Full duration of the test



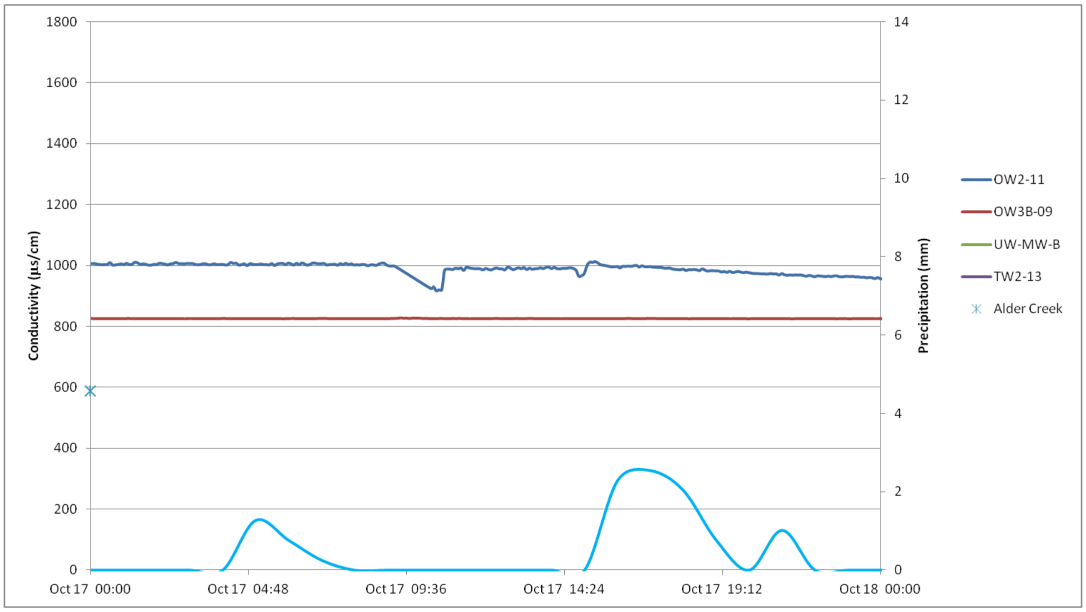
Start of the pumping test, August 19, 2013



Mid-test shut off period, September 20 to September 23, 2013

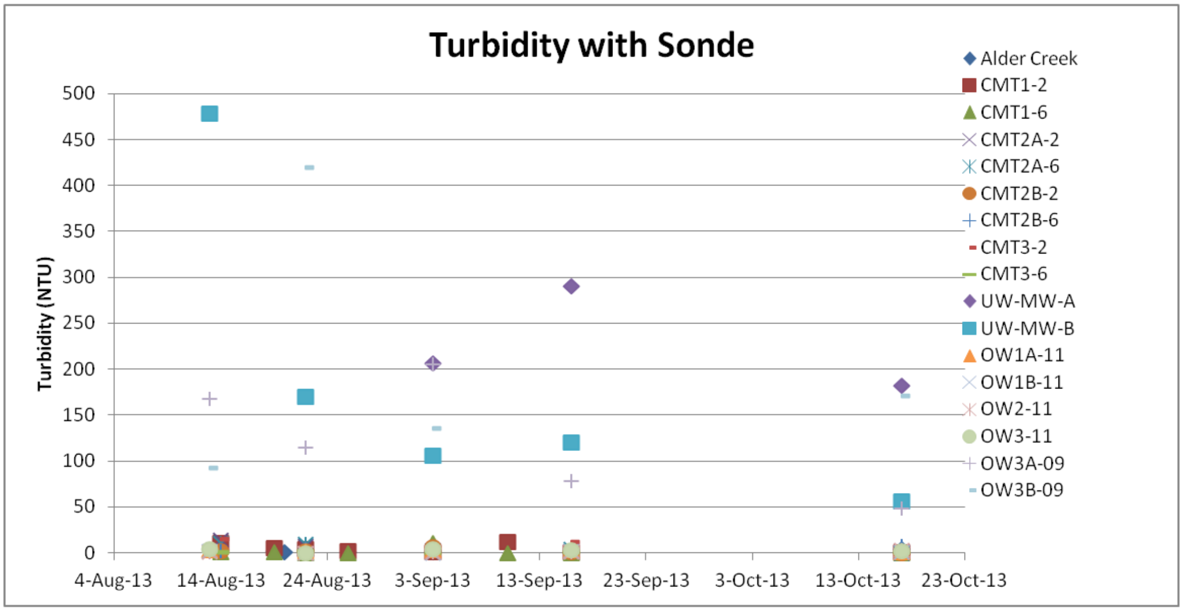


End of the pumping test, October 17, 2013.

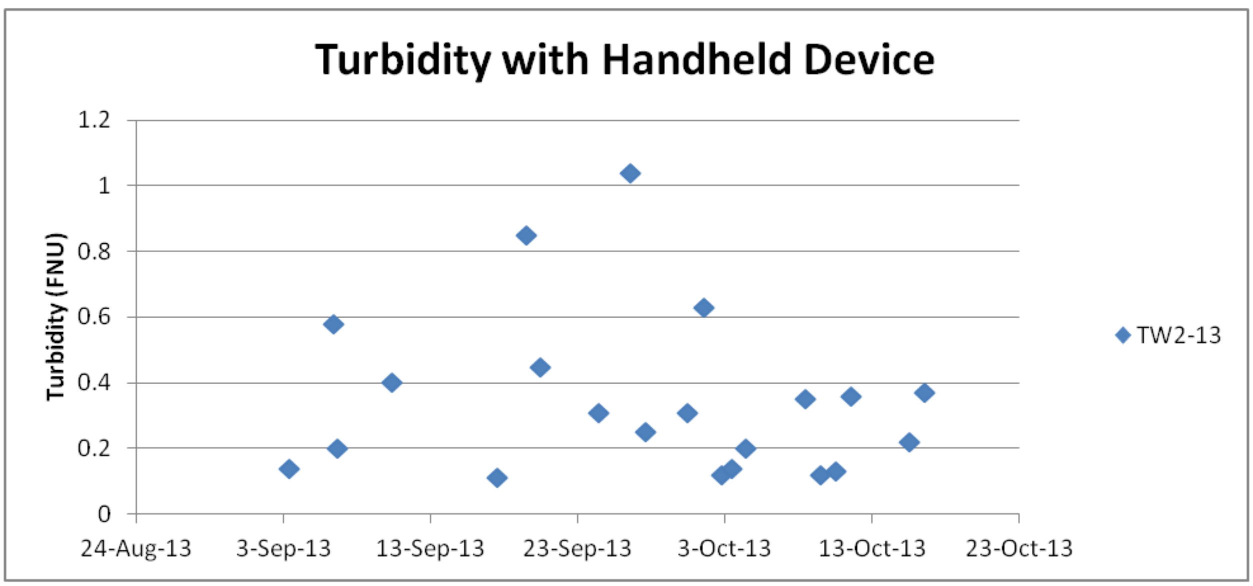


Appendix AH. Turbidity Data Figures

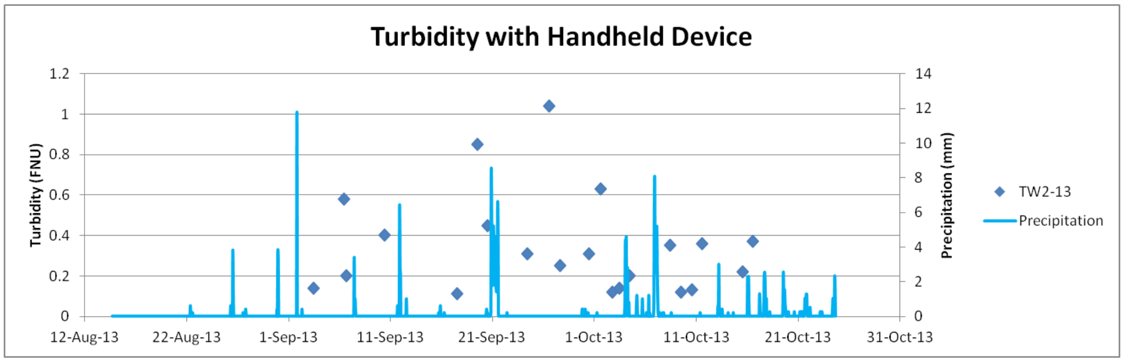
Turbidity data collected using the Sonde during sampling events throughout the test.



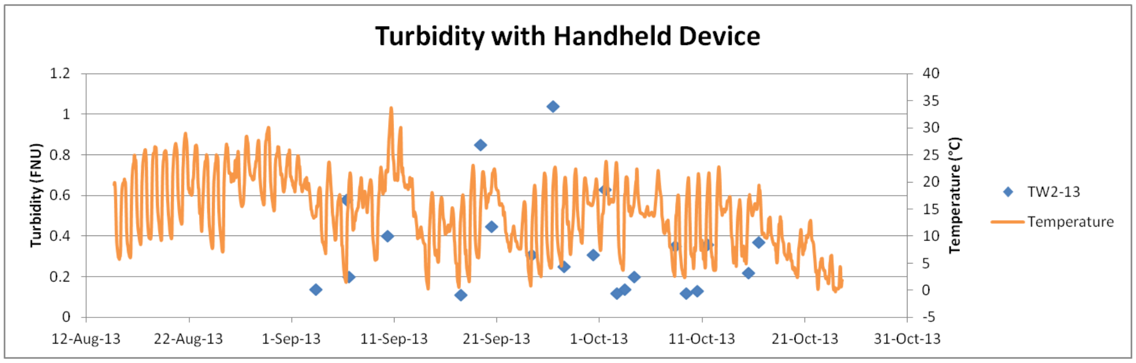
Handheld device turbidity measurements from the pumping well, TW2-13.



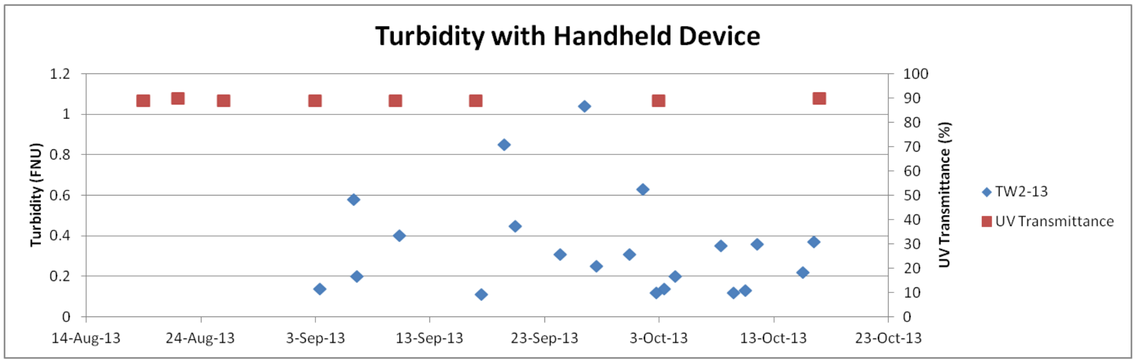
Handheld device turbidity measurements from the pumping well, TW2-13 compared to precipitation events.



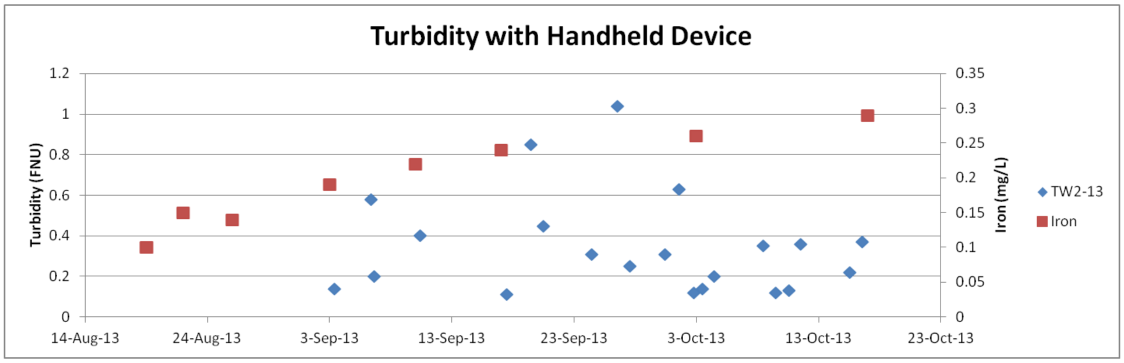
Handheld device turbidity measurements from the pumping well, TW2-13 compared to air temperature.



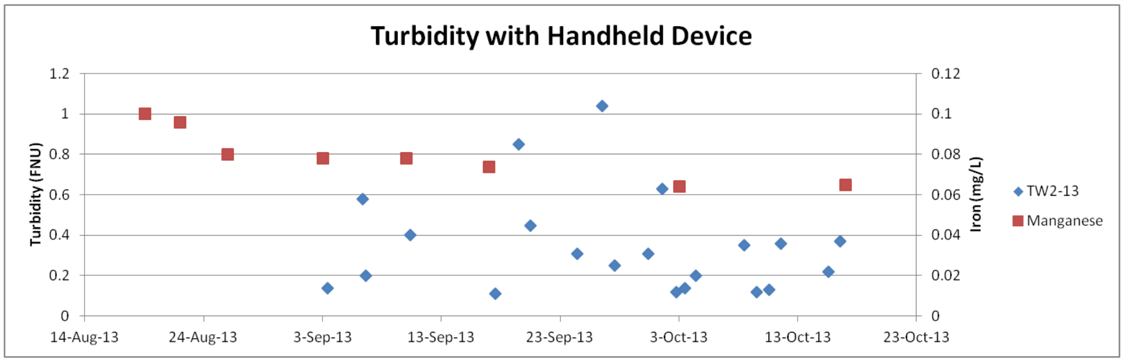
Handheld device turbidity measurements from the pumping well, TW2-13 compared to UV Transmittance from general chemistry samples.



Handheld device turbidity measurements from the pumping well, TW2-13 compared to Iron concentrations from general chemistry samples.

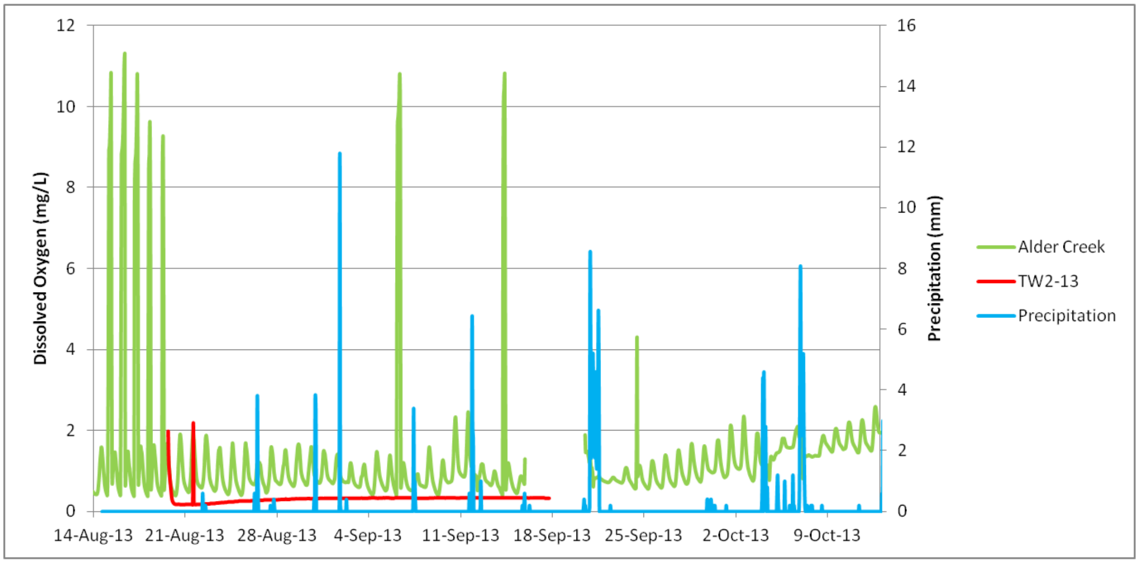


Handheld device turbidity measurements from the pumping well, TW2-13 compared to Manganese concentrations from general chemistry samples.

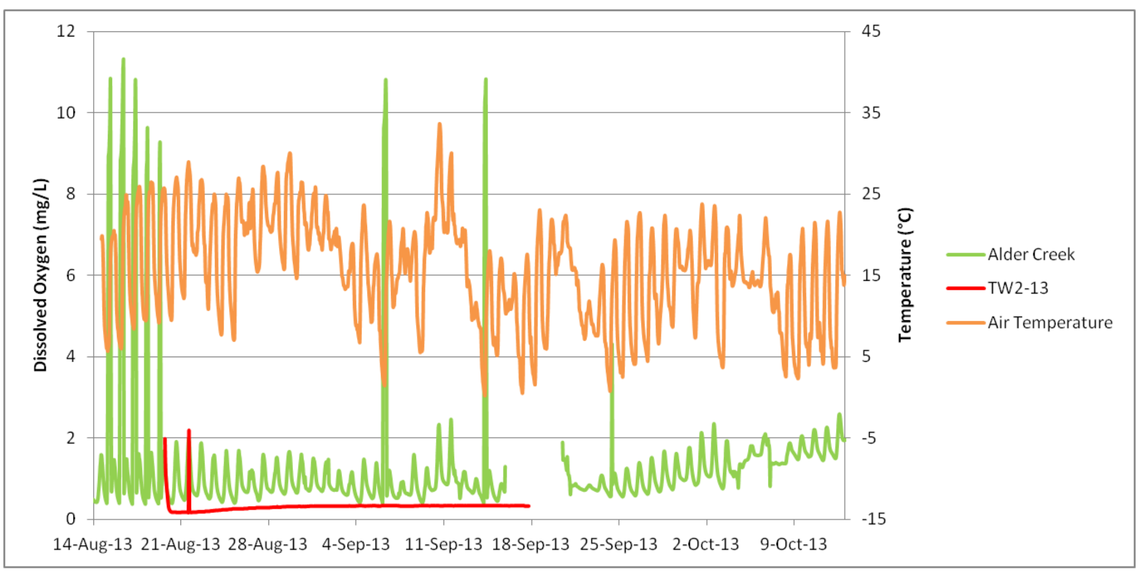


Appendix AI. Dissolved Oxygen Data Figures

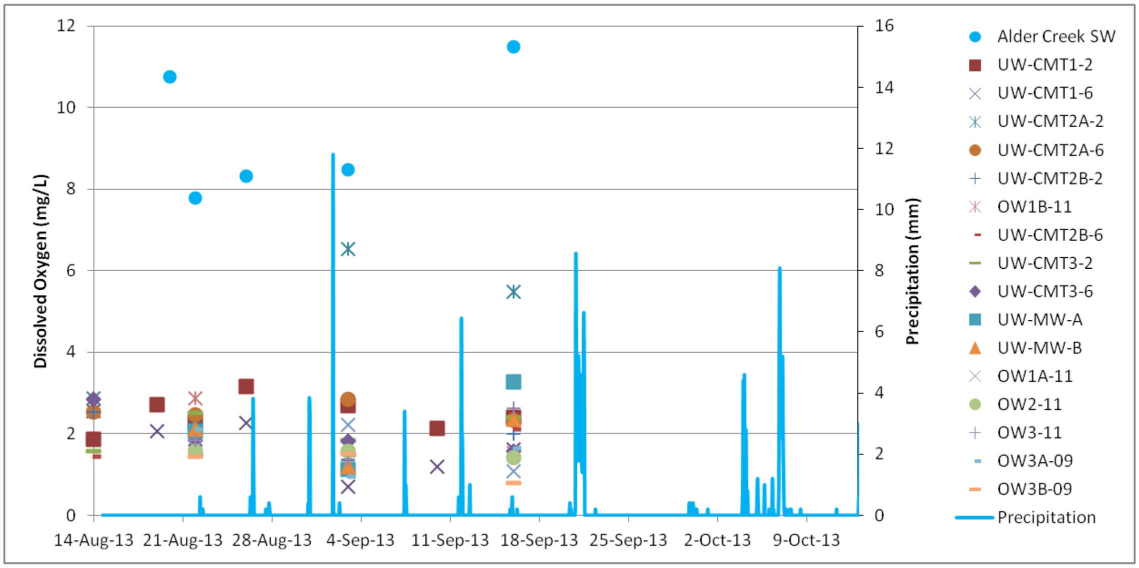
Continuous dissolved oxygen concentration from Sondes measuring Alder Creek and TW2-13 effluent and precipitation data throughout the pumping test.



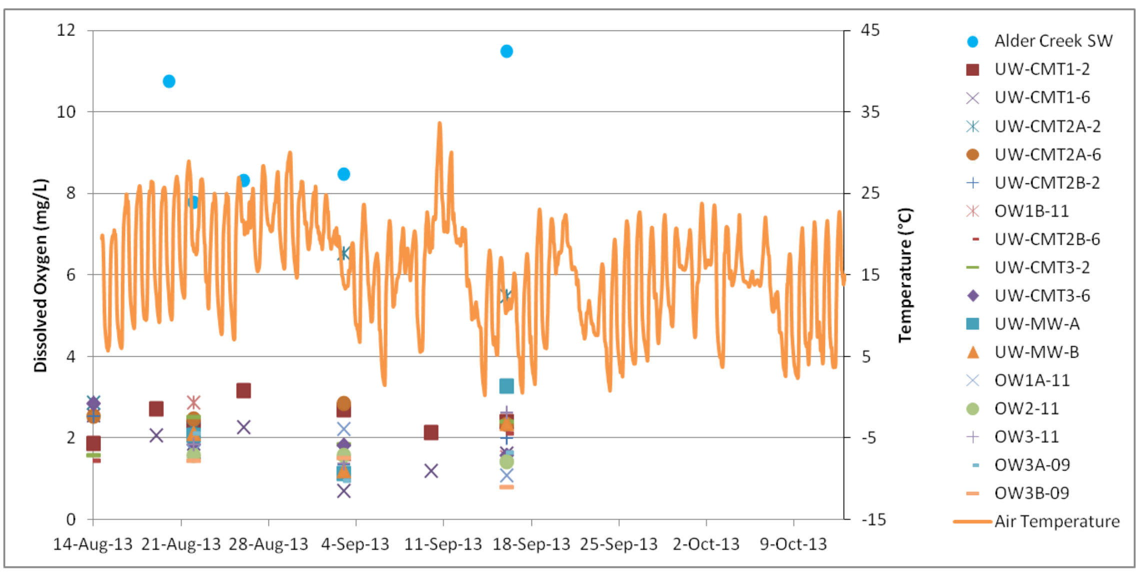
Continuous dissolved oxygen concentration from Sondes measuring Alder Creek and TW2-13 effluent and air temperature data throughout the pumping test.



Dissolved oxygen data collected using the Sonde during sampling events and precipitation data throughout the test.

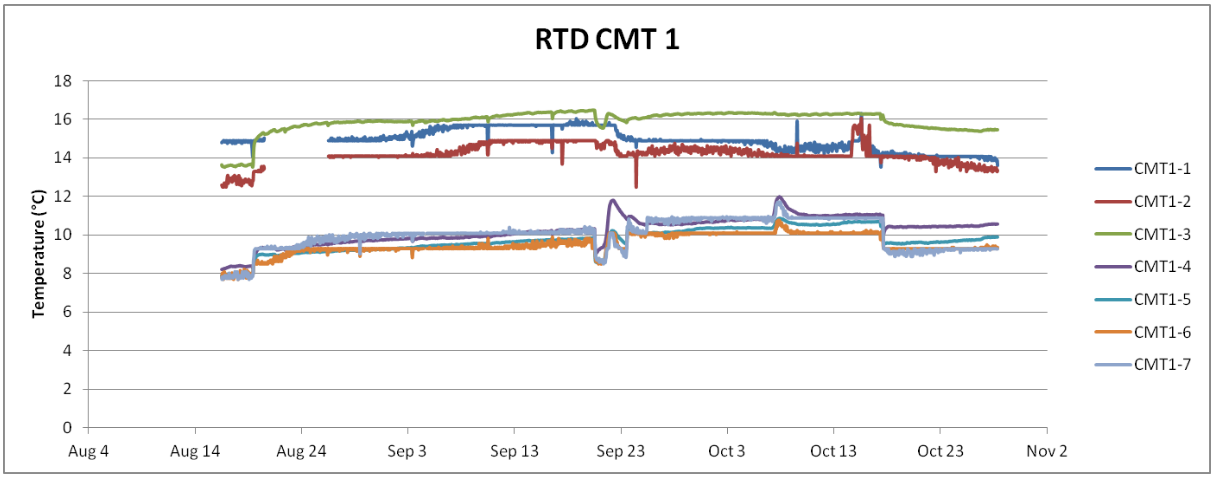


Dissolved oxygen data collected using the Sonde during sampling events and air temperature data throughout the test.

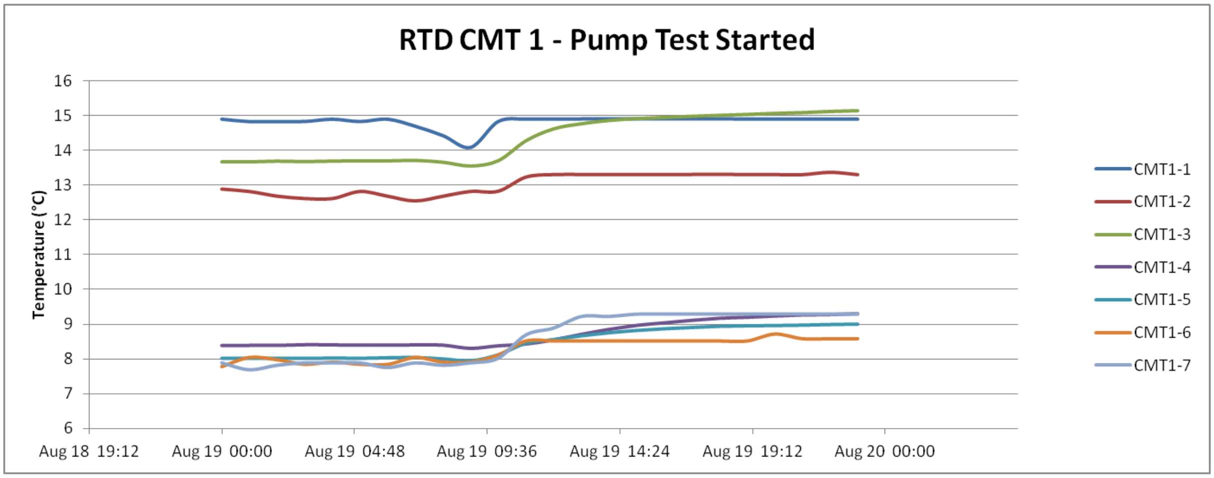


Appendix AJ. Temperature Data Figures from CMT Wells

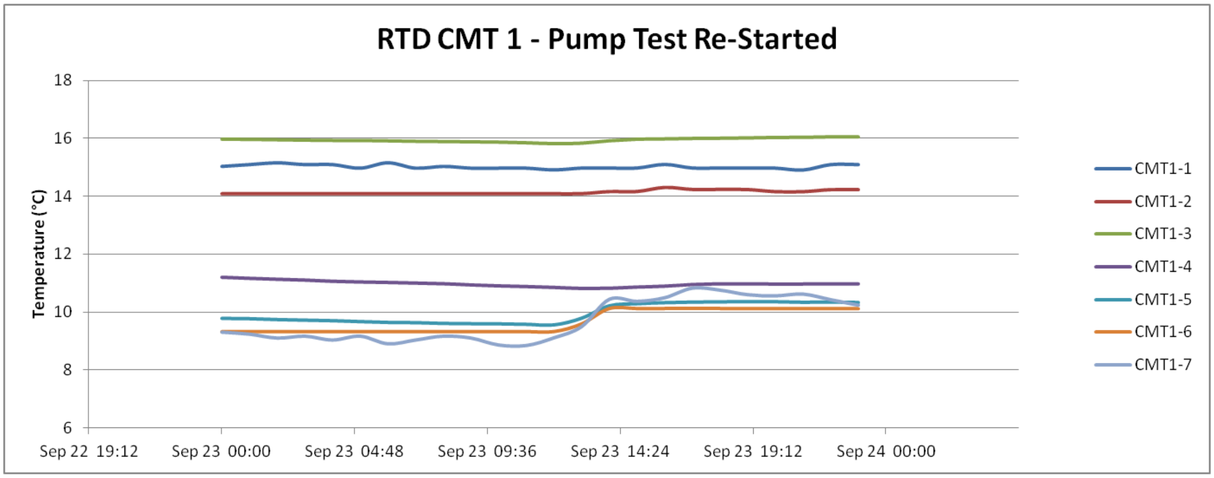
CMT1 temperature data for the duration of the pumping test.



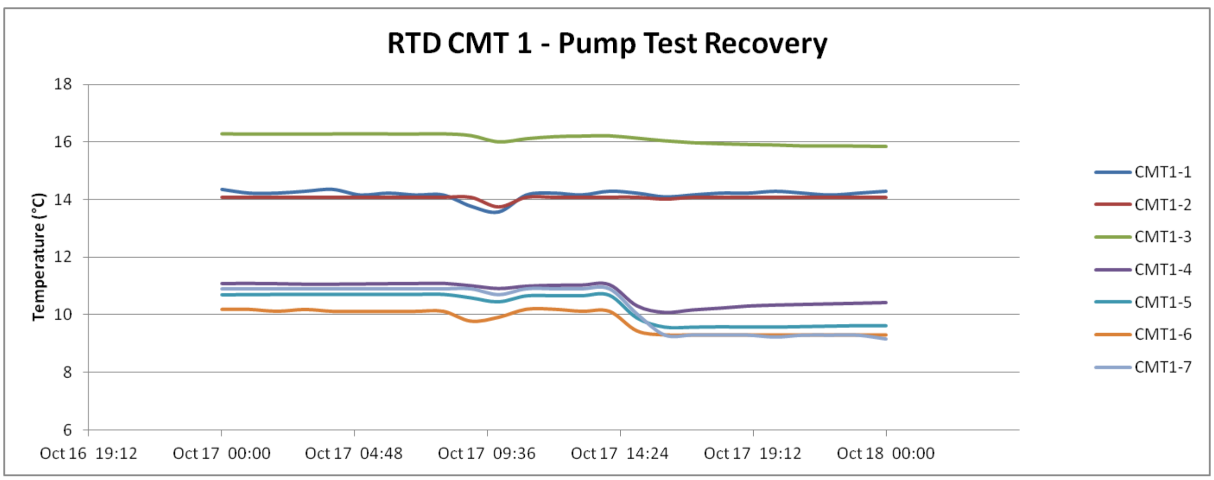
CMT1 temperature data for the start of the pumping test, on August 19, 2013.



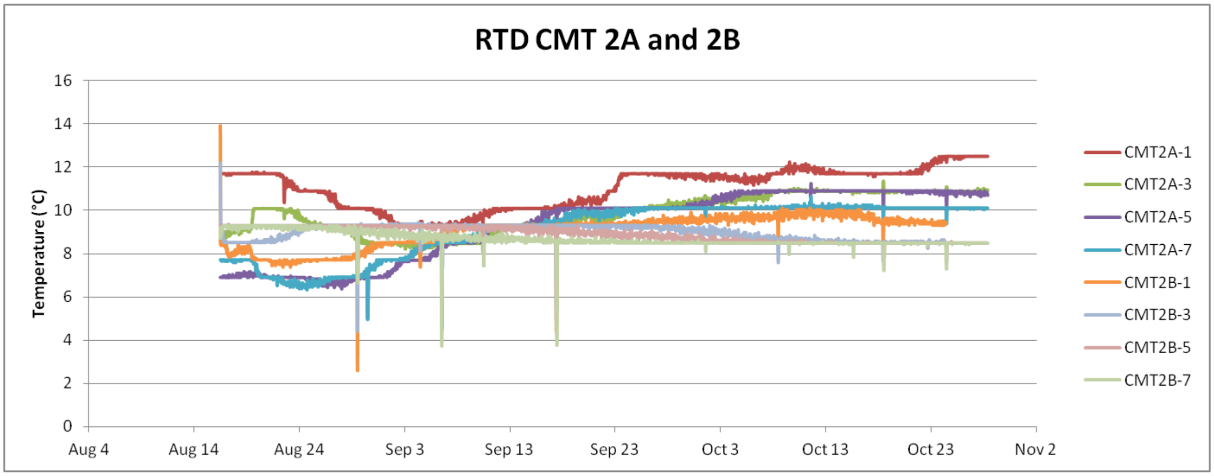
CMT1 temperature data for restarting of the pumping test, on September 23, 2013.



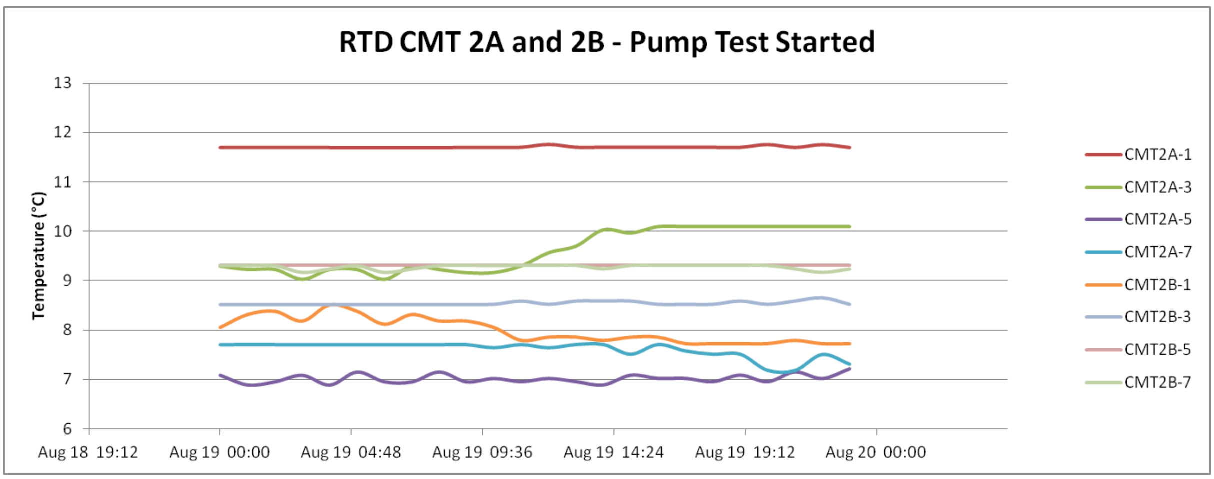
CMT1 temperature data for the end of the pumping test, on October 17, 2013.



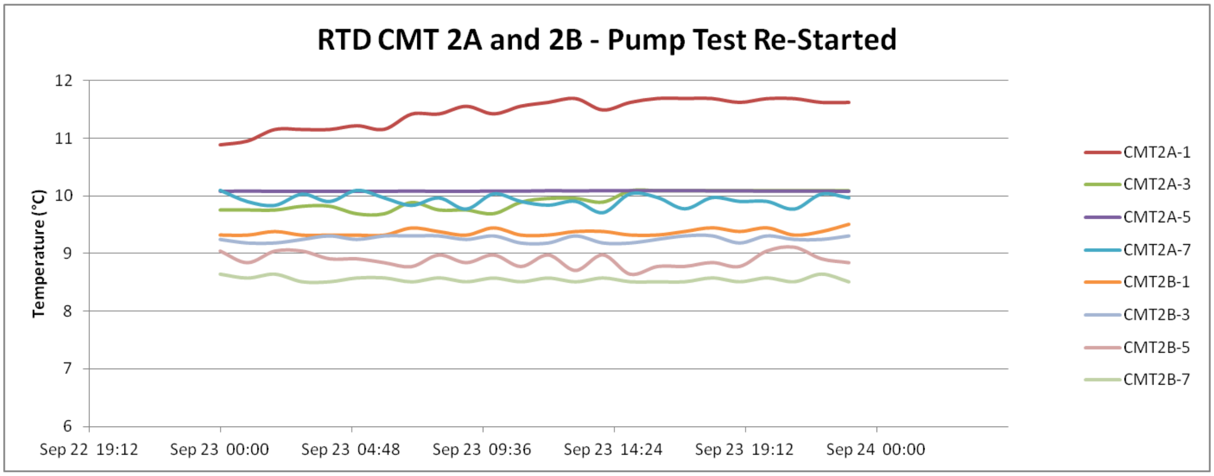
CMT2A and 2B temperature data for the duration of the pumping test.



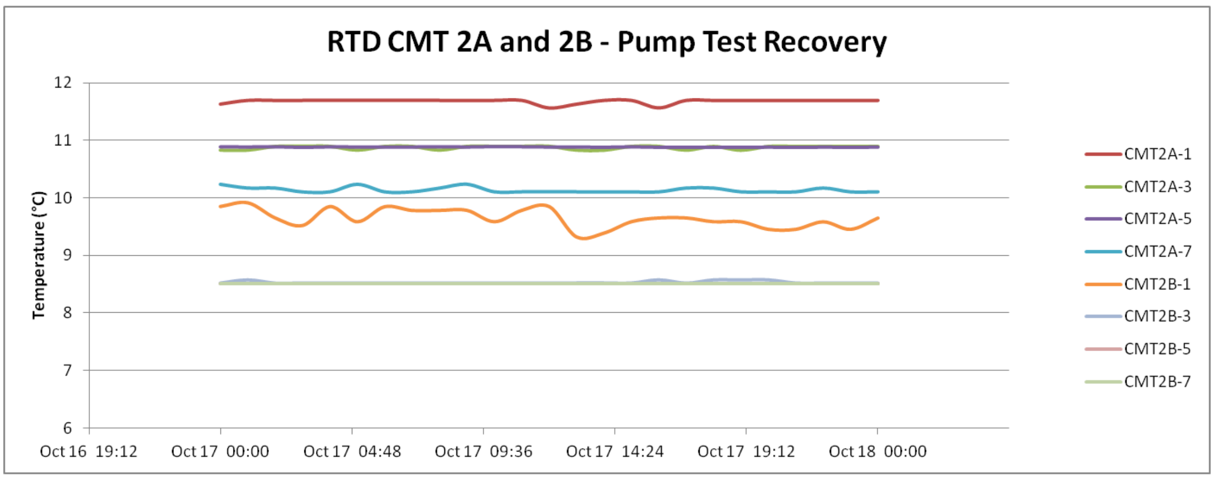
CMT2A and 2B temperature data for the start of the pumping test, on August 19, 2013.



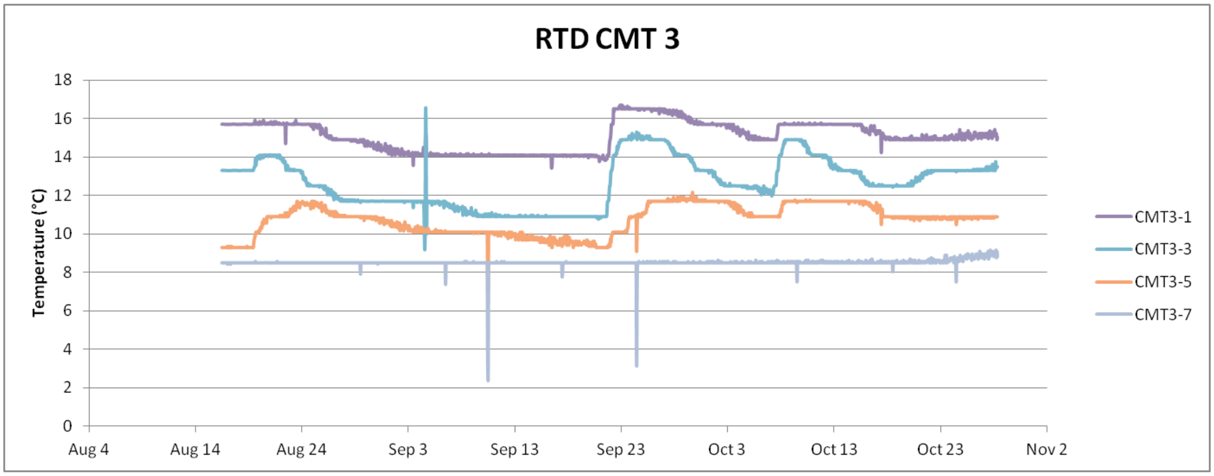
CMT2A and 2B temperature data for restarting of the pumping test, on September 23, 2013.



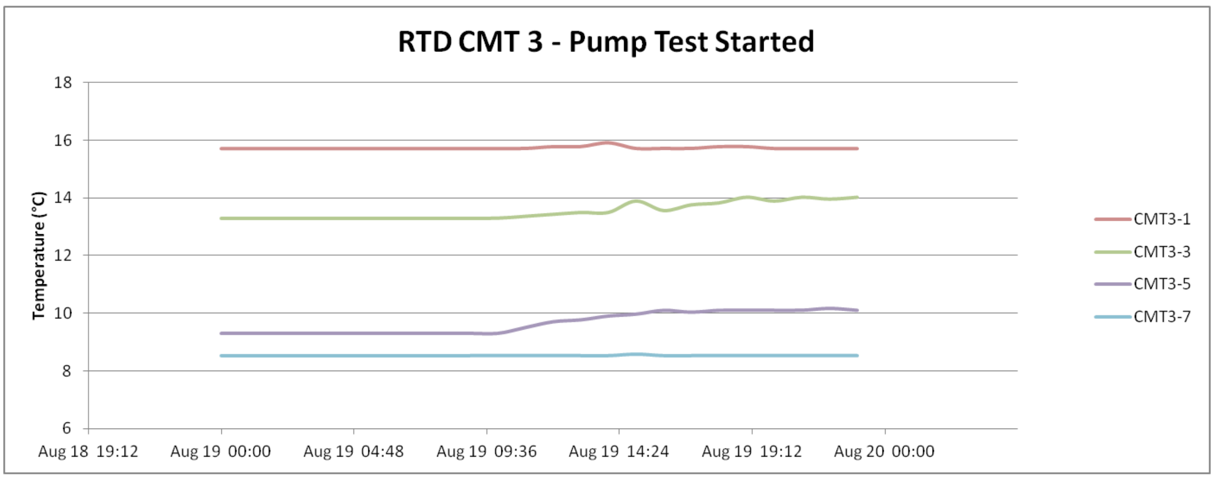
CMT2A and 2B temperature data for the end of the pumping test, on October 17, 2013.



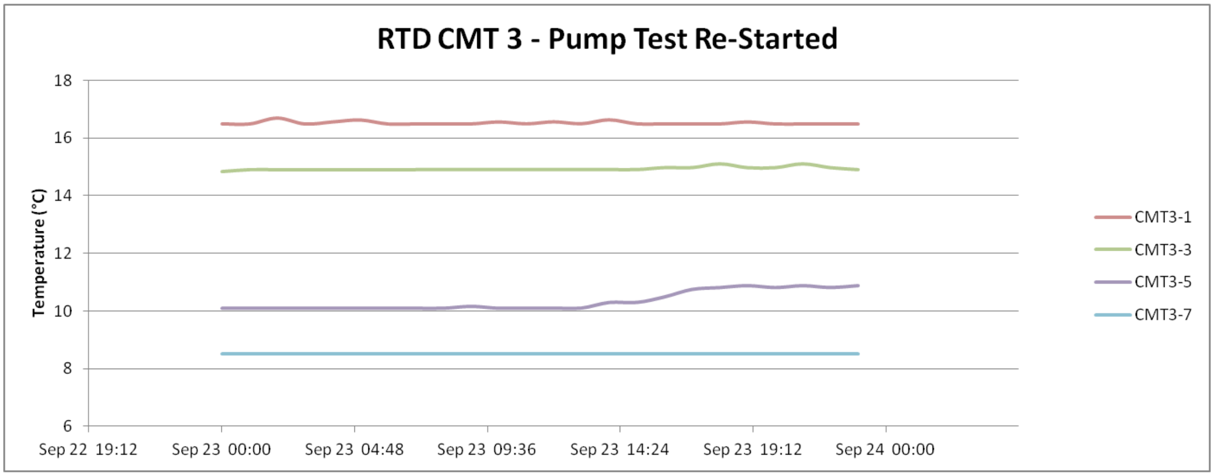
CMT3 temperature data for the duration of the pumping test.



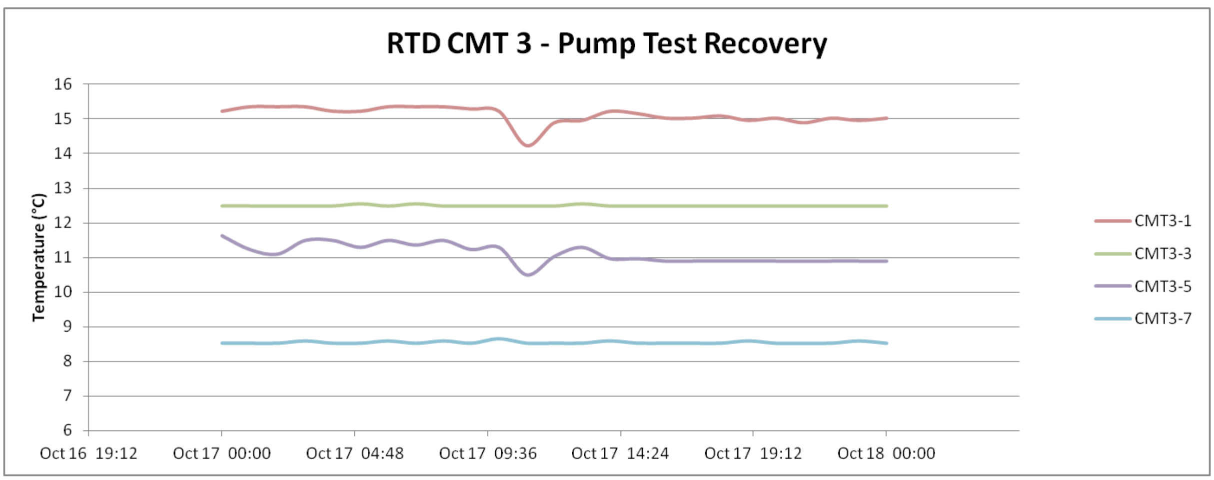
CMT3 temperature data for the start of the pumping test, on August 19, 2013.



CMT3 temperature data for restarting of the pumping test, on September 23, 2013.

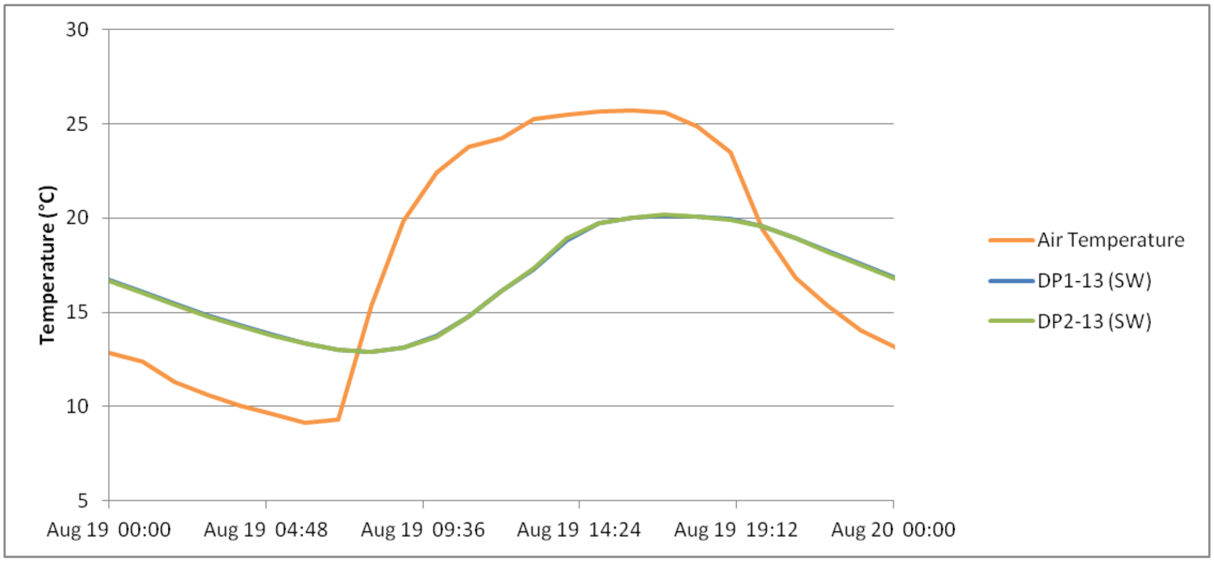


CMT3 temperature data for the end of the pumping test, on October 17, 2013.

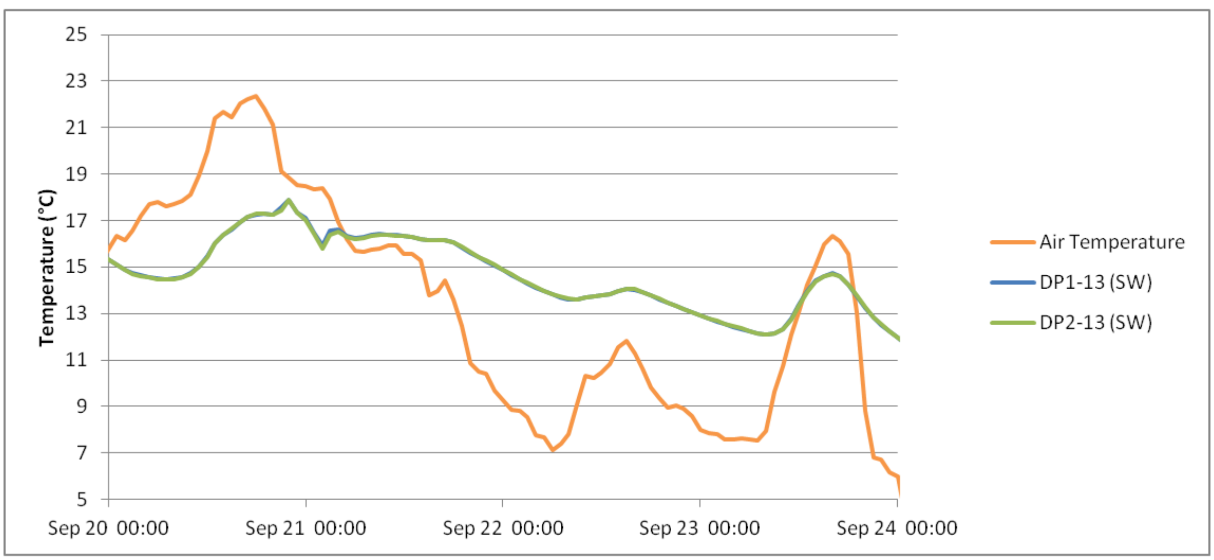


Appendix AK. Temperature Data Figures for Drive Points, Pump Test Well, and Monitoring Wells

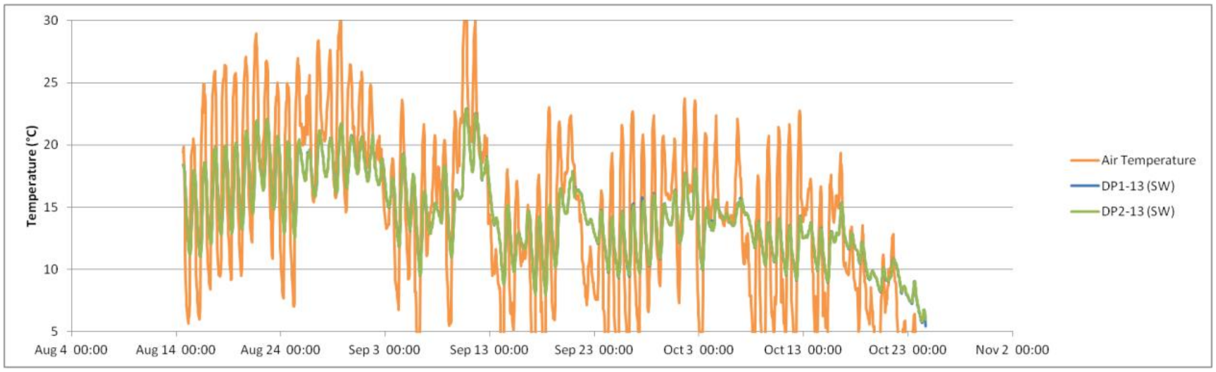
Drive point surface water and air temperature data for the start of the pumping test, on August 19, 2013.



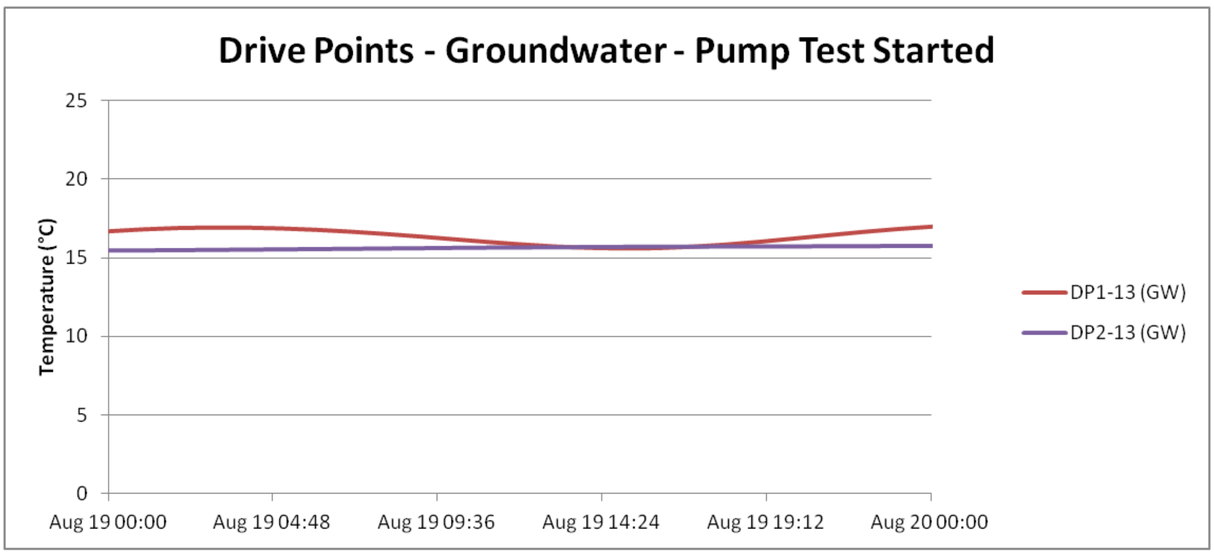
Drive point surface water and air temperature data for mid-test shut off period, from September 20 to 23, 2013.



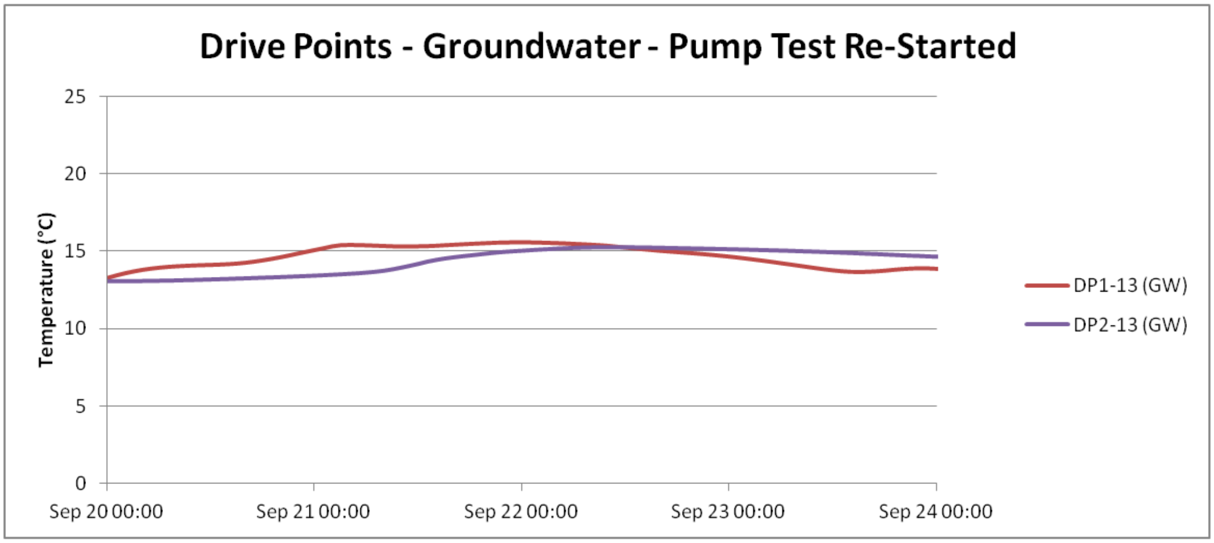
Drive point surface water and air temperature data for the duration of the pumping test.



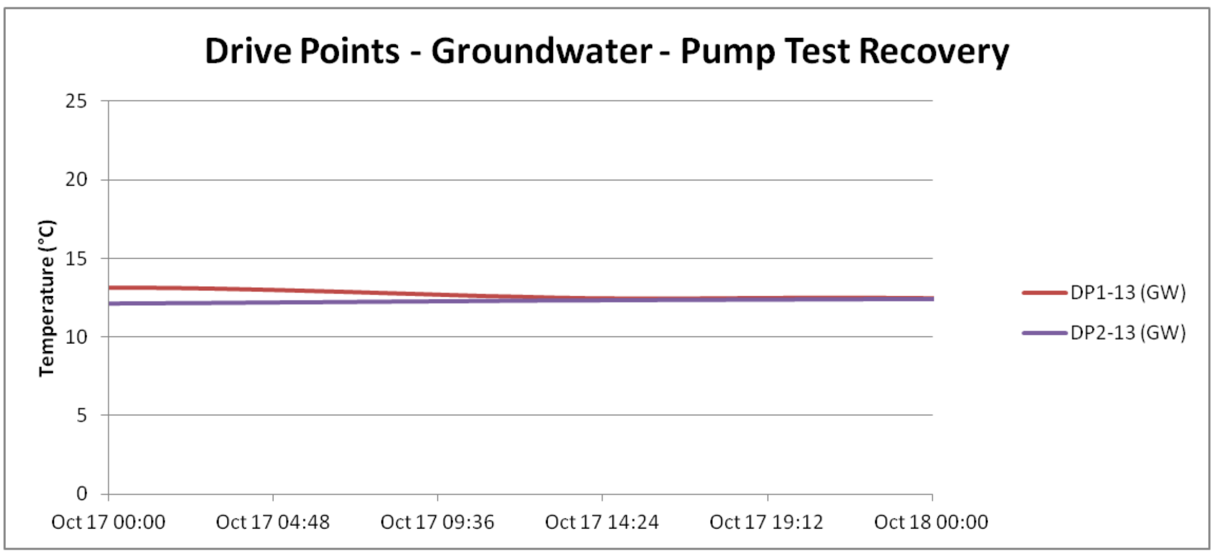
Drive point groundwater data for the start of the pumping test, on August 19, 2013.



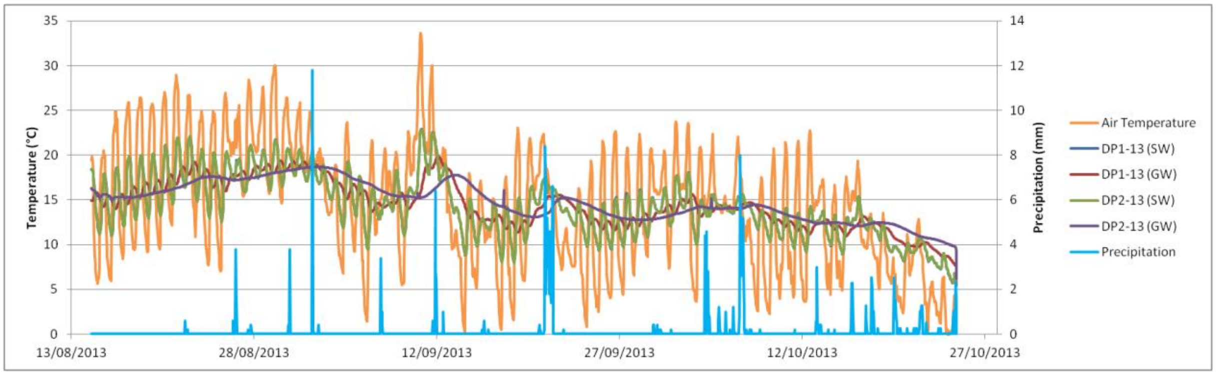
Drive point groundwater data for mid-test shut off period, from September 20 to 23, 2013.



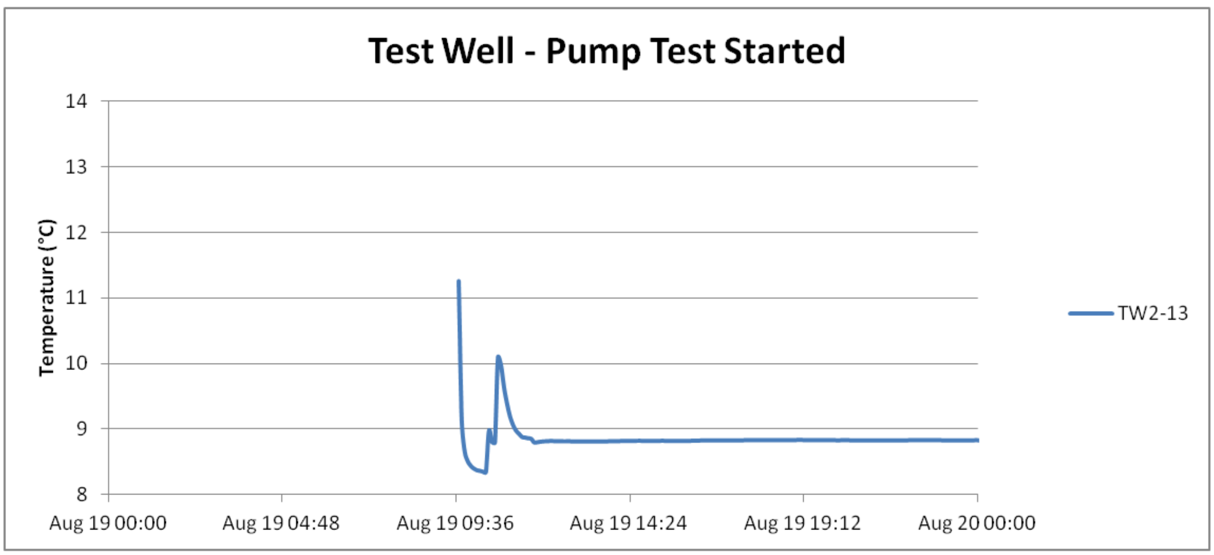
Drive point groundwater data for the end of the pumping test, on October 17, 2013.



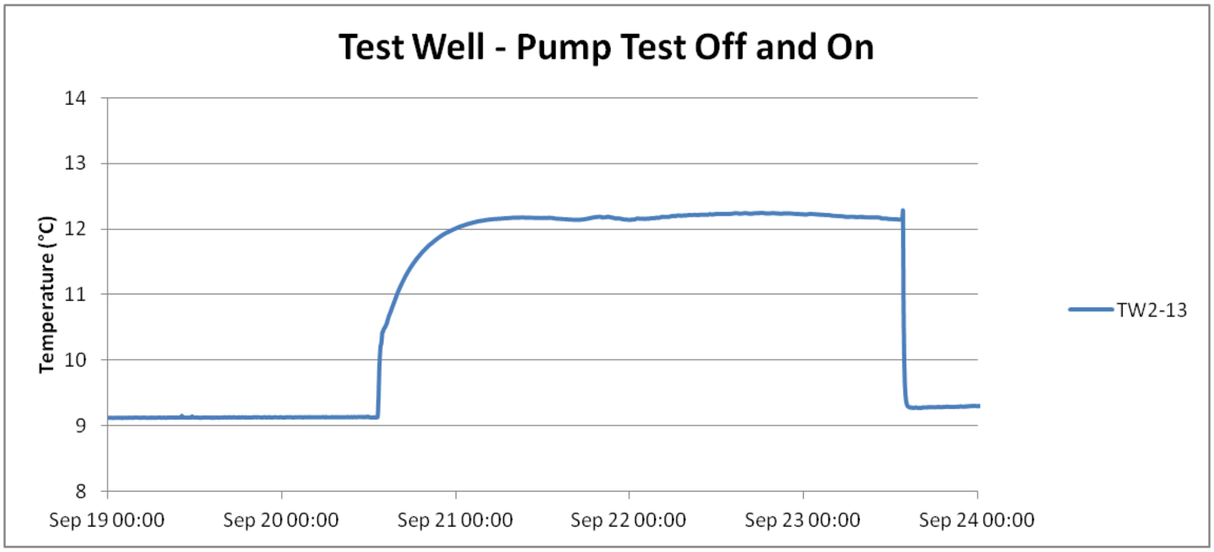
Air temperature, drive point temperature, and precipitation event data from the duration of the pumping test.



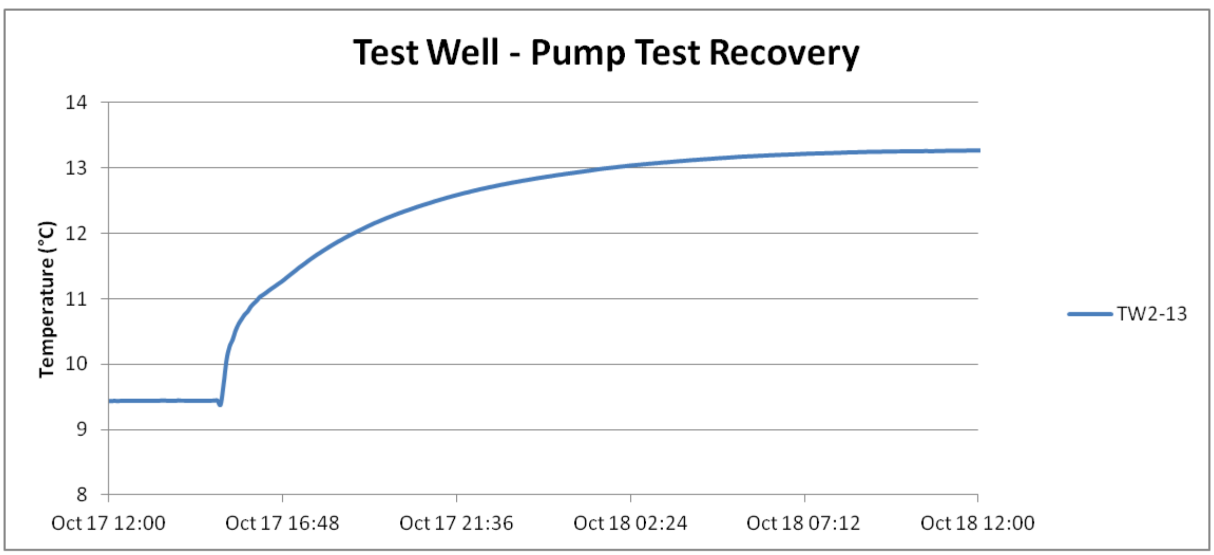
Pumping well TW2-13 temperature data at start of the pumping test, on August 19, 2013.



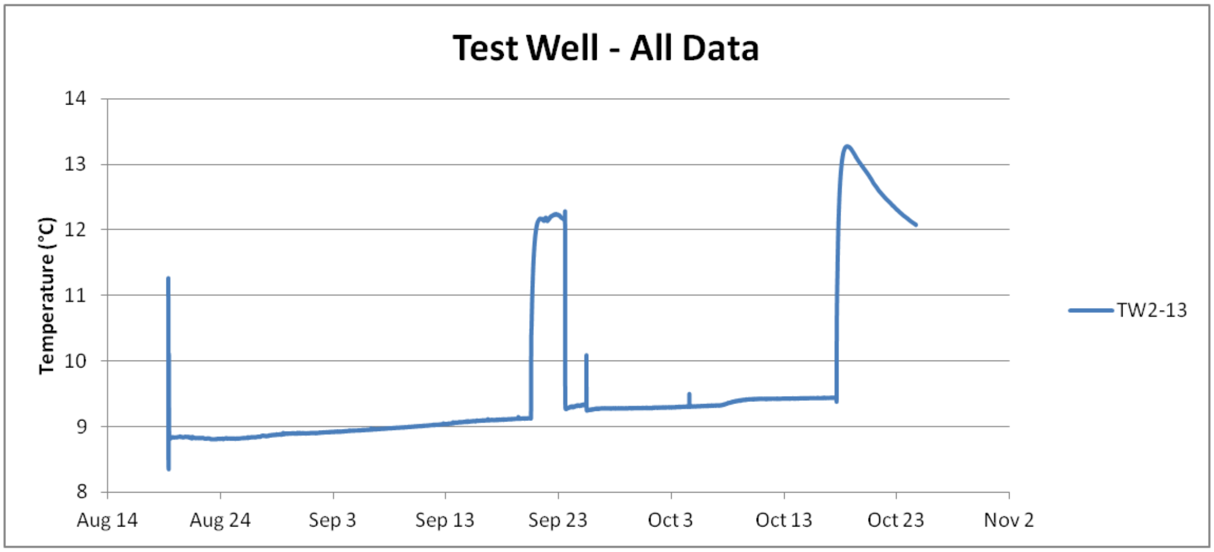
Pumping well TW2-13 temperature data over the mid-test shut off period, from September 20 to 23, 2013.



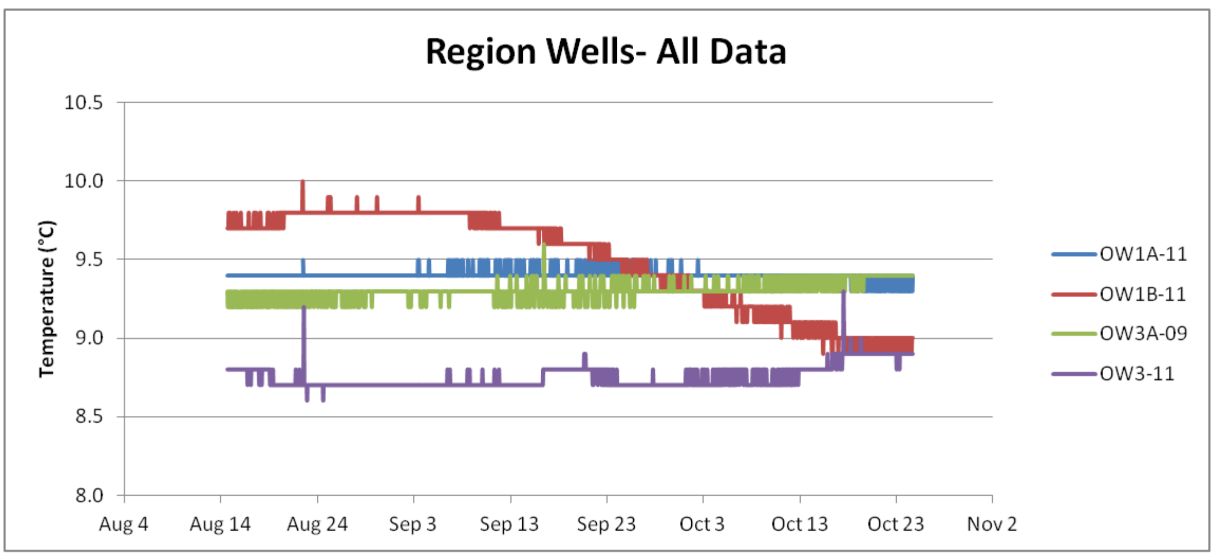
Pumping well TW2-13 temperature data at the end of the pumping test, on October 17, 2013.



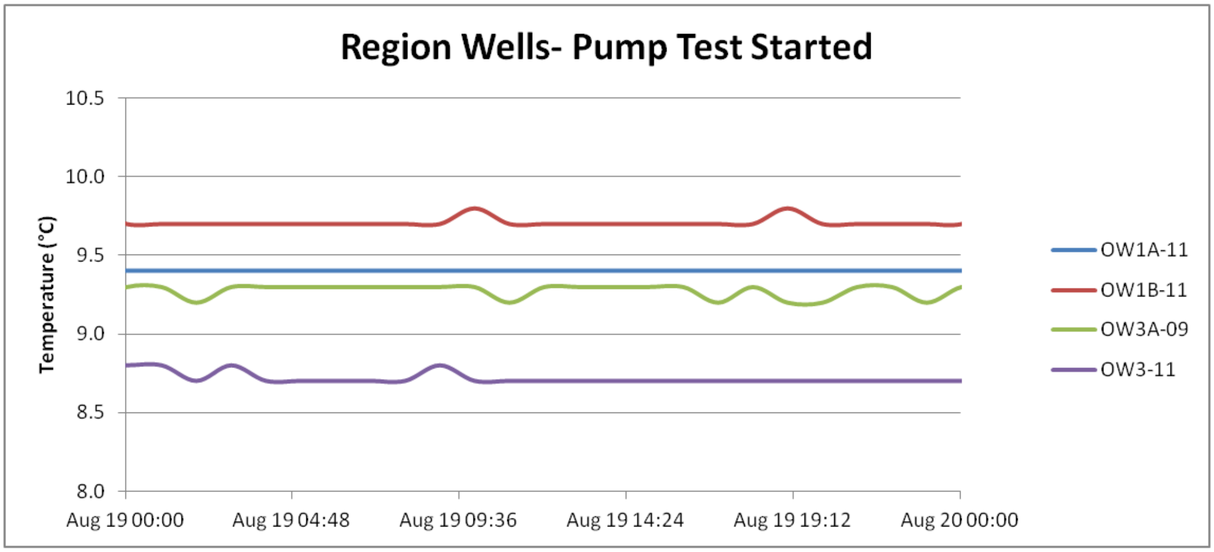
Pumping well TW2-13 temperature data over the duration of the pumping test.



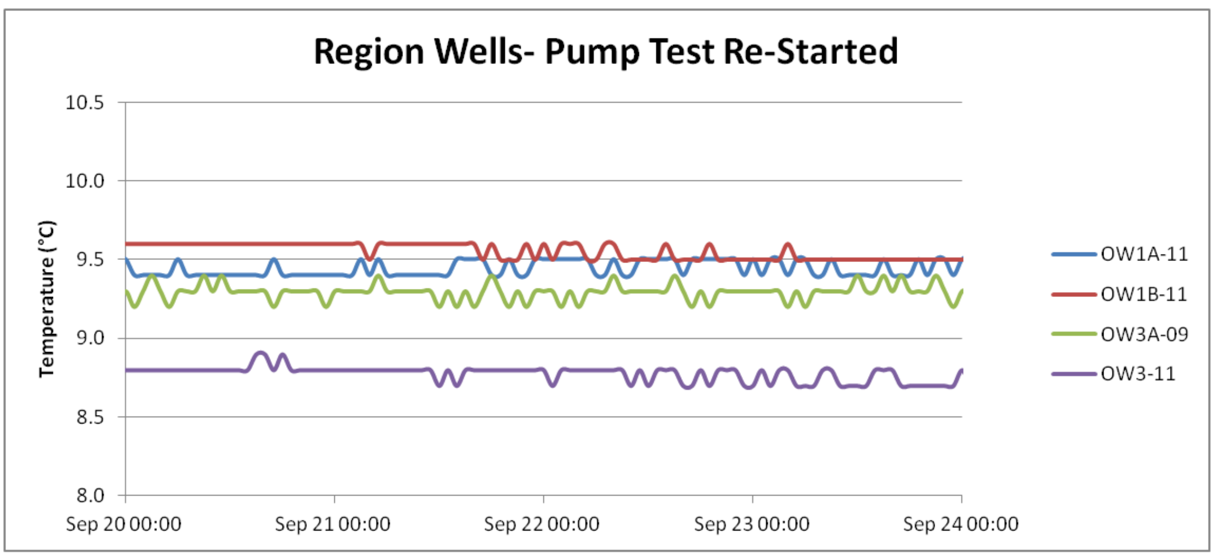
The distant Region wells, OW1A-11, OW1B-11, OW3A-09, and OW3-11, temperature data over the duration of the pumping test.



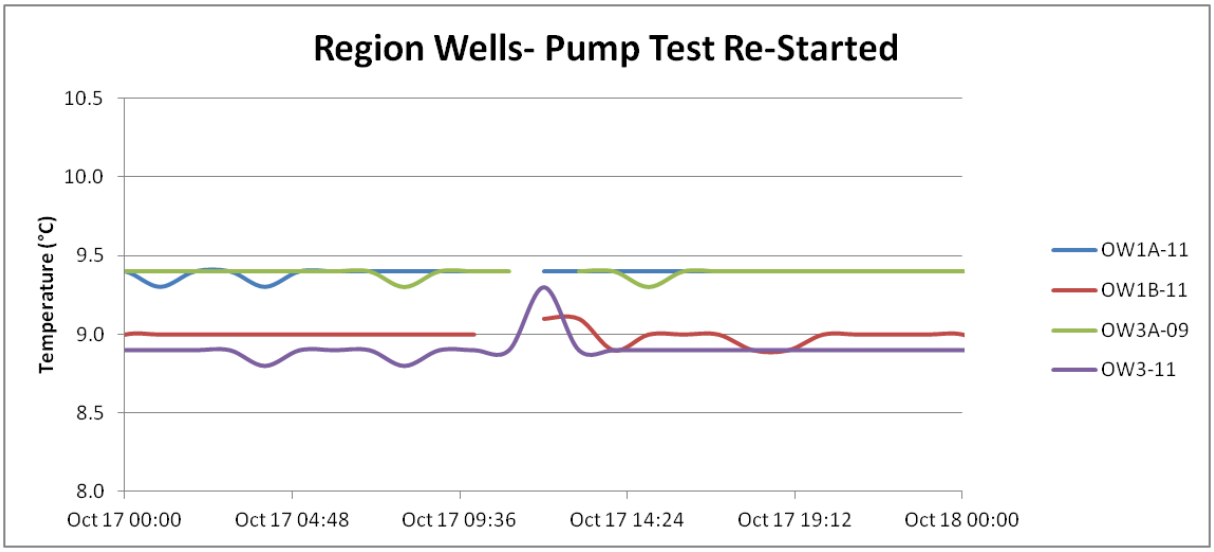
The distant Region wells, OW1A-11, OW1B-11, OW3A-09, and OW3-11, temperature data at start of the pumping test, on August 19, 2013.



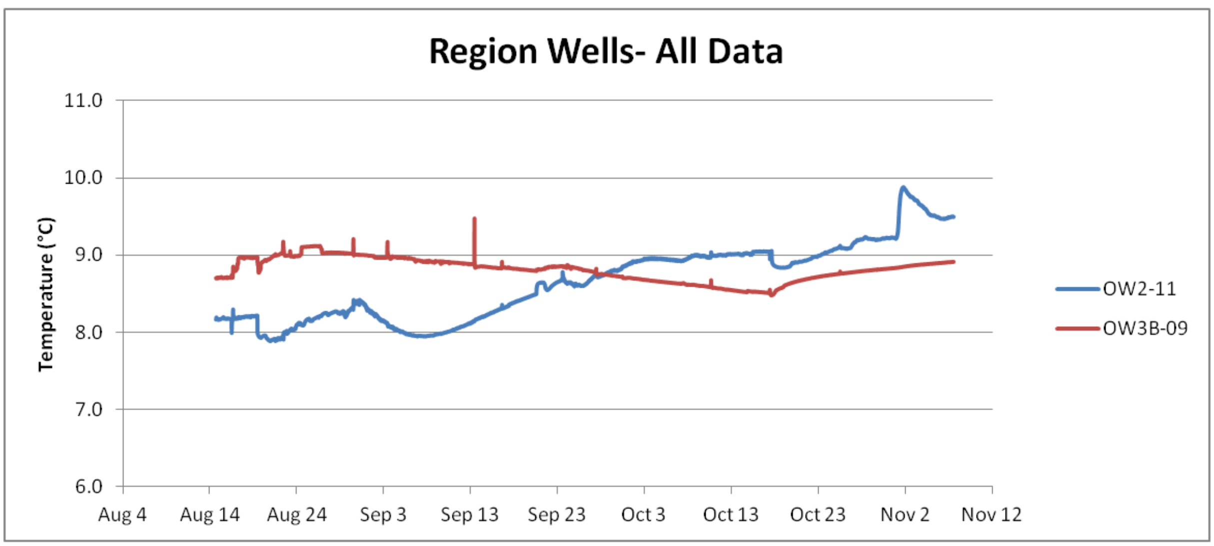
The distant Region wells, OW1A-11, OW1B-11, OW3A-09, and OW3-11, temperature data over the mid-test shut off period, from September 20 to 23, 2013.



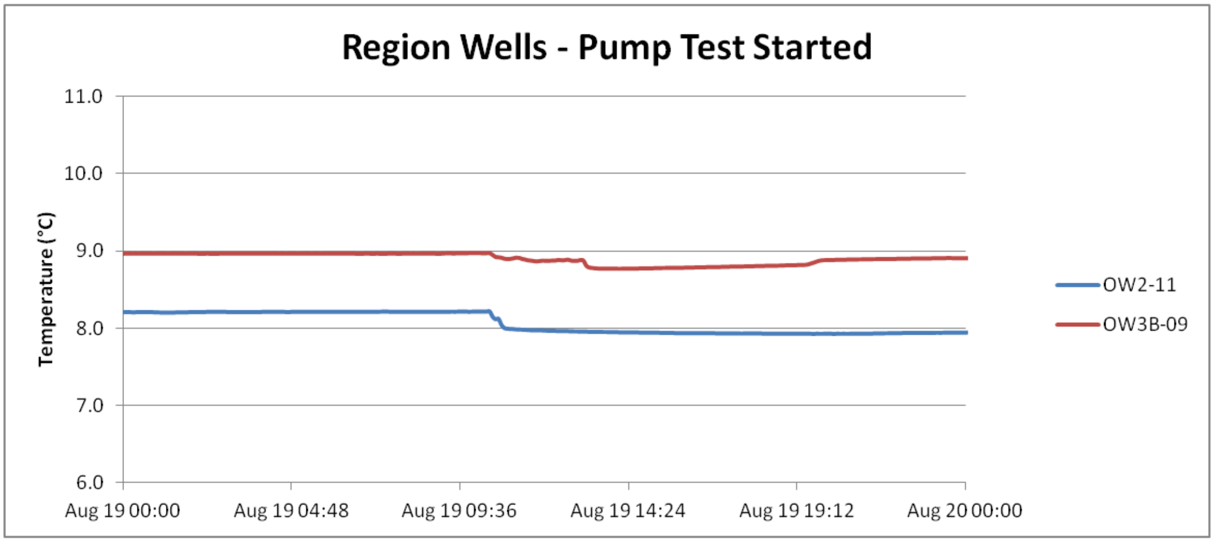
The distant Region wells, OW1A-11, OW1B-11, OW3A-09, and OW3-11, temperature data at the end of the pumping test, on October 17, 2013.



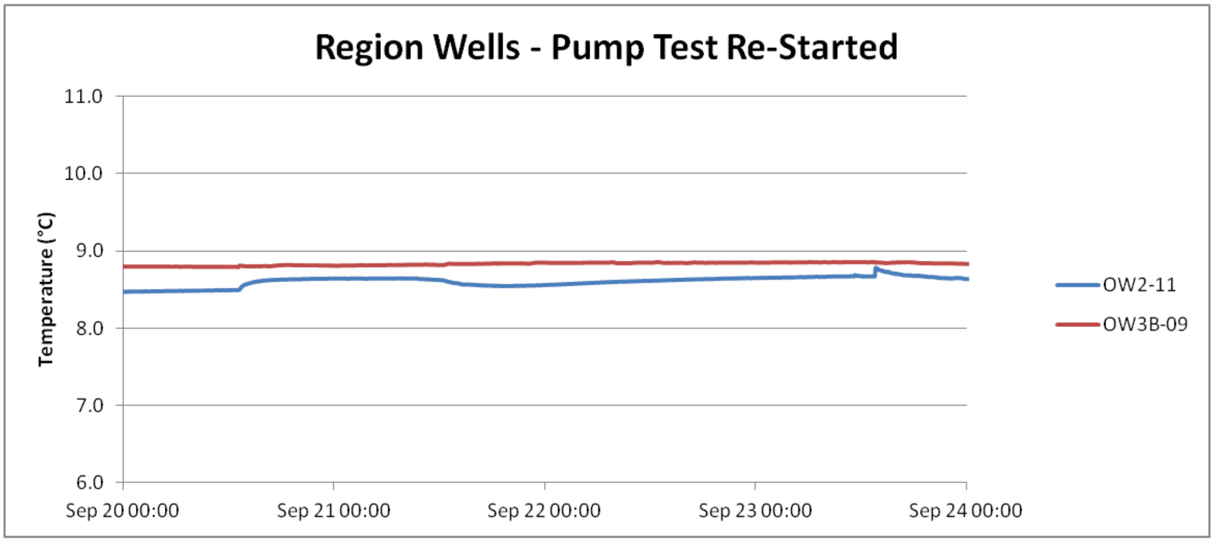
The nearer Region wells, OW2-11 and OW3B-09, temperature data over the duration of the pumping test.



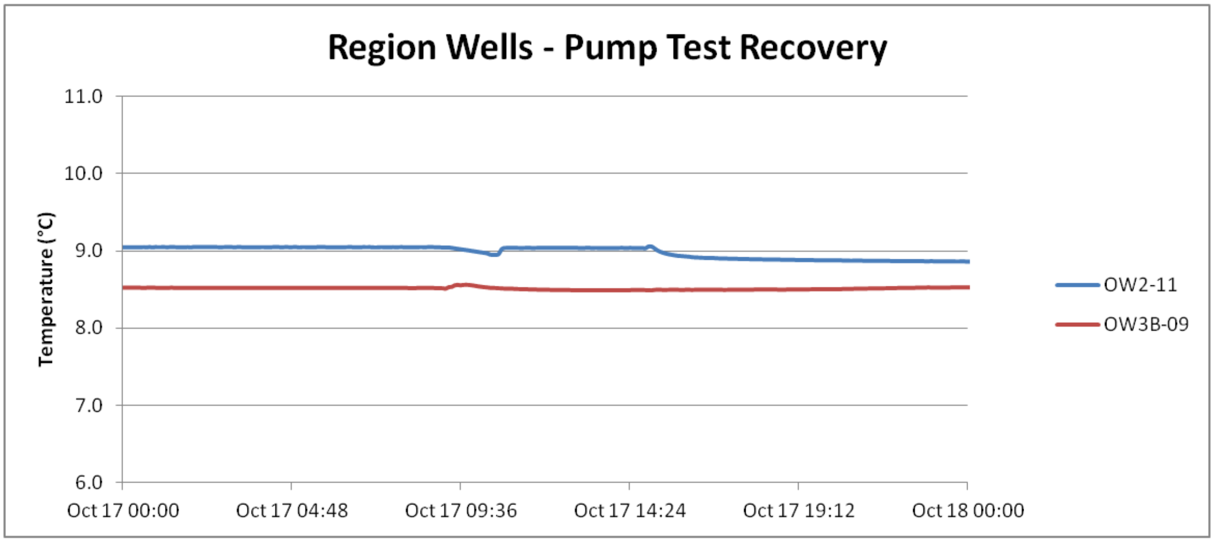
The nearer Region wells, OW2-11 and OW3B-09, temperature data at start of the pumping test, on August 19, 2013.



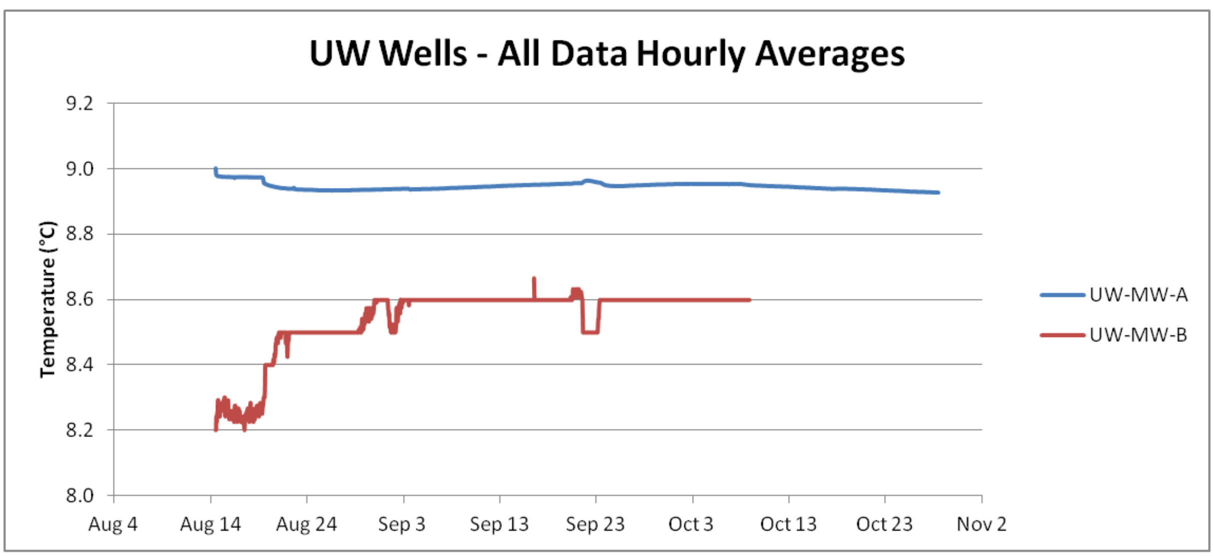
The nearer Region wells, OW2-11 and OW3B-09, temperature data over the mid-test shut off period, from September 20 to 23, 2013.



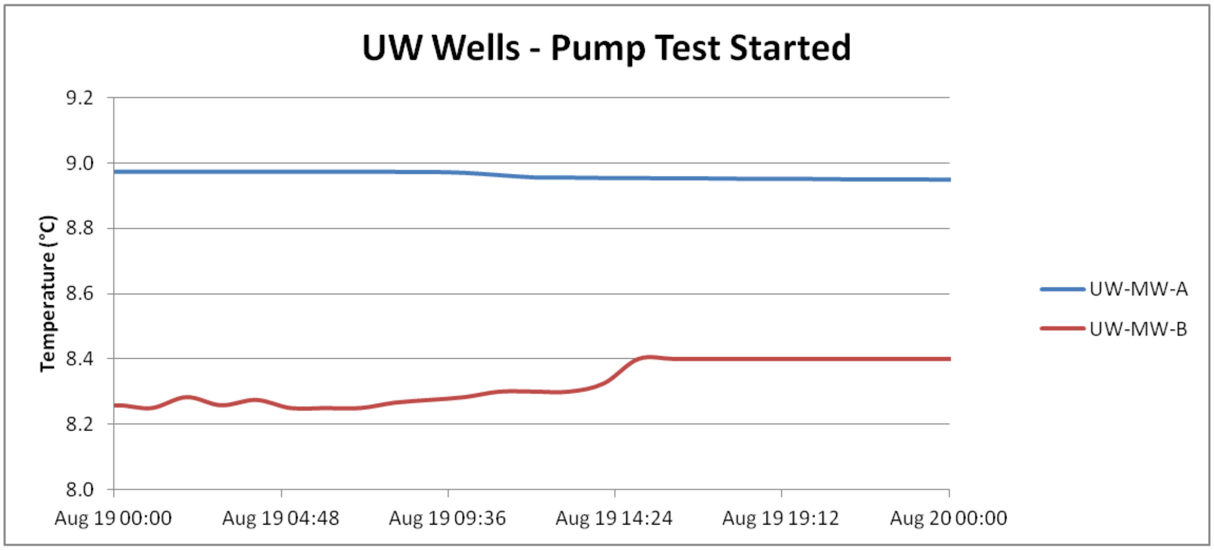
The nearer Region wells, OW2-11 and OW3B-09, temperature data at the end of the pumping test, on October 17, 2013.



Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, over the duration of the pumping test.



Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, at start of the pumping test, on August 19, 2013.



Temperature data from observation wells on the other side of Alder Creek, UW MWA and UW MWB, over the mid-test shut off period, from September 20 to 23, 2013.