AN ABSTRACT OF THE THESIS OF

Cathryn L. Mallonee for the Master of Science
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Title:

Dissolved Silica as an Indicator of ASR Performance in the Chao Phraya River Valley Aquifer, Central Thailand

Abstract approved: ______________________________

An Aquifer Storage and Recovery (ASR) project in the Chao Phraya River Basin in the Sukhothai Province of northern Thailand was conducted to examine the long-term storage of recharge water from the nearby Yom River. Short-term (9 days) and long term (51 days) injection and recovery cycle tests were conducted on both the upper and lower aquifers receiving ASR recharge water. Background groundwater and river samples were obtained and tested prior to commencement of cycle testing from the monitoring and injection wells in both upper and lower aquifers.

Chemical similarities between the recharge water and the groundwater in the upper and lower aquifers necessitated finding a suitable tracing element to support assessment of overall system efficiency and to facilitate delineation of spatial and temporal chemical variations within the aquifer during injection. Silica was examined as an alternative conservative tracer to the commonly utilized chloride, due to similar concentrations of chloride within the stream-aquifer system. Silica was selected due to its non-reactive, ubiquitous, naturally occurring presence in concentration levels significantly higher in the groundwater as compared to the recharge water. In initial ASR tests, chloride concentrations within the recharge water were artificially elevated by the addition of PACl for treatment of turbidity, allowing comparison of the chloride and silica concentrations during four ASR recharge and recovery tests.

During cycle testing, samples were collected from injection and monitoring wells during both the injection and the recovery portions of the tests. Silica and chloride concentrations were evaluated to determine upper and lower aquifer heterogeneity, and the efficiency of the injection system. Similar spatial distribution of concentrations within the aquifers during injection and recovery were observed. Dissimilar concentrations at various stages of recovery may be attributable to aquifer heterogeneity and/or the variations in chloride and silica amounts in the injected water. Total recovered chloride and silica amounts at the end of the tests indicate that both behaved conservatively. When 140% of injected water was recovered, chloride and silica were recovered between 70 to 97%. The results indicate that silica may be a useful chemical tracer in other ASR aquifers, where similar geochemical characteristics exist.

Keywords: aquifer storage and recovery, ASR, silica, chloride, conservative tracer, ASR efficiency.

# DISSOLVED SILICA AS AN INDICATOR OF ASR PERFORMANCE IN THE CHAO PHRAYA RIVER VALLEY AQUIFER, CENTRAL THAILAND

A Thesis

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# CHAPTER 1:   STATEMENT OF PROBLEM AND OBJECTIVES

## 1.1 Introduction

Effective water management is becoming increasingly important as demands on limited hydrologic systems continue to grow. Overburdened surface-water supplies are strained by increased urban and agricultural development. In response, communities are increasingly turning to groundwater to satisfy demands. Reliance on groundwater increases in areas where the population relies heavily on water-intensive crops such as rice to provide basic nutrition, or in geographic regions that are prone to drought. Groundwater supplies are not replenished as quickly as surface water sources. Constant pumping of diminished aquifers results in dry wells, which may require significant capital investment to rectify by drilling deeper. Deeper wells often require the deployment of more powerful pumps to access the limited groundwater supply, further increasing costs.

Geographic regions with extreme hydrologic variability pose a unique challenge to effective water resource management. Affected populations may resort to groundwater pumping to provide water during the annual drought and are later forced to manage an overwhelming volume of water during monsoon season. One possible approach that takes advantage of the excess water during the rainy season and mitigates the impact of pumping during the dry season, is to redirect and store the excess surface water in aquifers.

Aquifer storage and recovery, or ASR, is the injection and storage of water through a well into an aquifer during times of excess precipitation, and recovery of that water through the same well, during times of drought (Pyne, 1995). A two year pilot ASR project has been initiated by the Thailand Department of Groundwater Resources as a means to alleviate flood and drought crises in the Upper Chao Phraya River Basin in the Sukhothai Province of north-central Thailand. Monitoring the movement and recovery of injected recharge water in an aquifer system is a vital component to overall understanding of ASR system function. A conservative tracing element is used to monitor the recharge water during injection and recovery. Chloride is the most commonly used tracer of groundwater and recharge water mixing as it is unreactive in most aquifers. Concentration ranges for chloride in the river and native groundwater at this site overlap, making it difficult to track mixing of waters during ASR testing. A substitute tracer, silica, is being proposed as a possible surrogate. This thesis will test the hypothesis that silica will behave in a chemically similar manner to chloride during injection, storage, and recovery phases of the Sukhothai ASR project.

## 1.2 Objectives

This thesis evaluates a method for monitoring the injection and recovery of water into and out of the aquifer. The natural chloride concentrations within the river water and aquifer at the Sukhothai site are too similar to allow chloride to be used as a conservative mixing tracer. However, due to naturally high turbidity in the river water, the injection water was treated with polyaluminum chloride (PACl). PACl is a coagulant used in water treatment that reduces particulation and raises the pH of the injection water (Engelhardt, 2010). The addition will raise chloride concentration in the recharge water to a level effective for tracing. It is possible, however, that by increasing the pH of the injection water, calcite precipitation may occur resulting pore clogging within the aquifer. If precipitation occurs, a different method of treating the injection water will be required, and chloride will no longer be an effective traceable element, due to the aforementioned geochemical similarities between the injection and native groundwater. The amount of PACl added to the recharge water is not a fixed component at this time, which will also make the chloride concentrations more variable to effective tracing.

A substitute tracer, silica, is proposed as a possible surrogate. The goal of this thesis is to test the hypothesis that silica may be used as an alternative, low cost, non-reactive, traceable species to monitor the infiltration, and recovery of ASR recharge water within the aquifer. Chemical heterogeneity exists within the aquifer which complicates the analysis of any tracer. In addition, variations in the concentrations of the chemical tracers in the injection water can also affect comparisons between tracers. Silica will be considered an effective alternative if its distribution is similar to that of chloride during injection, and if the relative silica concentration in the reclaimed water is within the range of values possible for the relative chloride concentration during the sampling period.

# CHAPTER 2: BACKGROUND

## 2.1 Managed Aquifer Recharge

Managed aquifer recharge (MAR) programs have been implemented worldwide to attempt to recharge overused aquifers with surface water. An international effort, the International Symposium on Managed Aquifer Recharge (ISMAR) conference series was begun in Anaheim, California in August 1988 as the 1st International Symposium on Artificial Recharge of Ground Water (International Association of Hydrologeologists' Commission on Aquifer Recharge, 2013). Managed aquifer recharge (MAR) projects usually consists of surface infiltration pits and/or basins and/or injection wells. Surface water often requires treatment for turbidity before using for recharge. In basin recharge, some natural filtration of the recharge water occurs as it passes the soils before reaching the aquifer. Surface recharge uses large tracts of land, loses moisture due to evaporation, and usually infiltrates the aquifer more slowly than injected water. Surface recharge methods are also limited by the permeability and depth of the aquifer to be recharged.

## 2.2 Aquifer Storage and Recovery

Aquifer storage and recovery, or ASR, is a type of MAR system which uses injection wells to inject and extract recharge water from an aquifer. Some ASR systems utilize existing extraction wells which are then either modified for use as a combined injection/ extraction system, or dedicated injection wells may be added near the existing extraction wells. Newer ASR systems may utilize specialized pumps, which are not only capable of injecting the treated water into the aquifer, but also extracting the stored water via the same pumping system. In such systems, there are usually a number of monitoring wells installed from which water samples may be extracted throughout the recharge and recovery processes. The chemical information from these samples facilitates the tracking of injection-groundwater interactions to identify and attempt to mitigate instances of undesirable chemical interactions.

Injection wells offer a much faster method of moving large volumes of water into the aquifer than using basin filtration. However, management of injection wells is not without problems. Injection recharge may cause well restriction from the occlusion of well screens due to scaling or fouling, Pre-treatment of the injection water may help to ensure compatibility with the native groundwater, and limit bacterial activity within the aquifer.

### 2.2.1 The Use of a Chemical Tracer

The changes in the chemistry of groundwater samples must be analyzed thoroughly throughout the recharge and recovery processes to ensure effective ASR methods for the continued optimal viability of the aquifer. Evaluating the movement and storage of recharge water during and after injection is also of particular importance to modeling the efficiency of recharge water infiltration in the aquifer. The recharge migration of the treated water away from the ASR well during recharge must be monitored to determine the chemical interactions between the recharge water and the aquifer materials, and the advective mixing of the recharge and groundwater. For example, redox conditions will change within an aquifer if the oxygenated recharge water is injected into the more oxygen limited aquifer water. To monitor the distance and amount of mixing occurring, a natural conservative tracer such as chloride is often selected because it is fairly unreactive, is common, and is naturally occurring (Ball and Trudgill, 1997). The other requirement for a tracer is that its concentration in the injected and native ground waters needs to be quantifiably disparate enough that the concentrations of the tracing chemical will change markedly as the recharge water is mixed in with the existing groundwater. During recovery, the migration of the injected water can again be monitored by tracking the percentage of a selected chemical tracer within the recovered water to determine the percentage of injected water recovered. By monitoring the injected and recovered water, a better understanding of aquifer heterogeneity and ASR performance is possible.

## 2.3 Current Aquifer Storage and Recovery Projects in the United States

ASR wells have been used to store and recover water for drinking water supplies, irrigation, and even for ecosystem restoration projects (Environmental Protection Agency, 2013). Injection periods are often limited to times when the recharge water source is a defined amount above normal levels. Flood-stage recharge allows only excess capacity to be used as injection water, thus ensuring that base flow levels downstream are maintained, or reservoirs stay above a pre-determined volume. Storage of the recharge water within an aquifer requires that any chemical interactions which may occur between the recharge water and the existing groundwater and/or the aquifer materials be analyzed prior to initial injection. The recovered water must be monitored to ensure that it meets pre-established quality levels.

A “bubble” or zone of injected water around the well or well field forms within the aquifer for later recovery, but losses may occur due to mixing with the existing groundwater. Injection water that is stored in aquifers which contain lower quality water such as saline waters or highly mineralized waters may not be fully recoverable due to mixing or, if the regional groundwater flow in the aquifer is strong enough, the bubble of injection may move down gradient if stored for an extended period of time.

Managed aquifer recharge projects such as ASR are becoming more prevalent in both United States and internationally. As of February 2009, there were approximately 1200 AR and ASR wells operating or capable of operation in the United States (Environmental Protection Agency, 2013). A few ASR projects are presented for comparison. These established systems illustrate practical considerations that may need to be addressed during the Thailand project.

### 2.3.1 Wichita, Kansas

The Equus Beds aquifer supplies 60% of the water requirements to the residents and farms in and around the area of Wichita, Kansas. The Equus Beds aquifer is approximately 300 feet thick, consisting of alluvial sand and gravel deposits interbedded with clays and silts. It spans and area of 1,400 square miles over four counties in Kansas. A water well pumping field was originally developed by the city of Wichita beginning in the 1940s. By 1992, the water levels within the aquifer had dropped by up to 50 feet (Ziegler et al., 2010).

In response to concerns about the substantial water level decline, saltwater intrusion from nearby oil field brines northwest of the aquifer, and the increasing demands on its available water due to agricultural irrigation needs and population increases, the city of Wichita began its investigation in 1993 into the possibility of an ASR solution to recharge the aquifer and stem the saltwater intrusion into the aquifer (Desilva and Ary, 2011).

The amount of recharge water that may be removed from the river for the Wichita ASR is limited to above base flow volumes due to water rights on the Little Arkansas River. The ASR project must have water flow in Little Arkansas River above 30 cubic feet per second before it may be diverted for recharge purposes. When the Little Arkansas River is above base flow, it is capable of supplying up to 150 million gallons of water per day for recharge (Desilva and Ary, 2011). The water is diverted without pumping into bank storage diversion wells situated immediately adjacent to the Little Arkansas River. This captured water is then pumped into a nearby settling tank for removal of debris and sediment and is then pumped to a surface water treatment plant, where it is filtered through bundles of polypropylene fibers (known as membrane filtration) to remove any remaining solids, bacteria, pathogens and viruses greater than 500 microns in diameter. The filtering system has a lifespan of approximately 10 years. The filtered water is then subjected to an advanced oxidation process, (AOP), which uses ozone and hydrogen peroxide to break the bonds between organic chemical contaminants in the water. Ultra violet radiation also applies energy to the photolysis process which speeds up the oxidation process and increases the rate of decay. The chemicals break organic bonds at a faster rate than if just exposed to oxygen, thus destroying remaining viruses and organic molecules such as atrazine which may be present due to agricultural runoff into the river. After treatment, the recharge water meets EPA drinking water standards. It is then pumped to various injection wells back into the aquifer via injection pumps arrayed across the Equus Beds aquifer.

The Wichita ASR project is a multiphase undertaking which is currently nearing the end of its 2nd phase of development. There are currently 31 recharge/recovery wells, 20 pumping wells, and two river diversion systems with 5 pumps capable of pumping 33 million gallons per day (MGD). Future phases include the development of a system capable of recharging an additional 60 million gallons of water per day. The estimated total cost for the ASR system over time is projected to be $236,517,100 (U.S Dept. of Interior, 2009).

### 2.3.2 San Antonio, Texas

The Twin Oaks ASR project in San Antonio, Texas is intended to store excess Edwards Aquifer capacity during the rainy season for recovery during the dry summer months. The Edwards aquifer supplies over 90% of the water used by San Antonio. Rights to the waters within the Edwards aquifer vary depending on drought restrictions. In order to mitigate water shortages during periods of stress, the San Antonio Water System has undertaken an ASR project which allows the city to remove water from the Edwards aquifer when greater withdrawal rights are available, and store that water within the Carrizo aquifer beneath nearby Bexar County. The stored water is recoverable during the drier summer months when the Edwards aquifer rights are depleted. As of October, 2012, more than 29.6 billion gallons of water was being stored in the Carrizo aquifer (Malcolm Pirnie, Inc., 2012).

Up to 30 million gallons per day (MGD) of water can be extracted and pumped from the Edwards aquifer in San Antonio to the ASR well field overlying the Carrizo-Wilcox aquifer south of the city. The initial plan was to pump water out of the Carrizo-Wilcox aquifer to be replaced by higher quality water from the Edwards aquifer. Nearby landowners were concerned about their pumping rights in the Carrizo-Wilcox which resulted in plan alteration. It was eventually determined that storage would commence without pumping out existing water from the storage aquifer. The Edward’s recharge water is injected into the semi-confined sand aquifer. Before injection, the water is treated to meet EPA drinking water standards. There are a total of 29 high capacity ASR wells and three Carrizo-Wilcox pumping wells. Recharge capacity of these wells is between 1200 to 2000 gallons per minute (Malcolm Pirnie, Inc., 2012).

Differences between the Edwards aquifer native groundwater and that in the Carrizo-Wilcox aquifer require treatment of the recovered water before distribution to the city of San Antonio. The Carrizo-Wilcox aquifer has water with a natural pH of 5.5 and somewhat elevated concentrations of iron, manganese and hydrogen sulfide. So far, the recovered water from the ASR wells has not required retreatment other than disinfection. Due to increased water volumes in the Carrizo-Wilcox aquifer, there has been migration of the recovered water into areas not covered by the San Antonio water system agreement. Water pumped for irrigation to the west of the storage area has been of a higher quality than had been previously pulled from that area indicating migration of the water bubble of the injected water. The maximum volume of water which can be stored within the Carrizo-Wilcox aquifer is not known. Texas law allows for recovery of an equal volume of water plus an additional amount of water native to that aquifer. The native water is of lower quality and must be fully treated prior to distribution (Malcolm Pirnie, Inc., 2011).

The cost of the ASR project has been more than offset by the dollars that would have been associated with purchasing water from outside sources. The Texas Water Board estimated that by the year 2008, it had spent roughly $238,000,000 to implement the Carrizo-Wilcox ASR system. During that same period they would have required $600,000,000 to purchase additional water allocations from the Edwards aquifer, the net difference being a savings of $362,000,000 (Malcolm Pirnie, Inc., 2011).

### 2.3.3 Las Vegas, Nevada

The ASR system in southern Nevada began in 1987 as a means to maximize the use of water rights. Before recent changes in law, the excess water rights from the Colorado River could not be stored at Lake Mead. In order to utilize these water rights and not lose them, the Las Vegas Valley Water Authority, (LVVWD, 2011) began injecting this excess water into the principal aquifer underlying the valley. Injection water is solely supplied by the Colorado River. LVVWA treats and returns most of its wastewater back to the Colorado River at Lake Mead, and is able to receive a return flow credit for the returned treated water. By returning most of the water to Lake Mead, the area is allowed to take or divert the amount it has returned (in addition to its allocation of 300,000 acre-feet per year as permitted by Federal law). This excess water was stored via an ASR system beneath the Las Vegas area. The Southern Nevada water Authority, SNWA is a branch of the Las Vegas Valley Water District. The cities of North Las Vegas, Las Vegas, Henderson, Boulder City, as well as the Park Service and Nellis Air Force Base all participate in this system.

There are three major aquifer zones in the Las Vegas Valley, ranging from 300 to 1500 meters in depth. They are part of the carbonate rock aquifer of the Great Basin System in Nevada and Utah. The Great Basin is a thick sequence of limestone and dolomite with some shale and sandstone. This large, regional aquifer is composed of several flow systems which are recharged in the higher altitude mountains and basins and discharged into large springs in the lower altitude basins (Schaefer et al., 2006). The Las Vegas Valley encompasses approximately 1,600 square miles in southern Nevada. The Las Vegas Valley is located in a transition zone between the Great Basin province and the northern Mojave Desert (LVVWD, 2011). The valley is primarily an alluvial basin oriented northwest to southeast with colluvium nearer the surrounding mountain ranges. The northern and western mountains are predominantly composed of Paleozoic carbonate rocks with some Mesozoic clastic sediment. The eastern and southern ranges are largely of volcanic rocks of basaltic to rhyolitic composition.

Since its inception, more than 104 billion gallons (365,088 acre-feet) of water have been injected into the aquifer, realizing a recovery of over 110 feet of water depth within the aquifer. Injection into the aquifer is usually done during the period of October through April when water needs of the valley are less intensive. The maximum monthly injection into the aquifer occurred in January, 2004 when one hundred million gallons per day of water were injected through 60 wells throughout the aquifer (LVVWD, 2012).

The Las Vegas Valley water district is permitted for 78 recharge/recovery wells although not all of these wells are currently used. 35 of these wells have been converted into dual use wells capable of both injection and recovery. The wells are situated in the central and northwestern parts of the Las Vegas Valley where hydrogeologic conditions are more favorable for pumping and injection. The system is capable of injecting 100 MGD (LVVWD, 2011). Recovery capacity is up to 157 MGD (LVVWD, 2011). The water rights system in the state of Nevada is set up such that any water rights which are not utilized within the calendar year are lost at the end of that year. The program allows water to be stored for future use as well as providing replenishment of the aquifer and management of groundwater levels. Nevada Division of Environmental Protection (NDEP) and Nevada Division of Water Resources (NDWR) have regulatory authority over the artificial recharge program. Since December, 2011, no additional water has been injected into the aquifer system. Legislative changes to the Colorado River rights were altered so that excess water rights could be stored within Lake Mead. Due to the costs associated with pumping and treating the excess water from Lake Mead to the injection wells throughout the Valley, as well as the fact that the aquifer levels had been substantially restored, the LVVWA decided to discontinue the groundwater injection in January, 2012. The infrastructure is still available should injection be required at a later time.

### 2.3.4 Orange County, California

The Groundwater Replenishment System (GWRS) in Orange County, California is the largest purification system for potable water reuse in the world (GWRS, 2003). This system involves a process of microfiltration, reverse osmosis, and treatment with ultraviolet light and hydrogen peroxide to purify wastewater that would have otherwise been discharged into the Pacific Ocean. Instead the purified wastewater is injected into a seawater barrier system and into the water recharge basins which naturally percolate back into a water basin underlying northern and central Orange County. The project was conceived as a cooperative effort between the Orange County Water District (OCWD) and the Orange County Sanitation District (OCSD), in order to solve issues plaguing both groups. The OCSD needed to build a second ocean outlet to dispose of treated wastewater, and the OCWD had issues with both saltwater intrusion into the water basin and dwindling water availability. Together, the two entities conceived of the GWRS to effectively address both issues. By treating the wastewater to such a degree that it met, and surpassed, drinking water standards, they were able to reroute waters that would have been discharged into the ocean into both a water basin recharge system and a saltwater intrusion barrier. By implementing this project, Orange County is able to supplement its water supply using less than half of the energy than would be required to import water from other parts of the Southern California area, and less than one third of the energy required to desalinate an equal volume of ocean water (Orange County Water District and Orange County Sanitation District, 2003).

Purification of the wastewater is a three step process beginning with membrane filtration. The secondary wastewater obtained for the OCSD passing through bundles of polypropylene fibers which remove suspended solids, protozoa, bacteria and even some viruses which are larger than 0.2 microns in diameter. In order to maintain optimally efficient pressure within the filtration system, the fibers are backwashed every 22 minutes and are chemically cleansed every 21 days. After passing through the filtration process, sulfuric acid is added to the water before it enters the reverse osmosis (RO) cleansing process. This is done to improve RO performance. The water then proceeds to RO filtration, where the micro-filtered, acidified water passes through semi-permeable polyamide membrane bundles which are encased in pressure vessels. After passing through these membranes, the product water has been purified of dissolved salts, organic chemicals, pharmaceuticals and viruses (Orange County Water District and Orange County Sanitation District, 2003). Finally the product water is exposed to high intensity ultraviolet light and is disinfected with hydrogen peroxide in order to destroy any remaining organic compounds. The final product water is then checked to determine that the pH level is between 6 and 9 to ensure that the water is neither corrosive nor prone to scale formation. The addition of the acid prior to the RO processing and the ion removal which occurs during reverse osmosis tends to drive the pH of the water down to the point where it requires stabilization through air stripping to remove excess $CO_2$ and the addition of calcium hydroxide to increase pH. Cationic polymers are also added to settle any undissolved particles as well as to stabilize and buffer the water in order to maintain the required pH range throughout the reclaimed waters distribution system

The Groundwater Replenishment System (GWRS) has been operational since 2008, and is capable of supplying 70 million gallons per day of reclaimed water to recharge the water basin and act as a seawater barrier. By the year 2015, the reclaimed water volume is expected to be 100 MGD or 378,000 cubic meters with an eventual expanded capacity of 130 MGD after projected expansion of the project (Orange County Water District and Orange County Sanitation District, 2003). Approximately 30 MGD are injected into the aquifer's saltwater intrusion zone. The remaining water is then distributed to three different recharge basins through which the water naturally infiltrates the aquifer. The initial cost of the project was $481,000,000 dollars.

### 2.4 The ASR system in Sukhothai, Thailand

The Chao Phraya River basin is a major water resource in northern Thailand. The Yom River, a major tributary of the Chao Phraya River, is in an agricultural area which is a major location for rice crop production. With sufficient water resources, there would be a possibility of adding an additional harvest (SNT, 2010). Thailand's federal Ministry of Natural Resources has authorized implementation of an ASR project in northern Thailand as a means to relieve declining aquifer water levels (SNT, 2010). The depletion of underground water resources through increased usage of high capacity wells is both expensive and lowers an already depleted water table. While the region experiences drought-like conditions during most of the dry season, rainy season flows along the Yom River significantly impact downstream Bangkok through flooding. By diverting some of the flood waters, the flooding could be somewhat mitigated. The aquifer storage and recovery project being implemented by the Thai government will attempt to address these issues.

Phase I of the project was undertaken by the Thai government in 2010. Two ASR injection wells, RWS1 and RWD1 were installed as well as sixteen monitoring wells, eight in the upper, and eight in the lower aquifer. Ongoing issues with the installation and operation of the system forced the abandonment of this part of the project. Phase II of the project saw the installation of two new ASR wells, RWS2 and RWD2 and the installation of 16 new monitoring wells. The relevant features of the Sukhothai site, the locations of the new monitoring wells, and both the new and abandoned ASR wells, are shown in Figure 1.

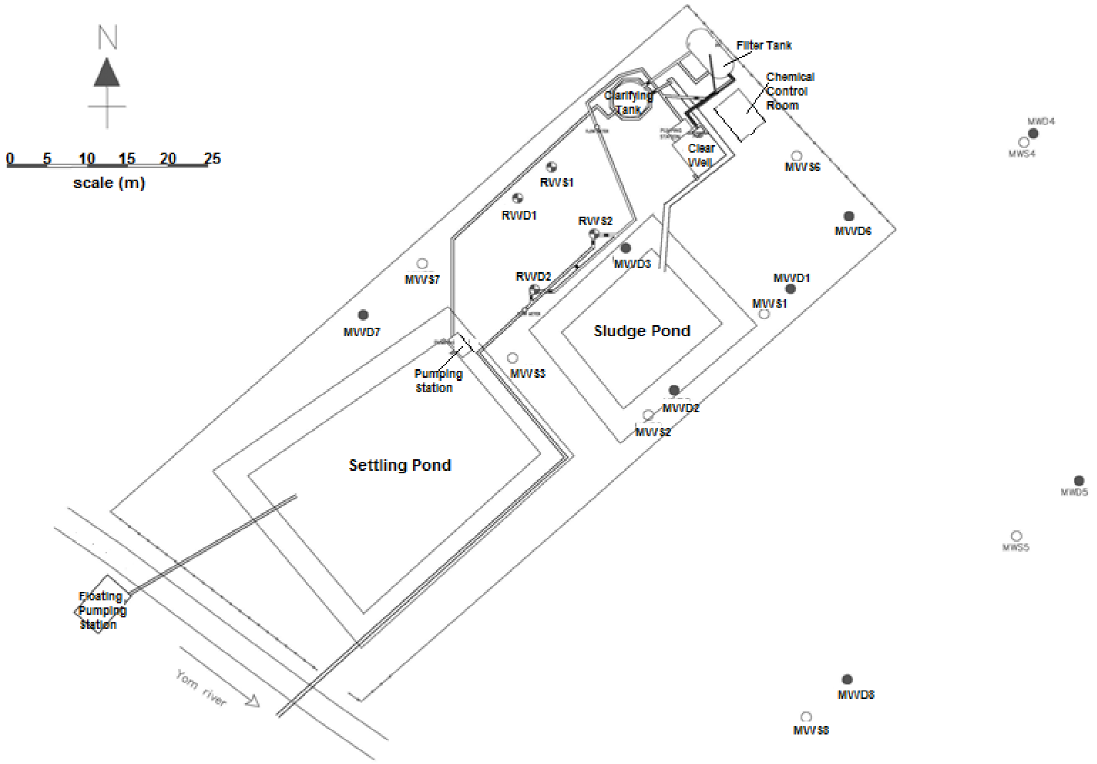

Figure 1. Phase II of the Sukhothai ASR site (SNT, 2010). Deep monitoring wells are indicated by dark circle, shallow monitoring wells are an open circle, and the ASR wells are a semi-filled circle.

### 2.4.1 Regional Geology

The Sukhothai ASR project is located in the upper central plain of the Chao Phraya River basin near Sawankhalok, Sukhothai, Thailand. The site is located in the Central Plains near the Central Highlands, approximately 425 km north of Bangkok, the capital city of Thailand (Figure 2; Thiramongkol, 1983). The Sukhothai Province has an area of 6,596 $km^2$ which is divided into nine smaller districts. The northern region of the Central Plain consists of floodplains, terraces, and peneplains. The central part of the Sukhothai Province is a plain which is bordered by highlands in the south (Figure 3). Sukhothai province contains several moderately sized mountains, the highest of which is the Khao Luang, at an elevation of 1,185 meters above sea level (SNT, 2010).

Figure 2. Sukhothai Province ASR site location (SNT, 2010).

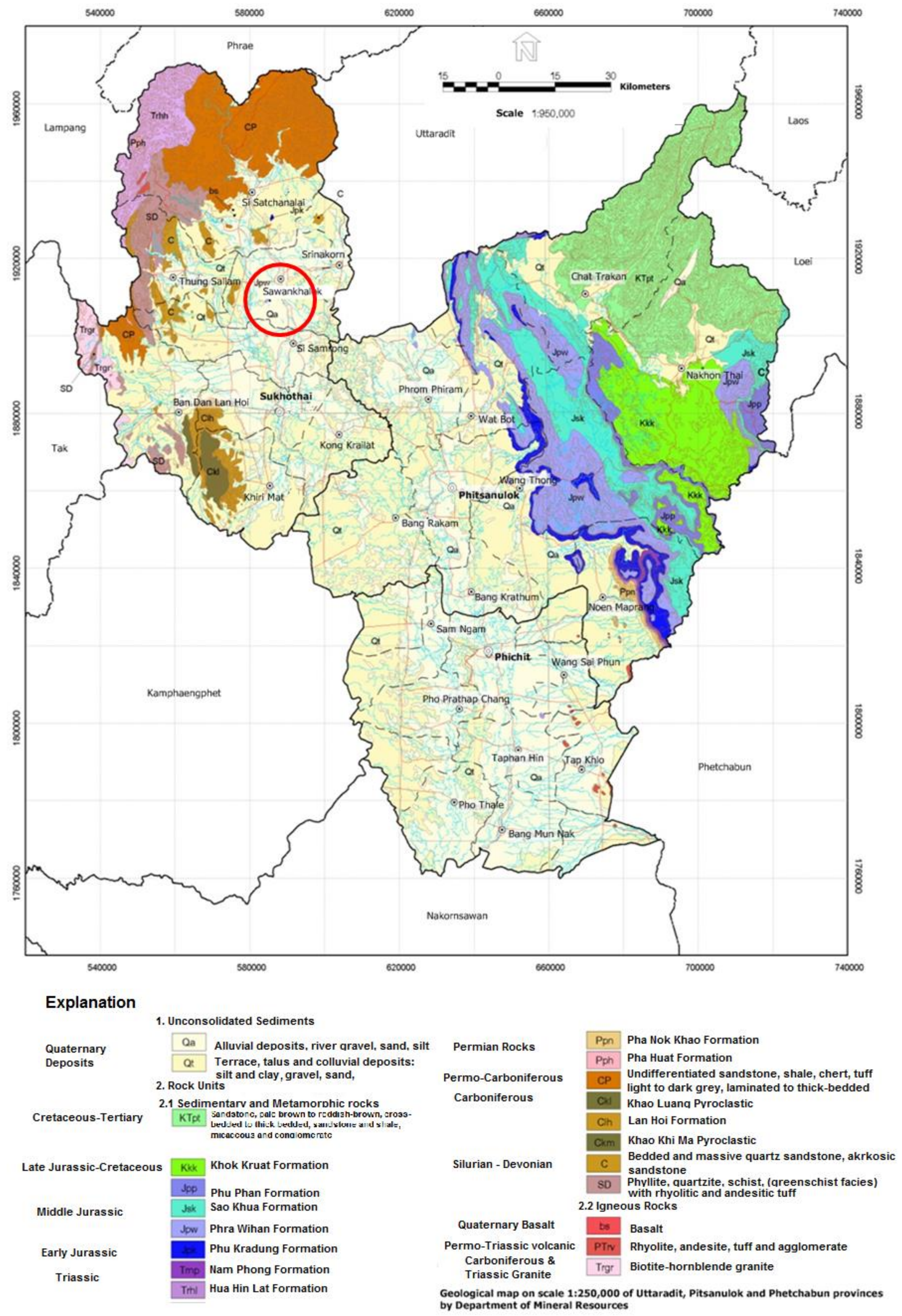

Figure 3. Geologic map of Sukhothai, Thailand (Department of Mineral Resources, Thailand, 2001).

### 2.4.2 Regional Hydrology

The Chao Phraya River basin is surrounded by uplands, which are drained by the Ping, Wang, Yom, and Nan Rivers. The rivers converge to form the Chao Phraya River at Nakhon Sawan, approximately 200 km north of Bangkok. The Yom River, which is the source of the recharge water for this project, winds through the Sukhothai district for over 170 kilometers.

One of the worst droughts in Thailand's history occurred in 2013. Forty-five provinces were declared national disaster areas (Thailand Government, 2013). This latest drought followed the extreme flooding of 2011, which affected 13.6 million people. Sixty-five of the seventy-two provinces within Thailand were declared flood disasters. In the 2011 floods, almost 90% of losses were located in the flood plains along the Chao Phraya River (Heyzer, 2012).

Thailand's Chao Phraya River basin drains approximately 160,000 $km^2$ area which includes around 40 percent of the total Thai population. The basin discharges at the Gulf of Thailand through Bangkok, the capital of Thailand (Figure 2). There are extensive well pumping systems in place within Thailand that support the population and agricultural needs. Since 1976, wells have over-pumped the Chao Phraya aquifer systems at a rate of 0.1 to 0.2 meters per year (Bhattacharya, 2013).

### 2.4.3 Aquifer Characteristics

The aquifer underlying the ASR site is heterogeneous and confined. It consists of Quaternary alluvial deposits of sand and gravel with interbedded colluvial sediments near its highland margins (Figure 4). The Chao Phraya aquifer consists of two principal

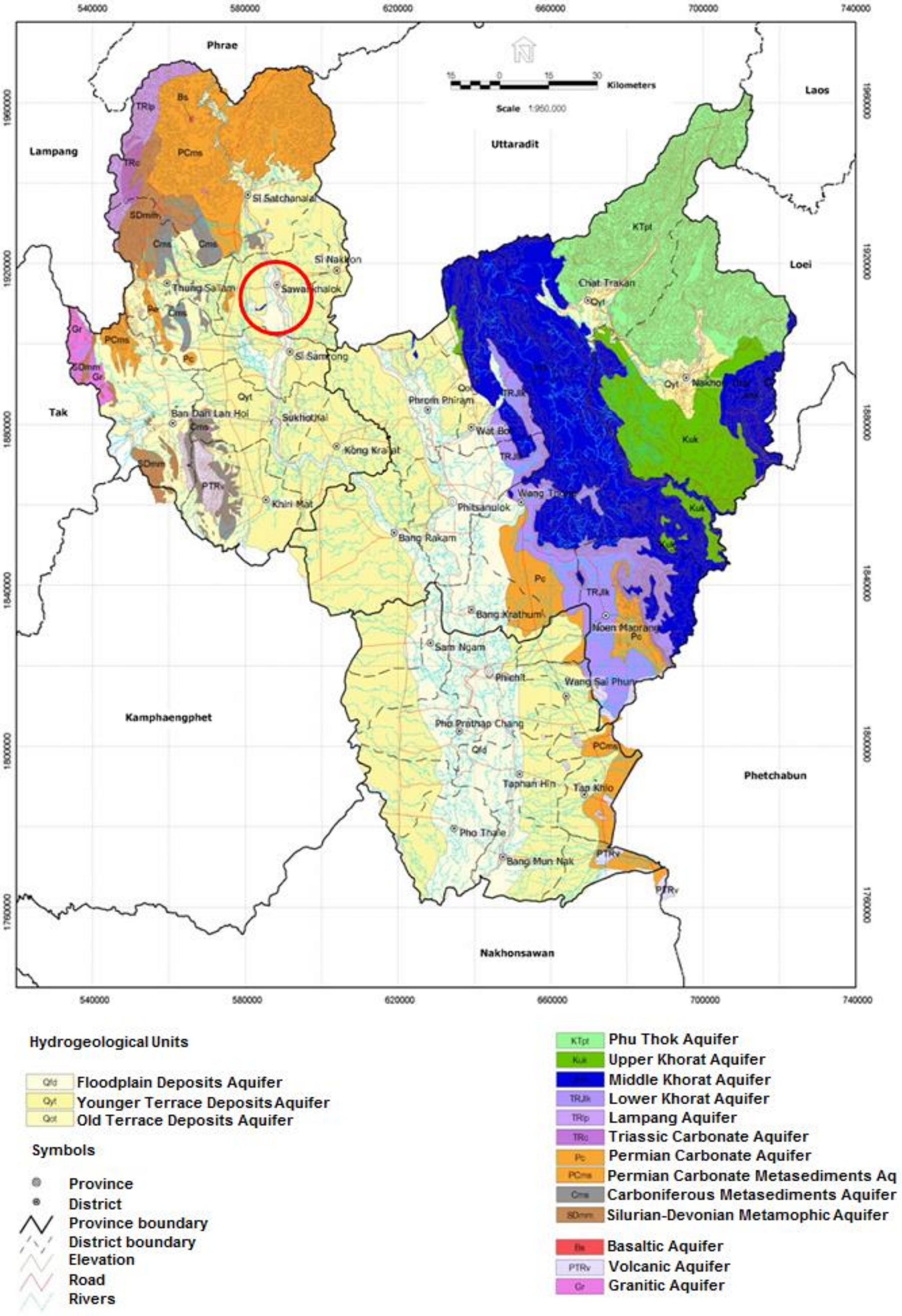

Figure 4. Aquifers within the Sukhothai Province, Thailand (after Department of Groundwater Resources, Thailand, 2001).

water-bearing levels, an upper or shallow aquifer, and a deep or lower aquifer considered in this study. The water quality and quantity available at this site is considered to be of high quality (Figure 5; Thailand Dept. of Groundwater Resources).

Sediment samples were obtained from well borings collected in a previous study to determine the site lithology (Figure 6; SNT, 2010). The site consists of a clay layer from 0 to 15 meters depth, and a clayey sand layer from 15 to 20 meters. The upper aquifer is 20 to 45 meters deep and consists of gravelly sand with clay lenses. A secondary clay layer, below the upper aquifer, extends from 45 to 55 meters. The lower aquifer lies below this layer from 55 to 90 meters and consists of gravelly sand and interbedded clay. The lower aquifer is underlain by an impermeable layer of bedrock (Figure 7). In 2010, water table was 12-16 meters below land surface, and the regional hydraulic gradient was northwest to southeast (SNT, 2010).

Downstream of Sukhothai, at a study site located between the Nan and Yom rivers in Phitsanulok, the Chao Phraya upper aquifer varies in thickness from 13 to 21.5 meters and consists of Quaternary alluvial deposits of sand and gravel with approximately 95% of the aquifer materials composed of quartz (Promma et al., 2005). The upper, or shallow, aquifer is overlain by a continuous clay layer with a thickness varying from 13 to 21 meters. The upper aquifer reaches a depth of approximately 60 meters and ranges from 14 to 45 meters in thickness. The upper aquifer is connected to both the Yom and the Nan rivers via a thin fine-grained lens of sand and is highly interactive with both rivers (Promma, et al., 2005). The deeper, lower terrace aquifer is located at a depth of 70 to 89 meters at the downstream location. The deep aquifer is separated from the upper

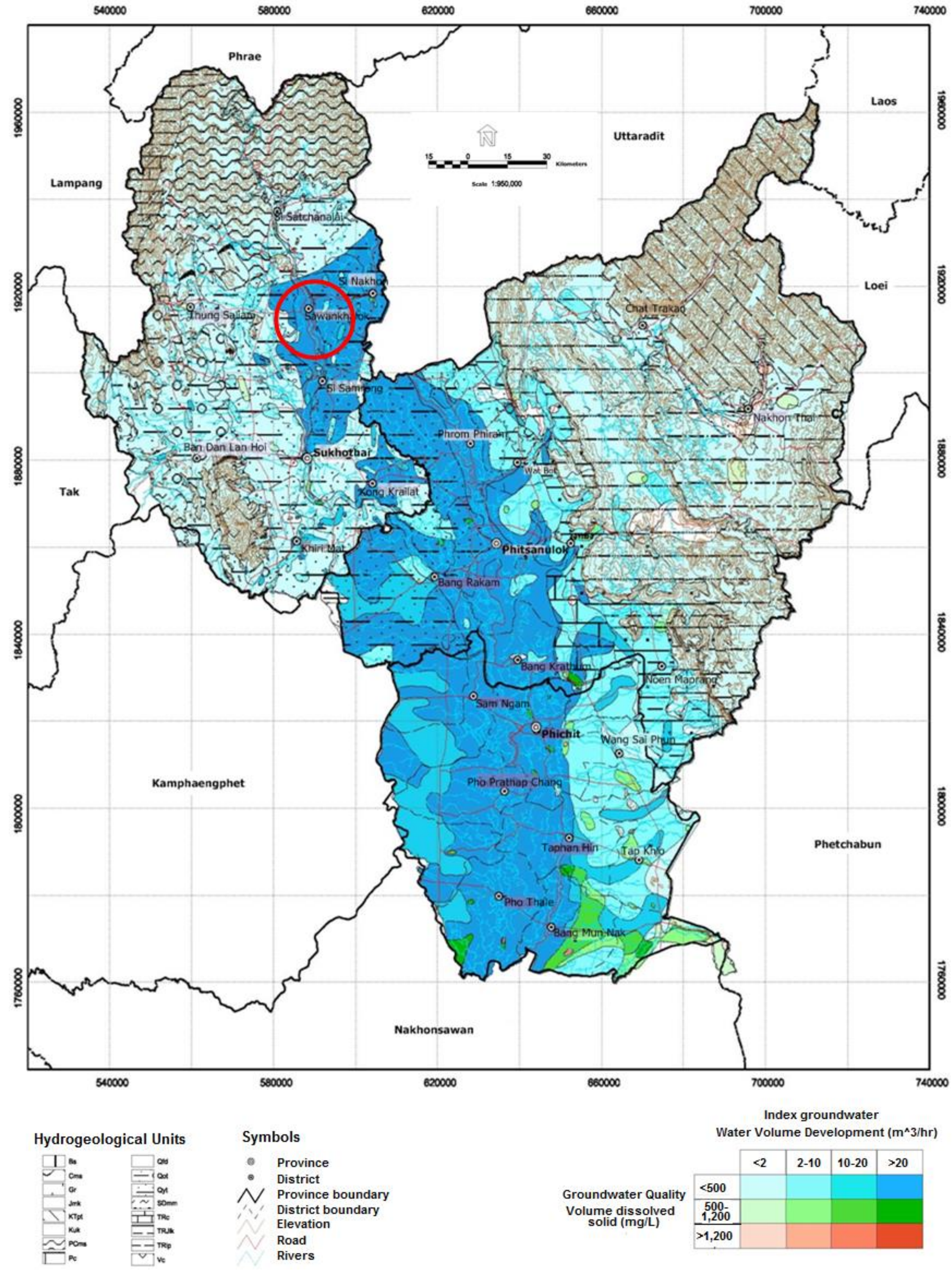

Figure 5. Aquifer quality and productivity estimates in the Sukhothai Province, Thailand (after Department of Groundwater Resources, 2001).

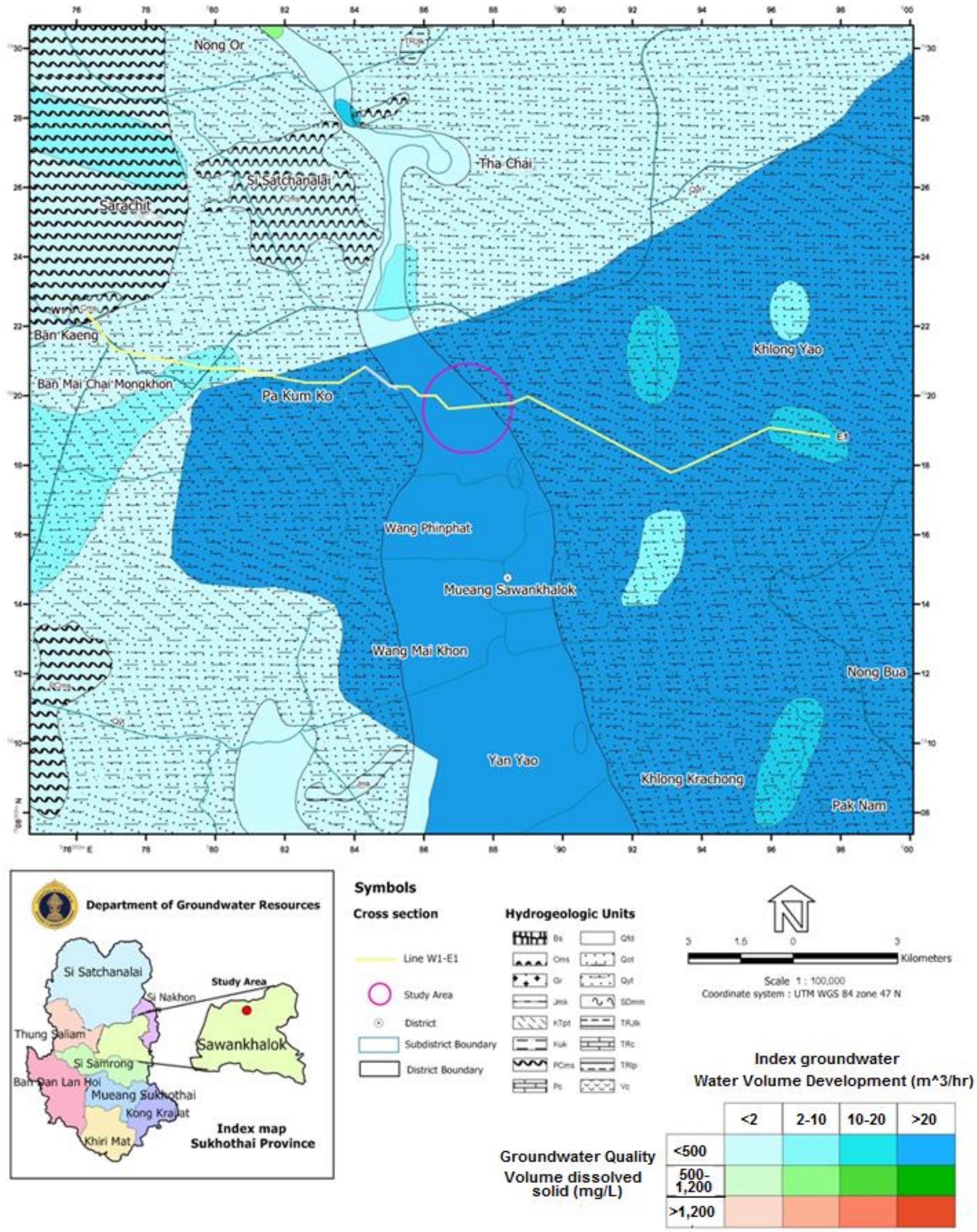

Figure 6. Location of site cross section (after SNT Consultants, 2010).

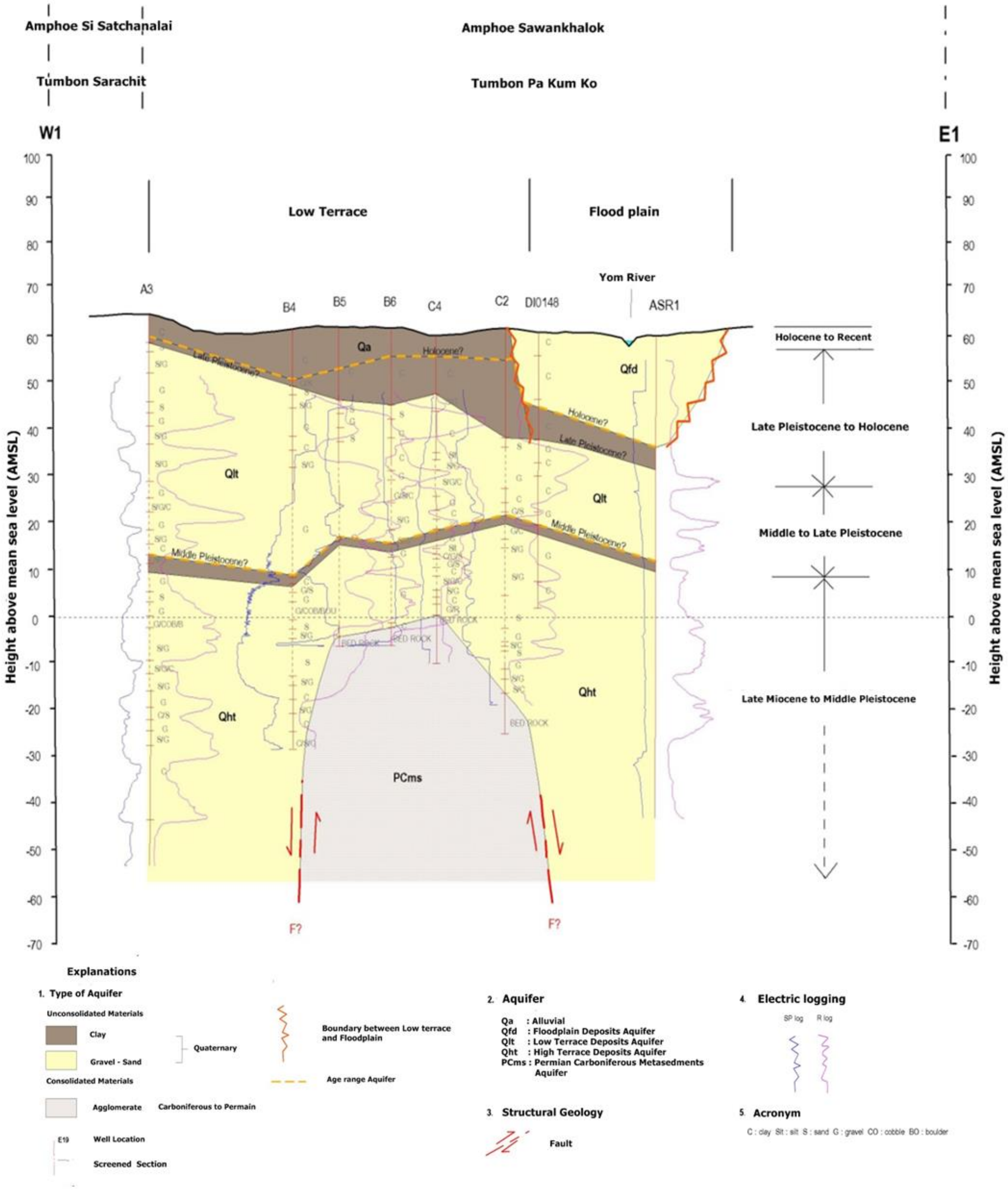

Figure 7. Geologic cross-section near the Sukhothai ASR site. The ASR site is located east of the river near the ASR1 well (after SNT Consultants, 2010).

aquifer by a clay confining layer similar to the Sukhothai site. The deeper aquifer ranges from approximately 68 to 100 meters below ground in this area, and varies in thickness.

### 2.4.4 Mineralogy of the Chao Phraya Aquifer

As part of the Thai government’s study, two, relatively undisturbed core samples were obtained from MW7 and RW2 in the upper and lower aquifer zones that were believed to represent the sedimentology of the zones (Chuangcham, 2012). The depths were chosen based on samples obtained in previous studies, and geophysical logs. Two continuous cores and ten unconsolidated samples were collected from auger flights for soil physical and chemical analysis. Shallow (33.5-34) and deep (88-88.5) continuous cores were stored in sealed plastic tubes. To remove drilling mud (bentonite), unconsolidated materials were gently rinsed prior to visual description of texture and color, and storage in plastic bags. Samples were submitted for analysis of: core photographs and descriptions, grain size, grain density, specific gravity, porosity, permeability (horizontal and vertical), cation exchange capacity, X-ray mineralogy and Scanning Electron Microscopy (SEM) plus Energy Dispersive X-ray Fluorescence (EDX) to Kasetsart University (Schulmeister, 2013).

Clay minerals were abundant in the two cores. High percentages of clay (59%) and silt (38%), little sand (3%) and no gravel occur in the shallow sample. The deep core contains less clay and silt (44% clay; 18 % silt) and more sand and gravel (21% sand and 18% gravel) than the shallow sample. Montomorillonite and mixed-layered illite/smectite clays generally have the highest cation exchange capacity (CEC) and are common in the alluvial sediments such as those at the Sukhothai site. Ca-montorillinite was identified in the deep core sample from MW7 (Schulmeister, 2012).

The silicate fraction in aquifer sediments is dominated by quartz and orthoclase feldspar. The SEM photographs of the 12 sediment samples demonstrate quartz minerals with smooth textures (Chuangcham, 2012). Smooth surfaces on quartz grains suggest little weathering or precipitation of quartz minerals (Figure 8). Past weathering of feldspars is apparent, as illite and kaolinite and Fe-oxides are abundant (Schulmeister, 2012). Reactions involving the dissolution of quartz or feldspar are generally slow under the existing pH conditions at the Sukhothai site and any weathering noted within the SEM photographs may be attributed to long term geologic weathering processes.

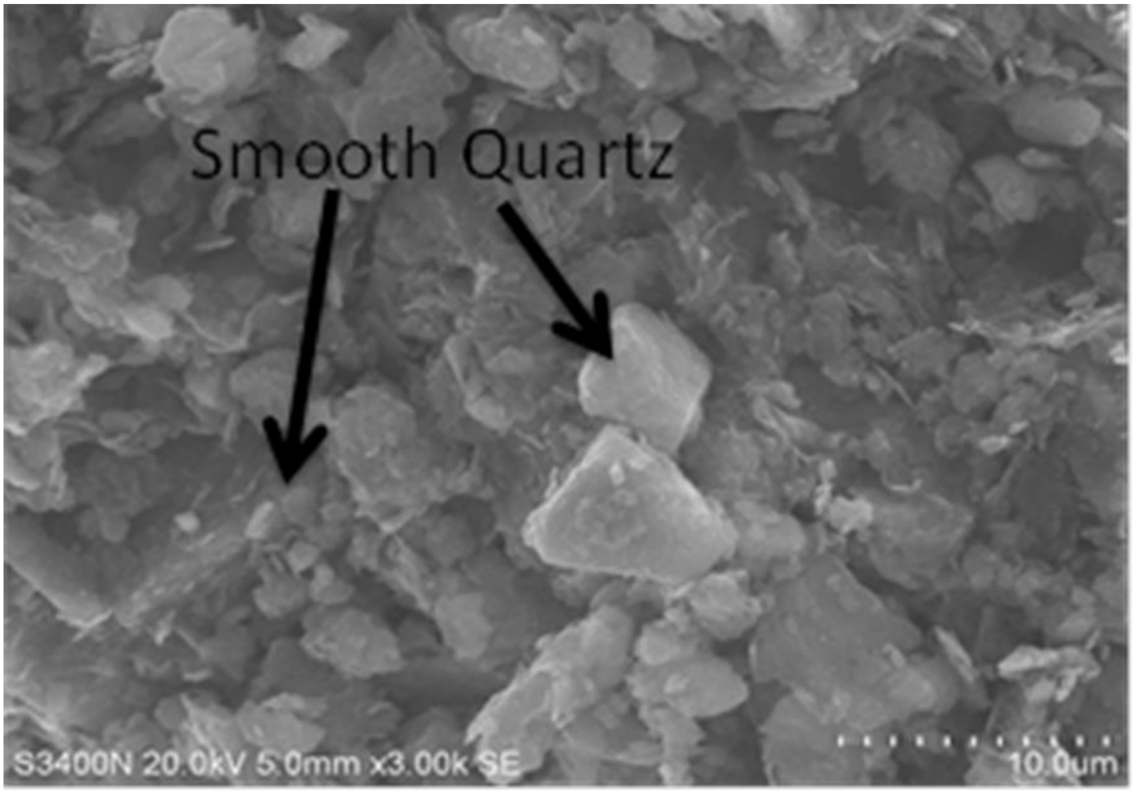

Figure 8. Smooth (unpitted) surfaces on weathered silica at the Sukhothai site (Chuangcham, 2012)

Near Phitsanulok, Thailand, the aquifer consists of Quaternary alluvial deposits of sand and gravel. The major composition of the aquifer at this location is approximately 95% quartz. No iron-rich sands were observed here, but minor iron bearing minerals such as hematite, pyrite, siderite, biotite, amphibole and pyroxene were found (Promma et al., 2006).

### 2.4.5 Geochemistry of the Chao Phraya Aquifer

Groundwater at the Sukhothai site was previously identified as Ca-Na-$HCO_3$ type water (Schulmeister, July 2012), and has the potential to precipitate or dissolve calcite and dolomite. The geochemical differences in upper and lower aquifers are consistent with differences in aquifer materials, mineral-water interactions, redox conditions and groundwater flow conditions in the two aquifers. Sodium-to-calcium and sulfate-to-chloride ratios are lower in the deep wells than in the shallow wells. Iron concentrations are also generally lower in the deep wells than in shallow wells (Schulmeister, 2012).

Calcium, sodium, and sulfate concentrations in the river are more similar to those in the deep wells than in the shallow wells, possibly suggesting a more direct relationship between the deep aquifer and the river (Table 1). A similar relationship has been observed in other parts of the Chao Phraya River basin by others (Putthividha and Koonthanakulvong, 2011), although the depths of their shallow and deep zones differ from those at the Sukhothai site. The pH in the shallow aquifer was between 6.12 and 6.38 and the deep aquifer was between 6.06 and 6.36 during background testing from May through September, 2012. The pH levels within the Yom River during the same period were from 6.55 and 7.56.

| | Average concentrations* (mg/L) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **Cl** | **$SO_4$** | **$SiO_2$** | **Fe** | **Na** | **Ca** | **Alk** | **Mg** | **K** | **$NO_3$** | **$PO_4$** |
| **Shallow** | **0.9<br>(0.6)** | **7.2<br>(2.2)** | **36.2<br>(1.2)** | **10.5<br>(2.7)** | **30.0<br>(4.6)** | **13.1<br>(1.8)** | **115.2<br>(11.0)** | **5.9<br>(0.7)** | **1.5<br>(0.6)** | **0.5<br>(0.3)** | **0.0<br>(0.0)** |
| **Deep** | **7.7<br>(0.1)** | **21.1<br>(4.1)** | **38.5<br>(3.9)** | **8.2<br>(3.2)** | **24.5<br>(3.9)** | **17.9<br>(1.8)** | **89.9<br>(12.6)** | **6.1<br>(0.75)** | **2.2<br>(0.18)** | **0.4<br>(0.17)** | **0.0<br>(0.0)** |
| **River** | **0.8<br>(0.8)** | **24.0<br>(2.8)** | **15.3<br>(1.6)** | **0.1<br>(0.1)** | **15.2<br>(4.1)** | **23.8<br>(2.2)** | **96.0<br>(16.6)** | **6.8<br>(0.5)** | **1.5<br>(0.4)** | **1.5<br>(0.7)** | **0.0<br>(0.0)** |

*Standard deviations in parentheses

Table 1. Average ion concentration in the shallow and deep aquifers and river

### 2.4.6 The Selection of a Chemical Tracer at the Sukhothai Site

The usefulness of an effective conservative tracer is threefold. It allows the scientist to monitor the movement of the injected waters within the aquifer. It may also be used to help identify zones of high permeability, and larger scale aquifer heterogeneity which may provide valuable information for monitoring and maintaining the long-term viability of an ASR system. Thirdly, it may be used to gauge the efficiency of the ASR in determining the proportion of injected water which may be recoverable. To evaluate the use of silica for identifying physical heterogeneity of the Upper Chao Phraya aquifer at the ASR site, comparisons of spatial silica and chloride distributions obtained at different stages of the injection, storage and recovery process were made.

To determine spatial and temporal variations in aquifer geochemistry during the injection, it is important to monitor how the injection water is mixing into the native groundwater. Mapping the distribution of the tracer concentrations at the various monitoring wells is a useful method to determine aquifer heterogeneity. Periodic measurements of a conservative tracer's concentration during injection, storage and recovery can be plotted against its expected concentration to identify mixing conditions.

Deviations from the predicted (ideal) tracer curve can identify dispersion, preferential flow, and aquifer heterogeneity.

Chloride is the most commonly used tracer for ASR projects. At Sukhothai, the natural chloride concentration in the upper and lower aquifers and the Yom River are too similar to allow chloride to be used as an effective tracer. The average concentration of chloride measured during the August and September background testing of the river water was 0.79 mg/L. The chloride concentration in the lower aquifer at the injection site for this same period ranged from 4.2 to 9.2 mg/L and in the upper aquifer the values ranged from 0.4 to 2.3 mg/L. The mixing of these waters with very similar chloride concentrations would indicate that the chloride concentration would not vary significantly enough to be an effective indicator of how far within the aquifers that the injection water had traveled, or when removed from storage, how much of the injected water had been recovered.

#### 2.4.6.1 Chemical Treatment of the Recharge Water to Remove Turbidity

During the first year of testing, the river water was treated with polyaluminum chloride (PACl) to remove the high turbidity prior to injection. PACl is a coagulant used in water treatment to reduce turbidity and raise the pH (Engelhardt, 2010). Its addition at this site causes increased chloride concentration of up to 57 mg/L. Increased chloride concentrations from the addition of PACl allow chloride to be used as a mixing tracer. Recent results have indicated that PACl has not been successful at removing turbidity. In the second year of the pilot project, an alternative treatment approach will be used that contributes less chloride to the injection water, so chloride will no longer function as a usable trace ion. It is for this reason, that a possible alternative, silica, is being investigated as a surrogate mixing indicator.

### 2.4.7 The Behavior of Silica in Natural Water

Silica minerals and materials are ubiquitous in natural systems with nearly 20 percent of the exposed crust of the Earth is volumetrically composed of quartz (Nesbitt and Young, 1989). Silica solubility is generally a function of pH and temperature conditions. Silica content in natural water is less variable than any of the other major dissolved components (Davis et. al, 1964). Typical silica concentration in natural water varies from 1 to 30 mg/L, with the median groundwater value of silica of 17 mg/L (Hem, 1985). In the Sukhothai groundwater, the average silica concentrations range between 30 and 45 mg/L (Schulmeister, 2013). The natural silica concentrations within this system are higher than in most groundwater systems and are likely due to the high degree of weathering of the Sukhothai sediments.

Quartz is the most common type of silica polymorph in weathering environments, and is also the most chemically and physically resistant to weathering (Dove, 1995). The solubility of crystalline and amorphous silica is minimal at pH levels below 8.5. When pH levels are near 9, weakly acidic $H_4SiO_4$ dissociates to the point where it may become a natural buffer to further disassociation if free silica is present (Figure 9; Dove, 1995). The solubility of quartz is about one-tenth that of the amorphous silica (Figure 10).

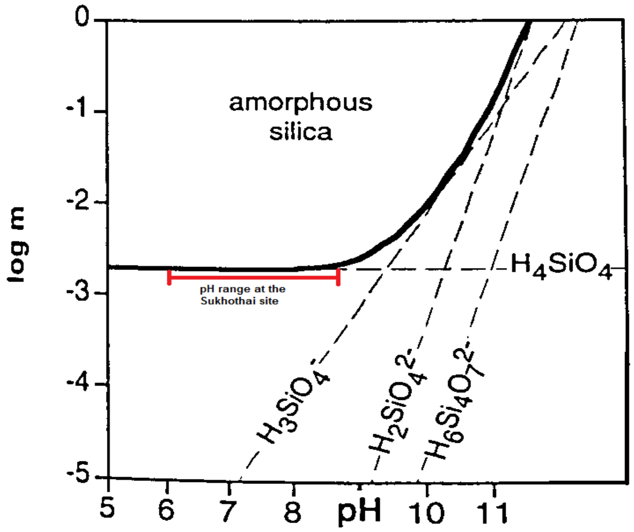

Figure 9. Solubility of amorphous silica as a function of pH. The red line indicates the approximate range of pH levels in native groundwater at Sukhothai (after Dove, 1995).

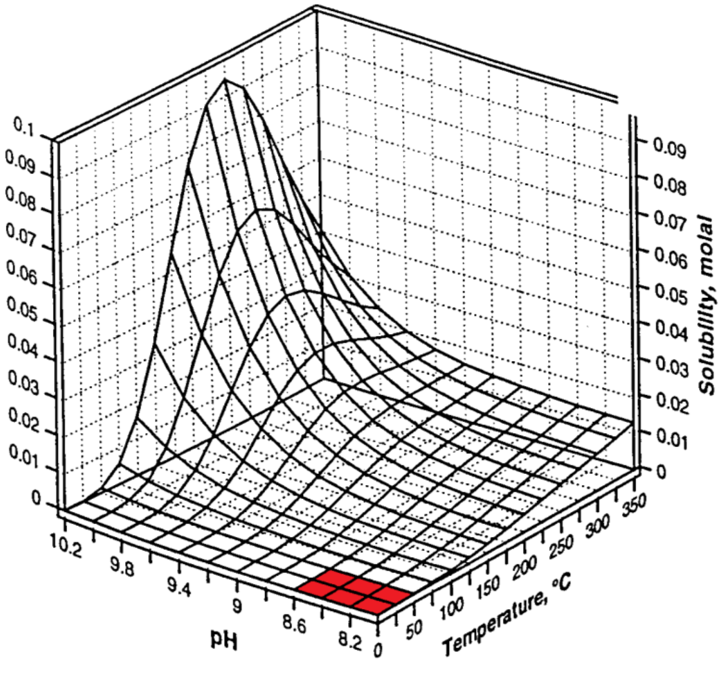

Figure 10. Solubility of quartz as a function of temperature and pH (after Dove, 1995). The red area indicates the highest levels of temperature and pH of the injection water at the Sukhothai site.

The average pH levels during injection were between 8.25 and 8.32. The time periods of the ASR testing processes are no longer than 51 days. Given the solubility of quartz as a function of temperature and pH (Figure 10), and the temperature and pH present in the injection water at Sukhothai project site, the dissolution of quartz should be negligible and little silica should be contributed to the groundwater during the testing intervals. Additional silica weathering due to injection during the short periods of time for tracing the mixing of the injection water with the existing groundwater should not be a factor. Dissolved silica does not behave like a charged ion or a colloid in most waters (Hem, 1985).

The average concentration of silica in the river water during background testing during August and September was 14.3 mg/L while concentrations in the upper aquifer ranged from 33 to 38.2 mg/L, and in the lower aquifer ranged from 29.9 to 44.6 mg/L. The differences in concentration between the injection water and the aquifer waters should be sufficient to trace the movement of the injection water within both the lower and the upper aquifers.

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# CHAPTER 3. METHODS AND PROCEDURES

## 3.1 ASR Sample Test and Schedule

Study design for this thesis examined the data obtained from four pressure recharge injection (cycle) tests within the lower and upper aquifers. Sampling was conducted during the four cycle tests: nine-day short-term lower aquifer, nine-day short-term upper aquifer, 51-day long-term lower aquifer and 51-day long-tern upper aquifer. The sampling was done to monitor dilution, mixing, advection and dispersion of the non-reactive silica and chloride which may have occurred during and post injection and to assess ASR performance.

### 3.1.1 Short-Term Injection Tests

During the short-term testing in the lower and upper aquifers, there were four days of recharge injection under pressure, one day of storage of the recharge waters, and then four days of recovery. Samples were obtained on the third day of injection from the deep aquifer monitoring wells 1, 2, 3, 6 and 7. These wells are located closer to the ASR injection wells RWD2 and RWS2 than the other monitoring wells (Figure 1) and provided early injection information. These same wells were sampled after two to three days of recovery. The RWD2 and RWS2 were also sampled three times during the injection period, and five to six times during the recovery phase of the tests (Schulmeister, 2013).

### 3.1.2 Long-Term Injection Tests

Long-term injection testing on both the upper and lower aquifers consisted of 30 days of injection, 5 days of storage, and 15 days of recovery. The same five wells that were sampled during the short term testing (monitoring wells number 1, 2, 3, 6, and 7) were sampled at approximately 14 days after initial injection. Two additional, down-gradient wells, MW5 and MW8 (Figure 1), were sampled during the thirty days of injection. The recharge wells (RWD2 and RWS2) were sampled four to six times during the injection period and also 11 times during the recovery period. All of the monitoring wells were sampled a second time approximately one day after the recovery began (Schulmeister, 2013).

## 3.2 Comparison of Silica and Chloride

The goal of this thesis is to compare chloride, a widely accepted conservative tracer to silica to determine whether silica would provide an acceptable surrogate should the treatment of the injected water be modified such that chloride concentrations in the injected and aquifer water prove too similar. Silica is a solute whose concentration is only affected by dilution and not by chemical reactions which is the primary requirement for an effective tracer. Relative proportions of treated water and groundwater should change linearly during mixing, so similar proportions of conservative tracer from river and groundwater should as well. Concentrations of silica and chloride were measured to obtain background levels within the upper and lower aquifers prior to injection testing and also periodically throughout the injection and recovery processes.

### 3.2.1 Evaluation of Aquifer Heterogeneity: Spatial Distribution Maps of Silica and Chloride

Spatial distributions of silica and chloride were determined prior to injection and during each of the cycle tests in both the upper and lower aquifers (in the fall of 2012 and winter of 2013). A goal of this thesis was to evaluate similarities and differences between silica and chloride maps were evaluated. Spatial distribution maps were modelled using a kriging algorithm within the Surfer 9 software program to approximate values for points where actual data were not collected (Golden Software, 2009). Kriging is a mathematical interpolation technique based on regression against observed z values of surrounding data points, weighted according to spatial distance values (Isaaks and Srivastava, 1989).

### 3.2.2 Evaluation of Recovery using Silica and Chloride

Recovery graphs are used to help assess overall ASR system efficiency. Natural geochemical parameters can be used to track the fate of injected water if they are chemically conservative. The calculation of the relative silica and relative chloride during recovery is represented in the recovery curves are found by following formula:

$$\text{Relative Ion Concentration} = \frac{Ion\ concentration\ at\ RW2 - Treated\ water\ ion\ concentration\ before\ injection}{Treated\ water\ ion\ conc.before\ injection - Ion\ conc.in\ the\ aquifer\ \ before\ injection}$$

These values can be plotted to identify non-ideal conditions. As relative proportions of recharge and recovery water change within the aquifer, similar proportions of a conservative recharge tracer should follow. An ideal recovery curve would have the relative concentration of the tracing ion recovered being equal to the percentage of the recharge water recovered. One hundred percent recovery of the tracer injected would be possible at one hundred percent recovery of the volume injected if there were no losses due dispersion or mixing. Deviations from ideal recovery can be used to identify the dispersion of the injected water within the aquifer, and overall aquifer heterogeneity. The more horizontal the recovery curve, the more dispersion has occurred within the aquifer. Mixing will take place during injection which is affected by diffusion and dispersion within the aquifer. Results of these calculations are examined in the discussion section of this document.

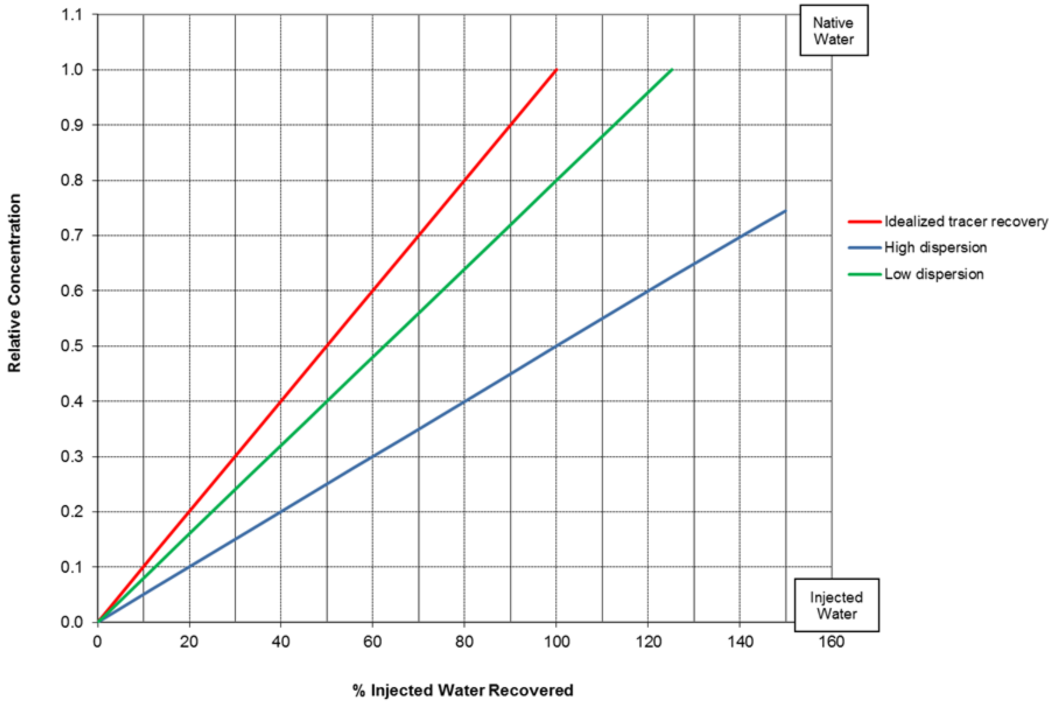

Figure 11. Idealized recovery of injected water.

### 3.2.3 Chloride and Silica as Indicators of Overall ASR Efficiency

Recovery efficiency in an ASR is a measurement of the amount of useable water that was injected for storage within the aquifer that can be subsequently recovered before reaching a defined standard of unsuitability. In cases where the aquifer chemistry is similar to the injected water chemistry, it is possible to achieve 100% recovery as the water quality remains consistent. The percentage of injected water recovered is calculated using the equation below (Pyne, 1995):

$$\text{Percentage of injected water recovered} = \frac{volume\ of\ water\ recovered}{total\ volume\ of\ water\ injected} \text{ x } 100$$

By examining the tracer percentage recovery, it is possible to accurately trace the actual “recovery of the injected water” instead of the recovery of “useful water” for later use. The recovery efficiency calculated using the method of tracer recovery will always lead to a lower estimate for recovery efficiency because there is no allowance for mixing which occurs between the stored water and the existing groundwater (Pyne, 1995).

## 3.3 Sampling Protocols and Intervals

The following sampling protocols and requirements for measurements of field parameters were followed in the collection of water samples from the Yom River, the recharge and recovery wells and the monitoring wells

### 3.3.1 Sampling Protocols

New, polyethylene containers were sterilized or acid washed prior to use for sample collection. All samples were labeled with the following: location, unique sample number, sample description, date and time of collection, signature of sampler, analytical parameters and method of preservation. To obtain reliable date, measurement of the concentrations or reactive chemical species must be measured in the field. The following field parameters were measured on site: temperature, specific conductance, pH, turbidity, dissolved oxygen, and Eh. Field parameters were measured in all samples (Schulmeister, 2013).

### 3.3.2 Measurement of Field Parameters

Unstable field parameters (turbidity, oxidation reduction potential (ORP), conductivity, and pH were measured after extensive well purging. Exposure to atmospheric conditions may impact these parameters. A Hanna 9828 Multiparameter sonde (Hanna, 2006) with an attached sealed flow-through cell was used to measure temperature, pH, specific conductivity, and oxidation reduction potential (ORP). The sonde was calibrated prior to sampling using a “Quick Calibration” standard solution provided by Hanna. The resolution of low dissolved oxygen concentrations was verified after each calibration using a Hanna $NaSO_3$ solution. Oxidation potential (Eh) values were calculated from the ORP readings obtained with a Hanna Pt/PtO electrode. Eh is standardized to a hydrogen electrode (Eh) range, which requires a correction factor of +200 mV applied to all ORP values collected (Nordstrom and Wilde, 1998). Calibration of the electrodes was conducted after each sample to ensure that potential drift associated with all of the electrodes was corrected. Comparison between the flow cell temperature measurements and pump discharge outlet temperature measurements were similar, indicating that the use of the flow cell did not affect accurate measurement (Schulmeister, 2013).

Field parameter measurements were monitored every minute for approximately 10 minutes until variations between successive readings were within 3% for all parameters. The final values were then recorded. After measurement of field parameters, total iron, total manganese, and turbidity were measured in the field in a subset of samples collected (Schulmeister, 2013).

River water field parameters were obtained from the Chao Phraya River between May and December, 2012. A multiparameter sonde was held 1 m below the water surface for field parameter measurements. Readings were monitored until they stabilized, and then were recorded. Total iron, total manganese, and turbidity were measured in the field using a subset of samples. Field parameters samples were taken from the Chao Phraya River between May 2012 and March 2013 (Schulmeister, 2013).

### 3.3.3 Background Sampling

A thorough understanding of the existing groundwater chemistry prior to the injection of the recharge water is necessary to properly evaluate changes in groundwater chemistry during injection and recovery. Native groundwater (background sampling) took place in August and September, 2012. Samples were obtained from the recharge wells and the monitoring wells in the upper and lower aquifers as well as from the Yom River. Pressure injection of the recharge water was required as injection was into a confined aquifer. Groundwater injection requires periodic backwashing of the recharge wells to eliminate clogging. To ensure that representative groundwater samples were obtained, monitoring wells were thoroughly purged of at least three well volumes prior to sampling.

### 3.3.4 Sample Collection Methods

Laboratory analysis is required for certain parameters: anions, alkalinity, total metals, dissolved metals, bacteria, and total organic carbon. The following sampling protocols were used for collection. All bottles were new, acid washed, and rinsed twice with sample prior to filling the bottles for laboratory analysis. Samples for the measurement of anions and alkalinity were collected directly from the well outlet into new 1-liter polyethylene bottles. These samples were kept on ice in the field and then kept cold until delivery to the laboratory. Total metals samples were collected directly from the well outlet into a new 1- liter polyethylene bottles. 4 ml of 1:1 nitric acid ($HNO_3$) was added to the samples before sealing. The samples for dissolved metals were filtered into a new 1- liter polyethylene bottles. 4 ml of 1:1 nitric acid was added to the samples before sealing. Samples for the analysis of bacteria were collected directly from the well outlet into a new 0.5 or 1-liter polyethylene bottles and were kept on ice in the field and then kept cold until delivery to the laboratory. Samples for total organic carbon were collected directly from the well outlet into a new 0.5 or 1-liter polyethylene bottles and were kept on ice in the field and kept cold until delivery to the laboratory (Schulmeister, 2013).

Water samples from the river were collected 6 - 12 inches below the water's surface. All samples were filtered using new, disposable, in-line filters using a hand pump in the field. Thirty-eight samples were collected from nineteen wells for laboratory analysis from the wells prior to the start of the injection tests for the purpose of identifying native groundwater conditions. The samples requiring laboratory analysis followed the same sampling protocol as used for the well sampling outlined above (Schulmeister, 2013).

## 3.4 Laboratory Analysis of the Water Samples

American Public Health Association (APHA) standard methods were used for laboratory analysis of the samples discussed in this thesis (Table 2).

| Parameter | Method No. | Method |
|---|---|---|
| pH | 4500-H B. | Electrometric pH Meter |
| Specific Conductance | 2510 B. | Laboratory Method - Conductivity Meter |
| Chloride | 4500-$Cl^-$ B. | Argentometric Method |
| Silica | 4500-$SiO_2$ C. | Molybdosilicate Method |
| Total Solids | 2540 C.C | TDS dried at 180˚C |

Table 2. Laboratory methods used for analysis of parameters discussed in this thesis (American Public Health Association, 1998).

Dissolved silica ($SiO_2$) is the form of silica measured and analyzed during these analyses since elemental silicon is not stable in most natural systems. Method 4500 $SiO_2$ C is a colorimetric method. Ammonium molybdate at pH 1.2 reacts with silica and phosphates present to produce acids. Oxalic acid is then added to destroy any molybdophosphoric acid which may have formed, leaving only the molybdosilicic acid (American Public Health Association, 1998). The more intense the yellow color produced, the more molybdate-reactive silica is present. It is noted within the American Public Health Association guidelines that large amounts of iron, color, turbidity, sulfides and phosphates may interfere with this method, and that photometric compensation to cancel interference from color or turbidity may be required. There is a large amount of iron in the groundwater so the possibility of impact on the test results must be considered.

Chloride was measured using method 4500 $Cl^-$ B, which is an argentometric (silver nitrate) titration method. The water sample is checked for pH level and the presence of sulfide, sulfite, or thiosulfate. If any of those is present, 1 ml of $H_2O_2$ is added to the 100 ml sample of water, is stirred and allowed to rest for 1 minute. If the pH range of the sample was between 7 and 10, the sample can be directly titrated. If the pH level is not in this range, it is adjusted using NaOH. The sample is then titrated using standard $AgNO_3$ (silver nitrate) titrant until the potassium chromate indicator turns a pinkish yellow. The amount of $Cl^-$ is then calculated based on the following formula:

$$\text{Mg/L Cl}^- = \frac{(A-B) x\ N\ x\ 35450}{mL\ sample}$$

where A = mL titration for sample, B = mL titration for deionized water blank, N = normality of $AgNO_3$, and 35450 is a unit conversion factor (American Public Health Association, 1998).

Total dissolved solids (TDS) were measure using American Public Health Association method 2540 C. In this method, a well-mixed sample of water is filtered through a glass fiber filter, and the filtrate is then evaporated in a dish of known weight to dryness at 180˚C. The dish with the dried filtrate is then re-weighed. The difference between the weight of the dish and the weight with the dried filtrate divided by the sample volume is the total dissolved solids in mg/L (American Public Health Association, 1998).

### 3.4.1 Validation of Laboratory Analyses

Analytical results from laboratories may contain errors both due to sample handling and analytical laboratory methods. Validation of laboratory analysis assesses these errors by determining whether parameters measured fall within known acceptable value ranges. Data evaluation of sample analytical methods ensures that accepted protocols are followed during collection, storage, and in the laboratory. The following tests are typically applied to laboratory data to assess the validity of the chemical data sets and to identify any errors in sampling and analysis.

### 3.4.2 Mass Balance

The mass balance is both a weight and charge balance as it takes into account the valence of major anions and cations and the gram atomic weight (molar) units of each ion. The anion and cation sums as expressed in milliequivalents per liter must balance because all potable waters should be electrically neutral. The molal concentrations are found by using the following equation:

$$(\frac{mg}{l} \times 10^{-3}) \div formula\ weight\ in\ grams = Molality$$

$$Milliequivalents\ per\ liter \times 10^{-3} = Molality\ \times valence\ of\ the\ ion$$

Acceptable difference between anions and cations is ± 0.2 meq/L if the anion sum is less than 3.0. If the anion sum is between 3.0 and 10.0 the acceptable error percentage is ±2% (American Public Health Association, 1998). To calculate the error percentage, the major cations (calcium, magnesium, sodium, potassium) are added together and are compared to the major anions (chloride, sulfate, bicarbonate, carbonate, and nitrate) as:

$$Error\ \% = \frac{(Cation\ sum\frac{meq}{l} - Anion\ sum\frac{meq}{l})}{(Cation\ sum + Anion\ sum)} \times 100$$

(American Public Health Association, 1998).

### 3.4.3 Measured TDS and Calculated TDS

Calculation of total dissolved solids is determined from the sum laboratory measured concentrations of its constituents. Total dissolved solids (TDS) measured in the laboratory should be higher than the calculated value due to the fact that a significant ion contributor may not be included within the calculation TDS is calculated according to the following formula using milliequivalents per liter values (American Public Health Association, 1998):

$TDS_{calculated}$ =

$(Na^{+} + K^{+} + Ca^{2+} + Mg^{2+} + Cl^{-} + SO_4^{2-} + SiO_3^{2-} + NO_3^{-} + F + 0.6(Alkalinity_{Total}\ CaCO_3)\}$

Dissolved silica $SiO_2$ was used in place of $SiO_3$ for the TDS calculation for this study. If the calculated value of TDS is more than 20% lower than the measured TDS, the total dissolved solids calculated should be analyzed by re-examining all of the components which contribute and the sample may need to be flagged as suspect. The acceptable ratio for TDS is

$$1 < \frac{measured\ TDS}{calculated\ TDS} < 1.2$$

(American Public Health Association, 1998).

### 3.4.4 Calculated Total Dissolved Solids versus Electrical Conductivity

Total dissolved solids (TDS) and electrical conductivity (EC) are separate measures of the ion concentration in solution and are directly related to one another. The accepted ratio of calculated total dissolved solids (TDS) to electrical conductivity (EC) concentrations is in the range of 0.55 to 0.7 (American Public Health Association, 1998). If the ratio falls outside these limits, the data are suspect and samples should be reanalyzed (American Public Health Association, 1998).

$$0.55 < \frac{TDS}{EC} < 0.7$$

# CHAPTER 4. RESULTS

## 4.1 Evaluation of Laboratory Analysis

In this study, 171 water samples were collected from 18 monitoring wells, two recharge wells, and the river during injection, storage and recovery stages of each test. A quality control evaluation of sample handling and laboratory analyses was conducted as discussed in chapter 3 prior to comparisons of silica and chloride.

### 4.1.1 Charge Balance

Analysis of charge/mass balance error was assessed using the anion and cation concentrations for each sample and are presented in Appendices A-C and F. Charge balances for all 171 samples meet the criteria of ± 0.2 meq difference between the cations and anions, indicating good quality control in laboratory analyses and sample collection (Appendix A; American Public Health Association, 1998).

### 4.1.2 Total Dissolved Solids – Measured versus Calculated

TDS ratios for 165 of the 171 samples fall between 1.0 -1.2 ratio of measured TDS to calculated TDS, which indicates that collection and analysis of the samples were likely not a cause of error (Appendix E; American Public Health Association, 1998). Those ratios for the remaining six samples fall below the 1.0 acceptance value, which indicates that a higher TDS was calculated based on major ion concentrations than was measured directly in the laboratory. These samples may indicate sampling or laboratory analysis errors.

### 4.1.3 Calculated Total Dissolved Solids and Electrical Conductivity

The calculated ratios for TDS/EC are presented in appendix E. TDS/EC ratios are between 55 and 70% or 0.55 to 0.7 for 116 of the 171 samples, indicating that the analysis and collection of those samples were not suspect. The remaining 55 samples were all above the acceptable range, none were below. If poorly dissociated calcium and sulfate ions are present, the TDS may be as high as 0.8 times the EC (American Public Health Association, 1998). None of the TDS to EC ratios were higher than 0.8. The charge balances errors for all samples were within acceptable ranges. Two of the samples that did not meet the acceptable criteria for TDS/EC were also in the group of six samples that were low in the TDS/TDScalc comparison.

## 4.2 Range of Silica and Chloride Concentrations Used in Analysis

The chloride and silica concentrations in the native groundwater and the recharge water varied temporally over the period of ASR testing. It is important to take these differences into account when evaluating the performance of the ASR. Changes in silica and chloride concentrations in the injection water will affect the chemical gradients observed in aquifer, complicating comparisons of the distribution maps. Injection of inconsistent chloride and silica concentrations will also affect interpretations made during recovery. Natural spatial variations in the aquifer and temporal variations in injection water were determined prior to comparison of the two tracers.

### 4.2.1 Native Groundwater (Background Conditions)

Chloride and silica concentrations were measured in the injection and monitoring wells in August and September, before ASR testing began. Silica concentrations ranged from 36 to 44.6 mg/l in the deep aquifer, and from 33 to 38.2 mg/l in the shallow aquifer.

Chloride concentrations ranged from 4.2 to 7.7 mg/l in the deep aquifer, and from 0.4 to 2.3 in the shallow aquifer. Both silica and chloride had a wider range of concentration within the deep aquifer. Concentrations for both ions were also higher in the deep aquifer. Highest and lowest concentrations in both aquifers and averages used in subsequent discussions are summarized in Table 3.

| **Silica and Chloride Concentrations in Native Groundwater** | Deep Aquifer | | Shallow Aquifer | |
|---|---|---|---|---|
| | Chloride mg/l | Silica mg/l | Chloride mg/l | Silica mg/l |
| **August High** | **7.3** | **43.9** | **2.3** | **38.2** |
| **August Low** | **5.4** | **38.7** | **0.4** | **33.0** |
| **August Average** | **6.3** | **41.3** | **0.8** | **36.3** |
| **September High** | **7.7** | **44.6** | **1.5** | **37.5** |
| **September Low** | **4.2** | **36.0** | **0.4** | **34.8** |
| **September Average** | **6.0** | **40.0** | **0.7** | **36.1** |

Table 3. Native groundwater variation in silica and chloride concentrations.

### 4.2.2 Injection Water

ASR recharge water was obtained from the nearby Yom River. As previously discussed, polyaluminum chloride was added to the recharge water to decrease the turbidity in the water, elevating the pH in the injection water. The amount of PACl that was added to the recharge water was varied by the ASR operators as the tests were conducted in an effort to control turbidity (Table 4). Chloride concentrations had the greatest variation during the long-term tests in both the shallow and the deep aquifers. Chloride ranged from 37.7 to 45.5 mg/l during the long-term deep aquifer cycle test, and from 35.4 to 55.4 mg/l during the long-term shallow aquifer cycle test. Chloride concentrations in the injection water were more stable during the short-term tests. During the short-term test in the deep aquifer, the chloride concentrations varied from 35.4 to 37.0 mg/l. During the short-term shallow aquifer cycle test, the levels ranged from 55.8 to 57.8 mg/l. Higher chloride concentrations were used in the upper (or shallow) aquifer testing than in deep (or lower) aquifer testing Silica concentrations in the injection water were much more stable, ranging from a 9.4 to 13.1 mg/l over the four cycle tests.

| **Silica and Chloride Concentrations in Recharge Water** | **Cycle Test** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Long-term Deep Aquifer | | Short-term Deep Aquifer | | Long-term Shallow Aquifer | | Short-term Shallow Aquifer | |
| | Chloride mg/l | Silica mg/l | Chloride mg/l | Silica mg/l | Chloride mg/l | Silica mg/l | Chloride mg/l | Silica mg/l |
| **Highest Level** | **45.5** | **13.1** | **37.0** | **12.2** | **55.4** | **14.0** | **57.8** | **10.5** |
| **Lowest Level** | **37.7** | **11.2** | **35.4** | **9.4** | **35.4** | **11.7** | **55.8** | **10.2** |
| **Average Level** | **41.6** | **12.28** | **36.5** | **10.7** | **46.9** | **12.6** | **56.7** | **10.4** |

Table 4. Variations in silica and chloride concentrations in the recharge water.

# CHAPTER 5. ANALYSIS

## 5.1 Groundwater Chemical Distribution during Tests: Aquifer Heterogeneity

Spatial distributions of silica and chloride were determined prior to injection and during all four cycle tests. Similarities and differences between the silica and chloride maps are discussed in the following sections. Injected silica concentrations are lower, and the chloride concentrations are higher, in the recharge water than in the groundwater, so the silica maps reflect dilution, whereas the chloride maps reflect enrichment of the tracer.

### 5.1.1 Deep Aquifer

#### 5.1.1.1 Background Conditions

Silica concentrations of 36 to 44 mg/l are observed in the deep aquifer (Figure 11). Chloride concentrations in the deep aquifer are between 5 and 8 mg/L. The chloride concentration at MWD3 was high when compared to the other background concentrations in August (Figure 12), but the September chloride concentration at this well was commensurate with the other wells (Figure 13).

Silica concentrations in September (Figure 13) are 25% lower at MWD3 than the August level which contorts the silica distribution in this map to appear more heterogeneous. The silica concentration only varied significantly in well MWD3 while the remaining monitoring well silica concentrations remained consistent. Except for the aforementioned anomalies, the background concentrations for both chloride and silica are fairly consistent.

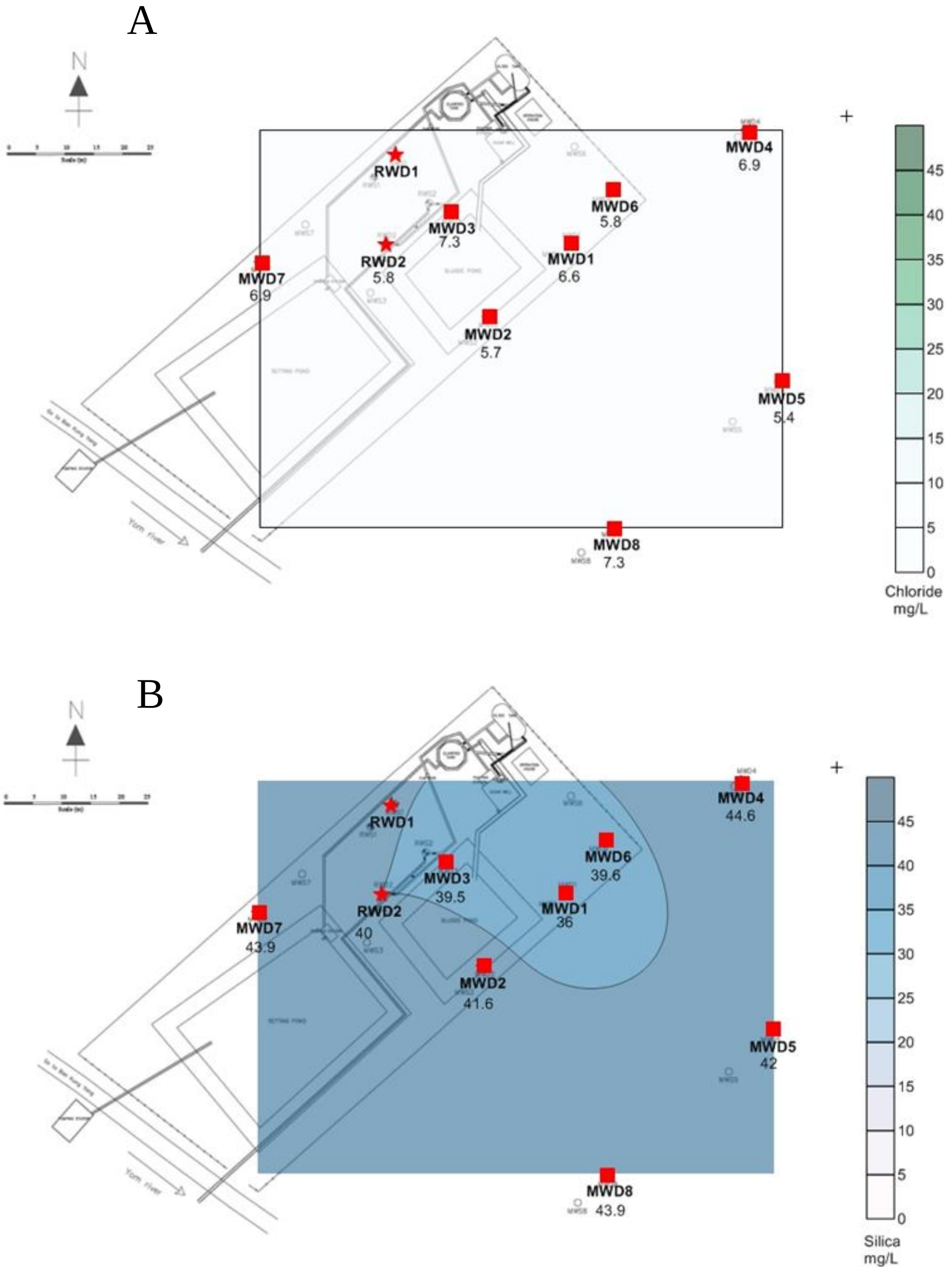

Figure 12. Chloride (A) and silica (B) distribution in the deep aquifer prior to ASR testing (August, 2012). Wells RWD1 and RWS1 were decommissioned injection wells used in a previous study. They are included in all maps in this section for reference purposes only, and no samples were obtained from them.

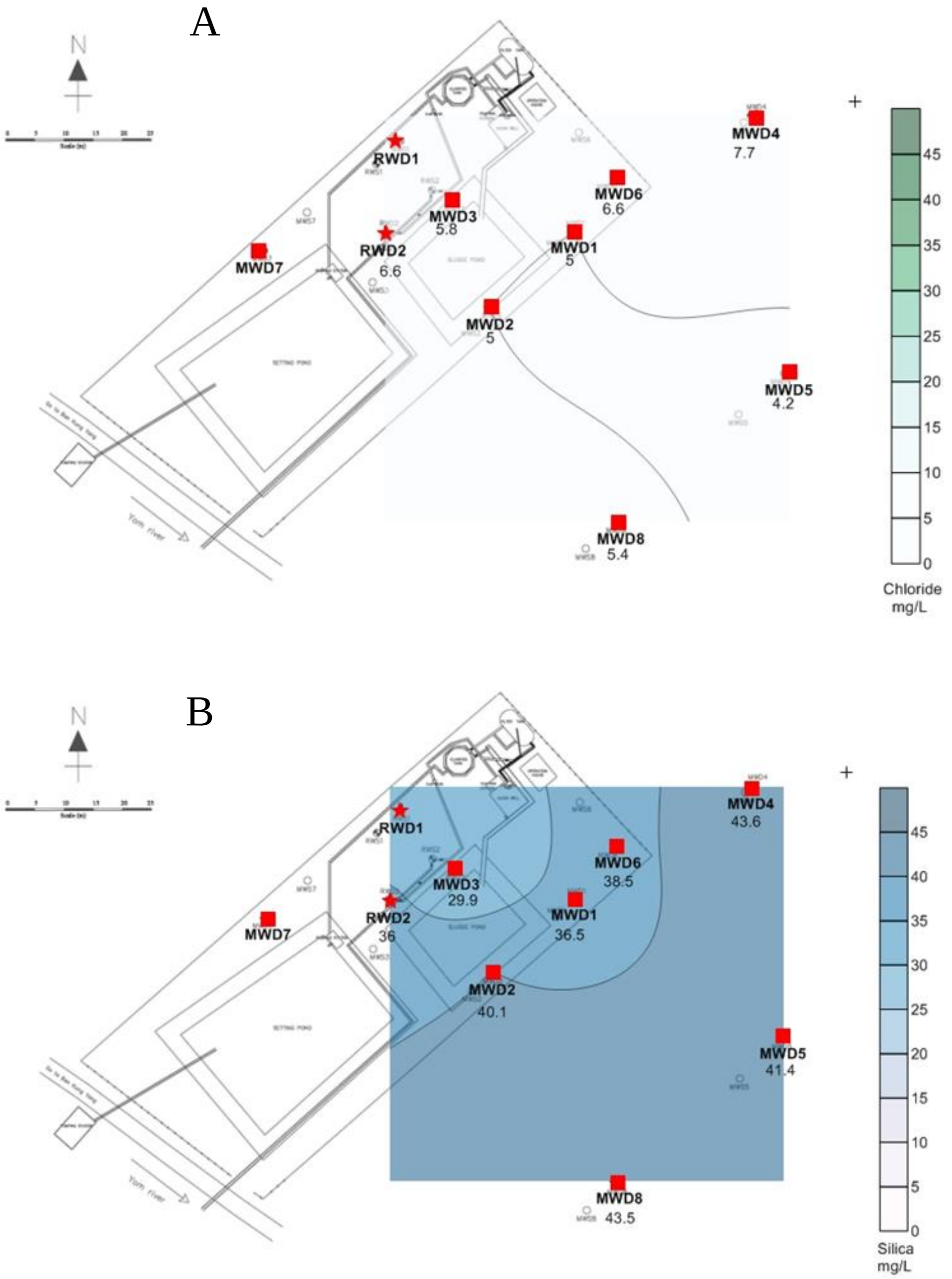

Figure 13. Chloride (A) and silica (B) distributions in the deep aquifer prior to ASR testing (September, 2012).

#### 5.1.1.2 Short-term Injection and Recovery

During the first injection test, a bull’s-eye pattern centered about the injection well emerges (Figure 14). Relatively high chloride (35.4 to 37.0 mg/l) and low silica (9.4 to 12.2 mg/l) concentrations were injected into the native groundwater. The silica and chloride concentration patterns are very similar after three days of injection. Given the southeast regional flow gradient, the distributions of chloride and silica during injection are expected to form southeast trending, elongated bull’s eyes. A more radial pattern is observed however, indicating that diffusive processes are more dominant than advective flow at this time during injection.

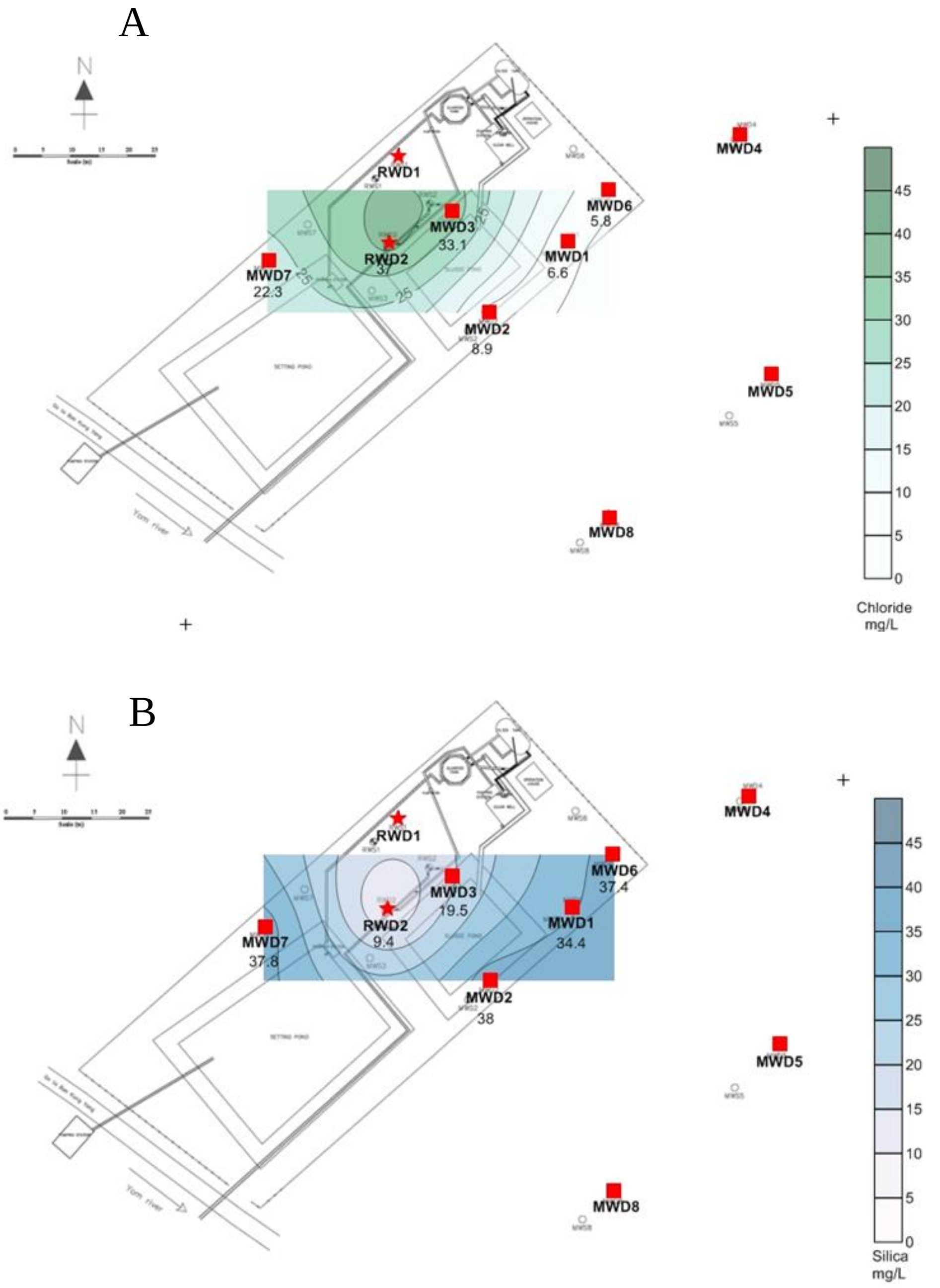

Figure 14. Chloride (A) and silica (B) distributions in the deep aquifer after 3 days of injection during the short-term injection test (September 15, 2012).

Recovery began one day after injection stopped. Chloride and silica exhibit similar distributions around the injection/extraction well, RWD2 on September 19, 2012 (Figure 15). The concentrations in the outer monitoring (MWD6 and MWD1) return to near background levels which indicates that the injection water has substantially been removed from this region of the aquifer. It should be noted that only 4,000 $m^3$ of recharge water was injected, so the monitoring well samples obtained shortly after recovery began show the radial pattern of the recovery process from the aquifer as would be expected. Additional samples were not obtained from the monitoring wells but additional samples were collected and analyzed from RWD2 as recovery continued. Analyses of these additional data are included in the section on recovery/mixing curves later in this document.

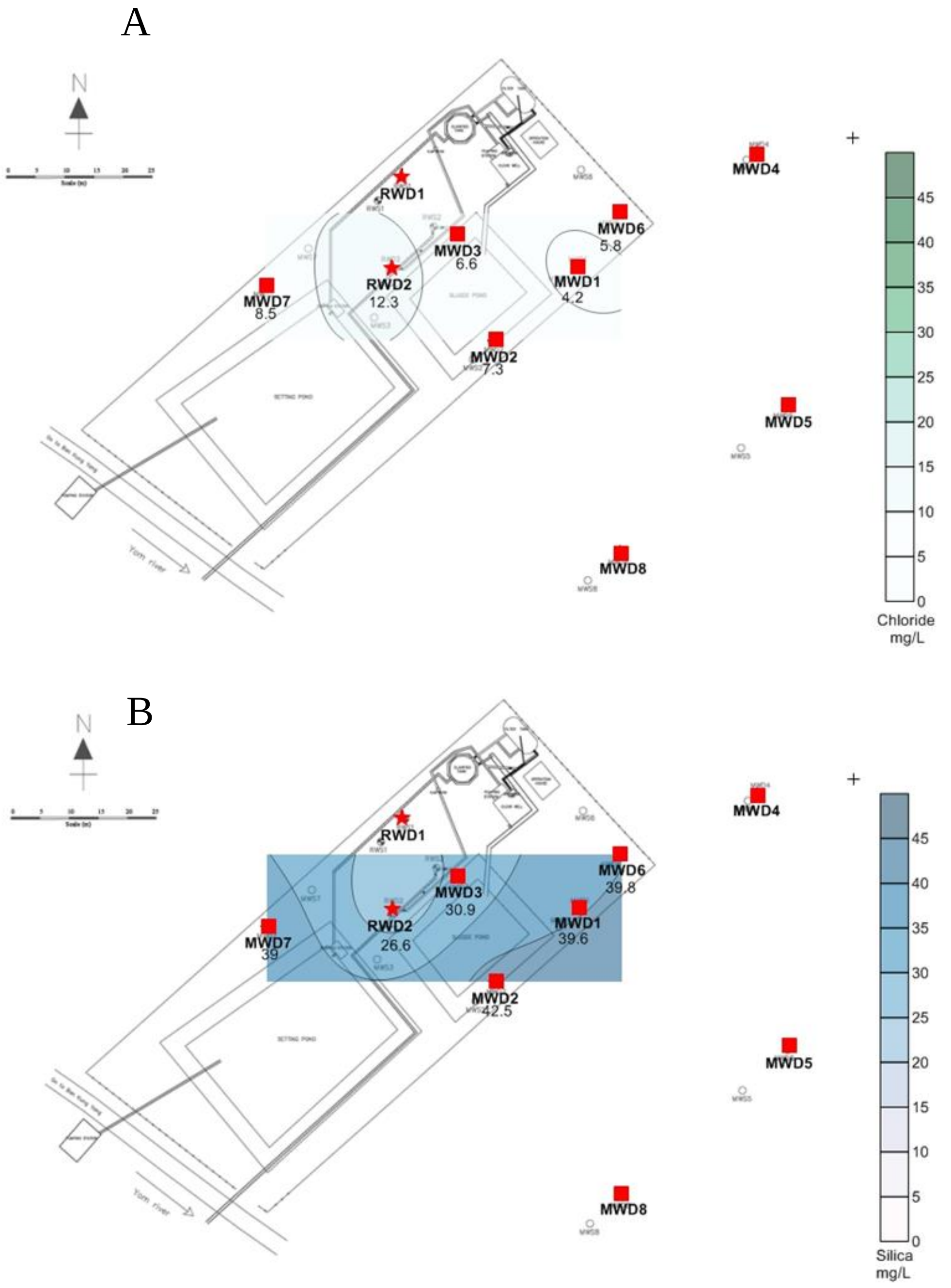

Figure 15. Chloride (A) and silica (B) distributions in the deep aquifer after 1 day of recovery during the short-term injection test (September 19, 2012).

#### 5.1.1.3 Long-term Injection and Recovery

The second deep aquifer test was a longer term injection of 30 days. The injection concentrations of chloride were from 37.7 to 45.5 mg/l and silica concentrations were from 11.2 to 13.1 mg/l). 12-14 days after injection began (October 31 – November 2, 2012), the distributions of silica and the chloride centered on well MWD1, indicating a lower chloride and higher silica concentration in comparison to the other monitoring wells (Figure 16). The post-injection concentrations at MWD1 are close to the background levels obtained for both ions in August and September, possibly due to: a less permeable region of the aquifer near MWD1, well installation at MWD1, inadequate well development at MWD1, or sample collection/recording error. Based on concentrations obtained (Figure 17), at the end of the long-term recharge on November 20, the concentrations around MWD1 are similar to the other silica and chloride concentrations in the aquifer. This finding indicates that the early anomalous pattern around well MWD1 was more likely due to sampling error rather than a well installation, or a less permeable area of the aquifer centered on MWD1. The injection patterns for both silica and chloride on the November 20, 2012 maps are very similar, but a higher concentration gradient exists in the chloride map. The difference in concentration between the injection and background is higher for chloride than it is for silica, which is reflected in the gradient differential.

Recovery of the injected water began five days after the injection ceased, on November 25, 2012. Samples from RWD2 were collected at commencement of recovery, and were obtained from the monitoring wells after approximately ten hours (Figure 18). The chloride concentration dispersion pattern differs somewhat from the

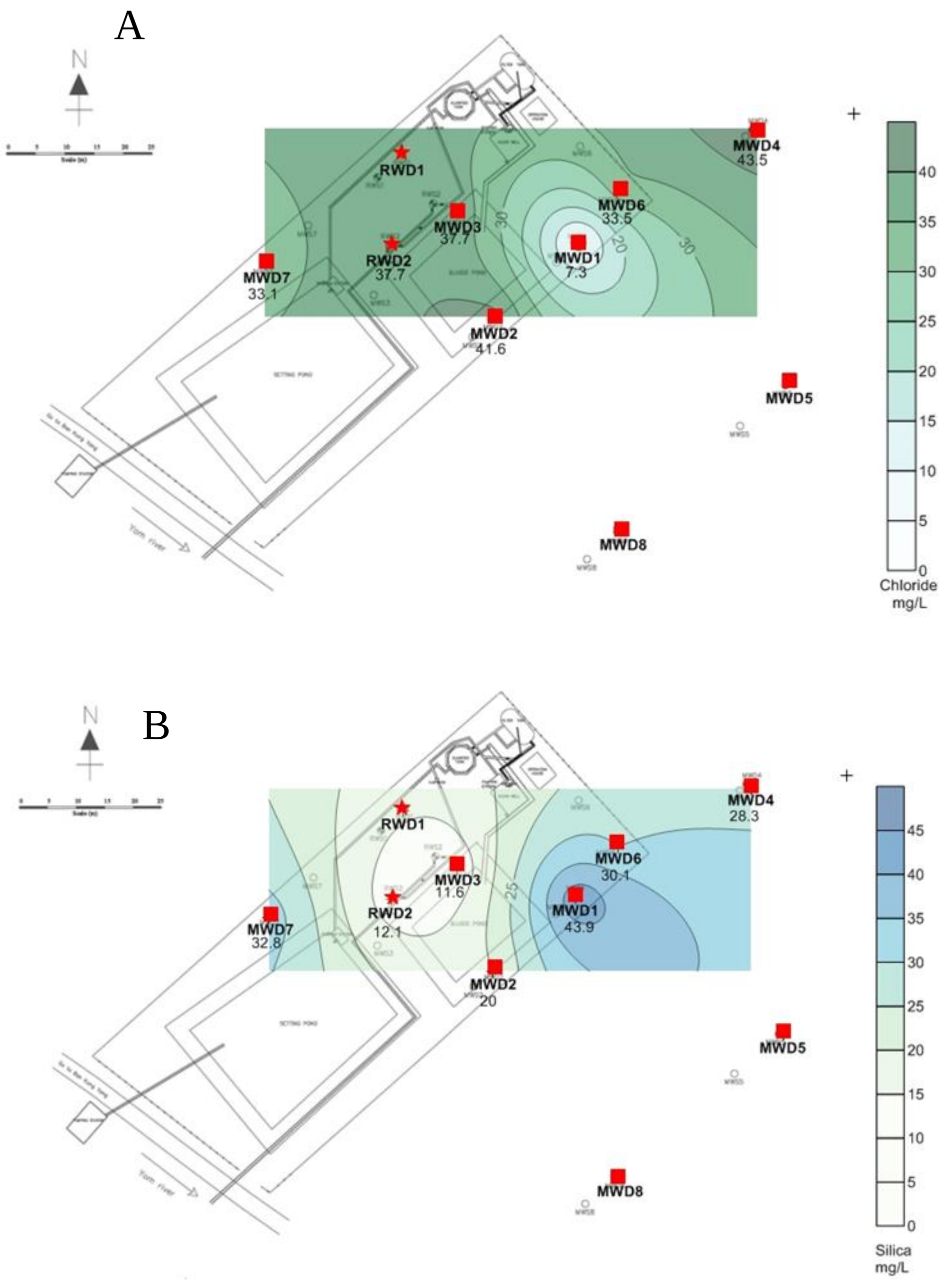

Figure 16. Chloride (A) and silica B) distributions in the deep aquifer after 12-14 days of injection during the long-term injection test (October 31 – November 2, 2012).

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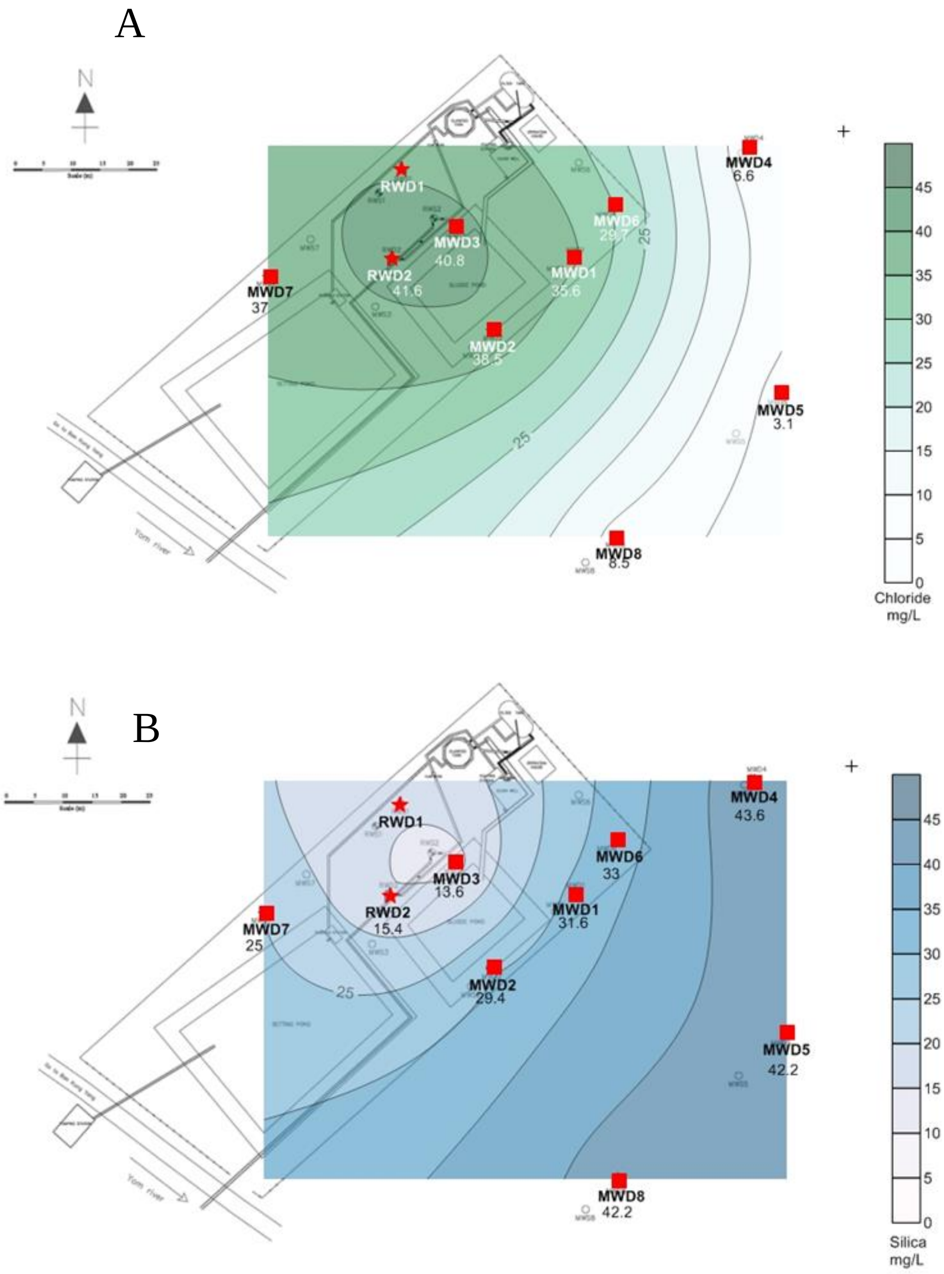

Figure 17. Chloride (A) and silica (B) distributions in the deep aquifer after 30 days of injection during the long-term injection test (November 20, 2012).

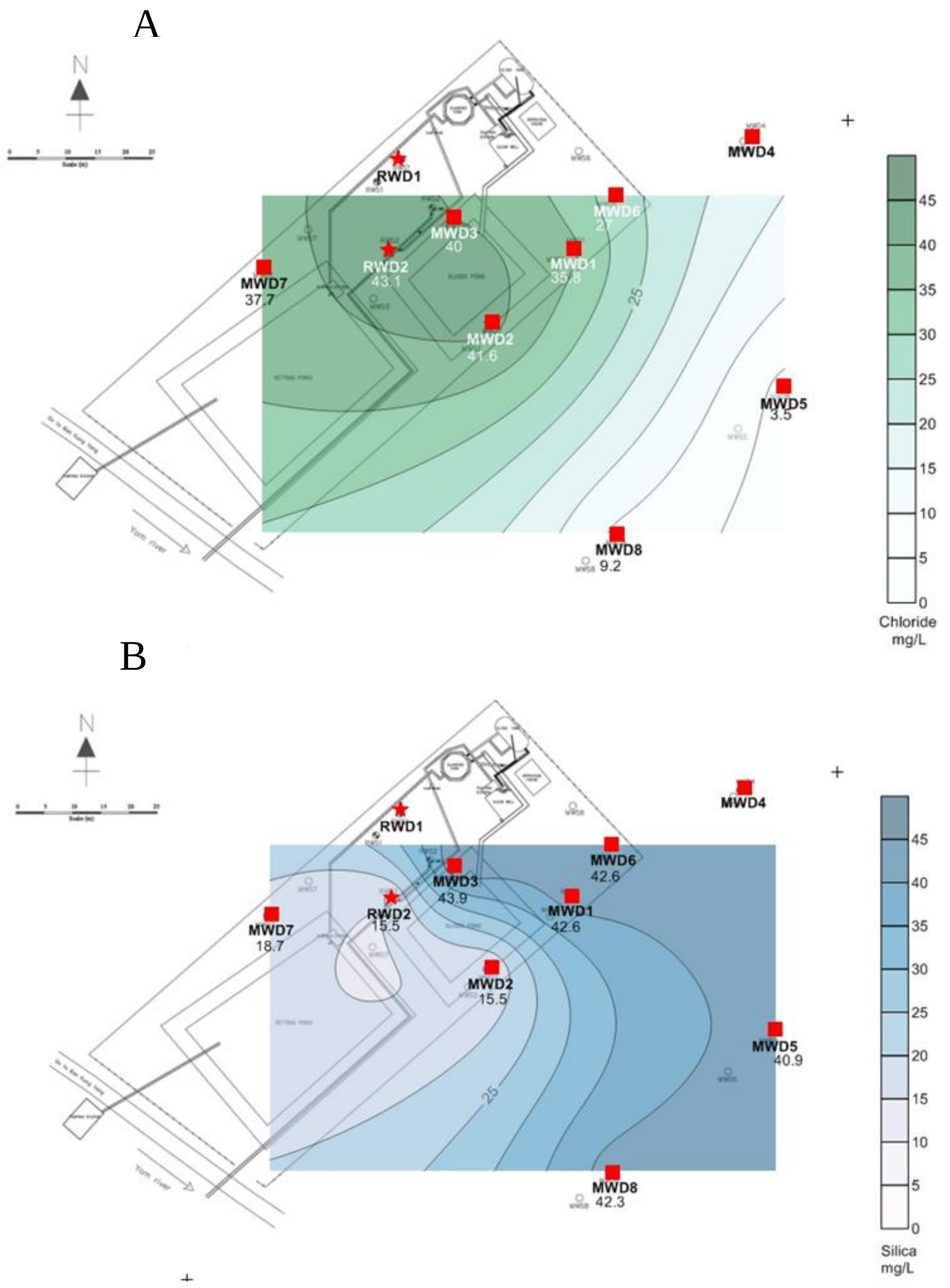

Figure 18. Chloride (A) and silica (B) distributions in the deep aquifer after 2 days of recovery during the long-term injection test (November 26, 2012).

silica pattern, particularly around wells MWD3 and MWD1. The silica concentration at these wells suggests that this area of the aquifer was returning to background conditions more quickly than would be indicated from the corresponding chloride concentration. Gradient differentials between silica and chloride concentrations may indicate that the variations in chloride concentration in the injection water may cause the higher chloride concentrations at wells MWD3 and MWD1 during recovery than would have occurred if the chloride injection concentrations had remained steady. Well MWD1 produced questionable concentrations earlier in the test (Figure 16) which may be further indication of well development or installation issues. The concentration patterns may be due to greater heterogeneity in silica concentration within the deep aquifer as was seen in the background maps (Figures 12 and 13). However, during background testing, the silica concentrations at those wells were between 36 mg/l and 39 mg/l (lower silica concentration area) than the other wells. Physical heterogeneity could be a factor in distribution of concentrations during recovery and should be monitored in future studies. The silica concentration during recovery (42.6 mg/l) at MWD1 and MWD3 indicate movement of native aquifer water into that area of the aquifer during recovery. The chloride concentrations do not support this contention; however, the chloride concentrations injected during this test varied between 45.5 mg/l on October 23, 2012 to 37.7 mg/l on October 31, 2012 and then to 41.62 mg/l on November20, 2012 . The wide variation in chloride concentrations throughout injection undoubtedly had effect on the concentration maps for this test. If the chloride concentrations had remained constant, they would likely have better emulated the movement of silica concentrations within the aquifer. Future testing with more consistent injection water chemistry would be beneficial for comparison.

### 5.1.2 Shallow Aquifer

#### 5.1.2.1 Background Conditions

Short-term and long-term testing on the shallow (upper) aquifer was completed in October and November, 2012 and January through February, 2013 respectively. The background concentrations in August and early September were substantially consistent (0.4 to 2.3 mg/l for chloride and 33 to 38.2 mg/l for silica). Both the silica and the chloride concentrations in the upper aquifer are lower than in the deep aquifer. The background concentrations of both ions are uniform throughout the aquifer (Figures 19 and 20).

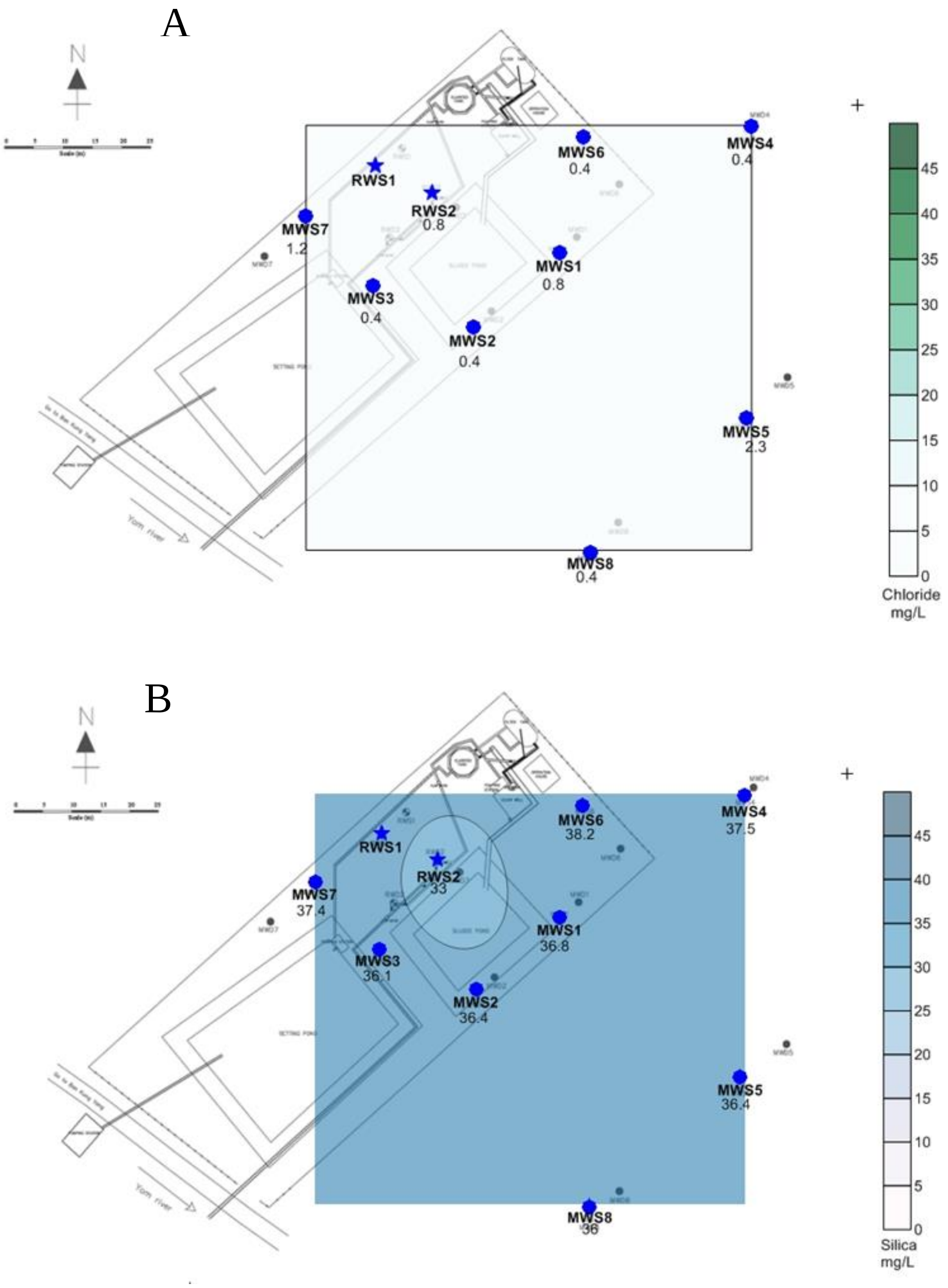

Figure 19. Chloride (A) and silica (B) distributions in the shallow aquifer prior to ASR testing (August, 2012).

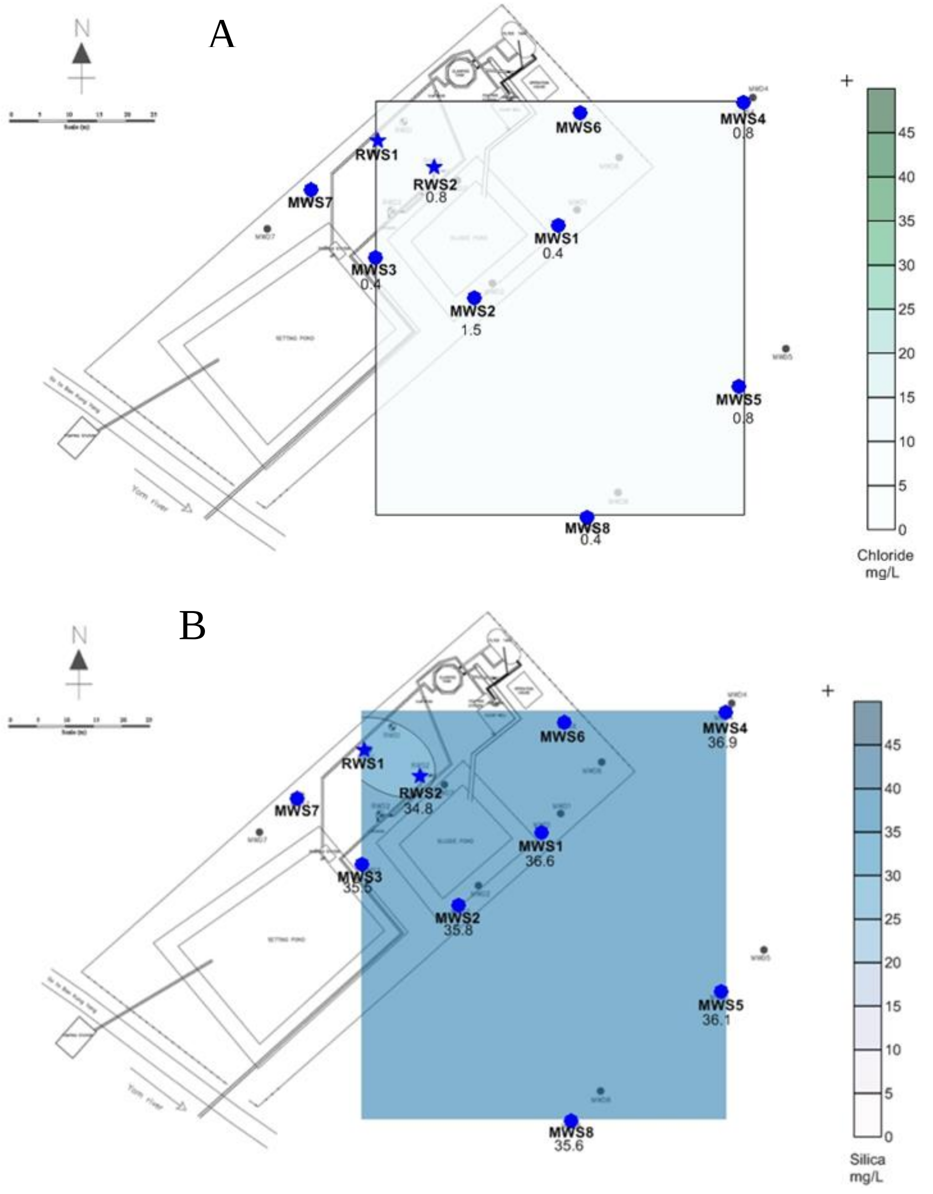

Figure 20. Chloride (A) and silica (B) distributions in the shallow aquifer prior to ASR testing (September, 2012).

#### 5.1.2.2 Short-term Injection and Recovery Test

Short term injection testing began on October 10, 2012 (Figure 21). Chloride concentrations in the injection water varied from 55.8 to 57.8 mg/l and silica concentrations varied from 10.2 to 10.5 mg/l. The initial injection concentrations for both the silica and the chloride have very similar overall dispersion patterns within the upper aquifer. The southeast regional flow gradient was expected to produce a southeast trending, elongated bull’s eye for both chloride and silica. A more radial pattern is observed, indicating that diffusive processes from injection are more dominant than advective flow.

Recovery began on October 13, 2012 with monitoring well sampling taking place between the 13th and 15th. The fact that the samples were obtained over a two-day period may have slightly influenced the recovery concentrations within the aquifer, but overall recovery maps of two ions are substantially similar (Figure 22).

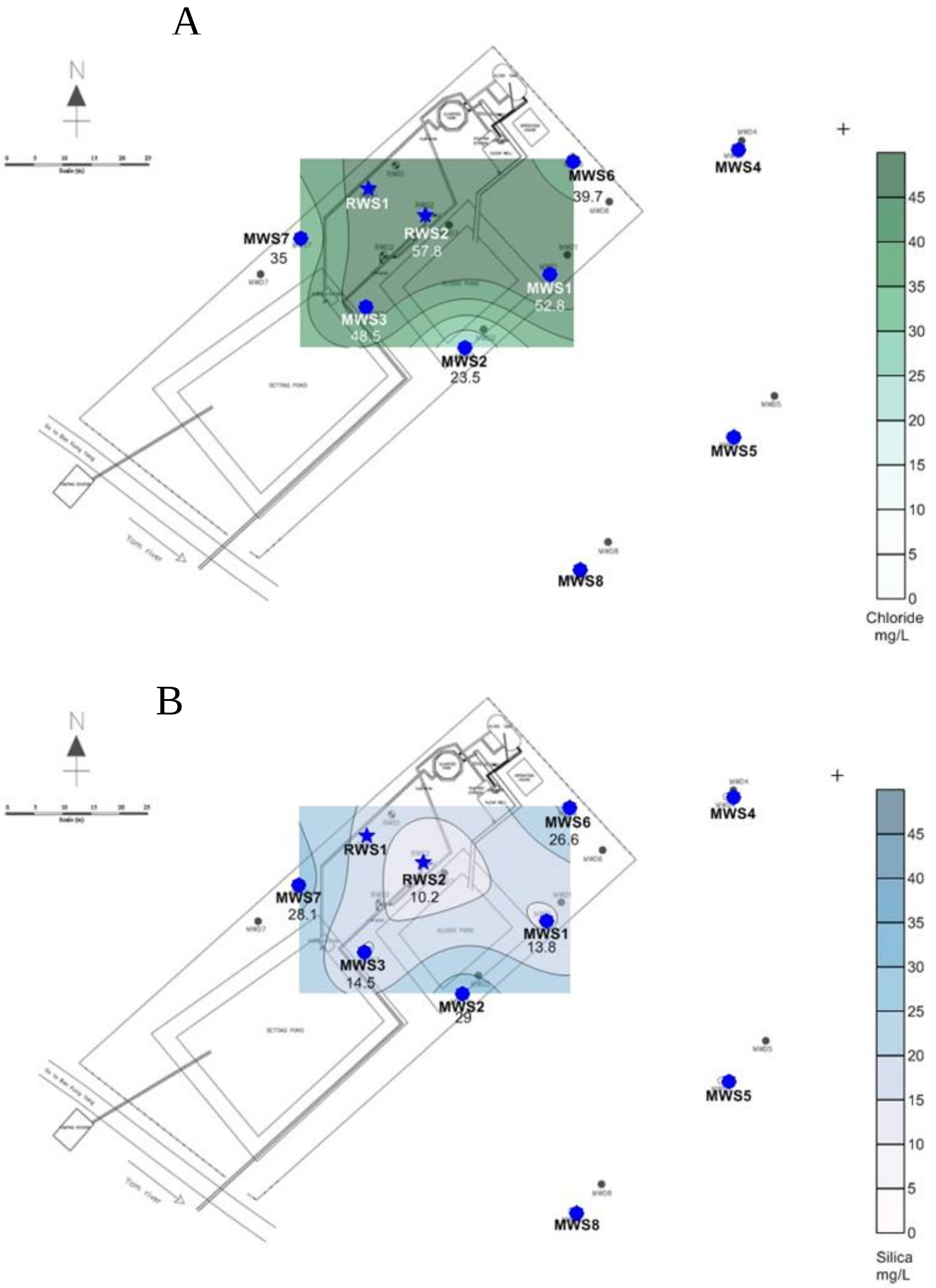

Figure 21. Chloride (A) and silica (B) distributions in the shallow aquifer after 3 days of injection during the short-term injection test (October 10 – 11, 2012).

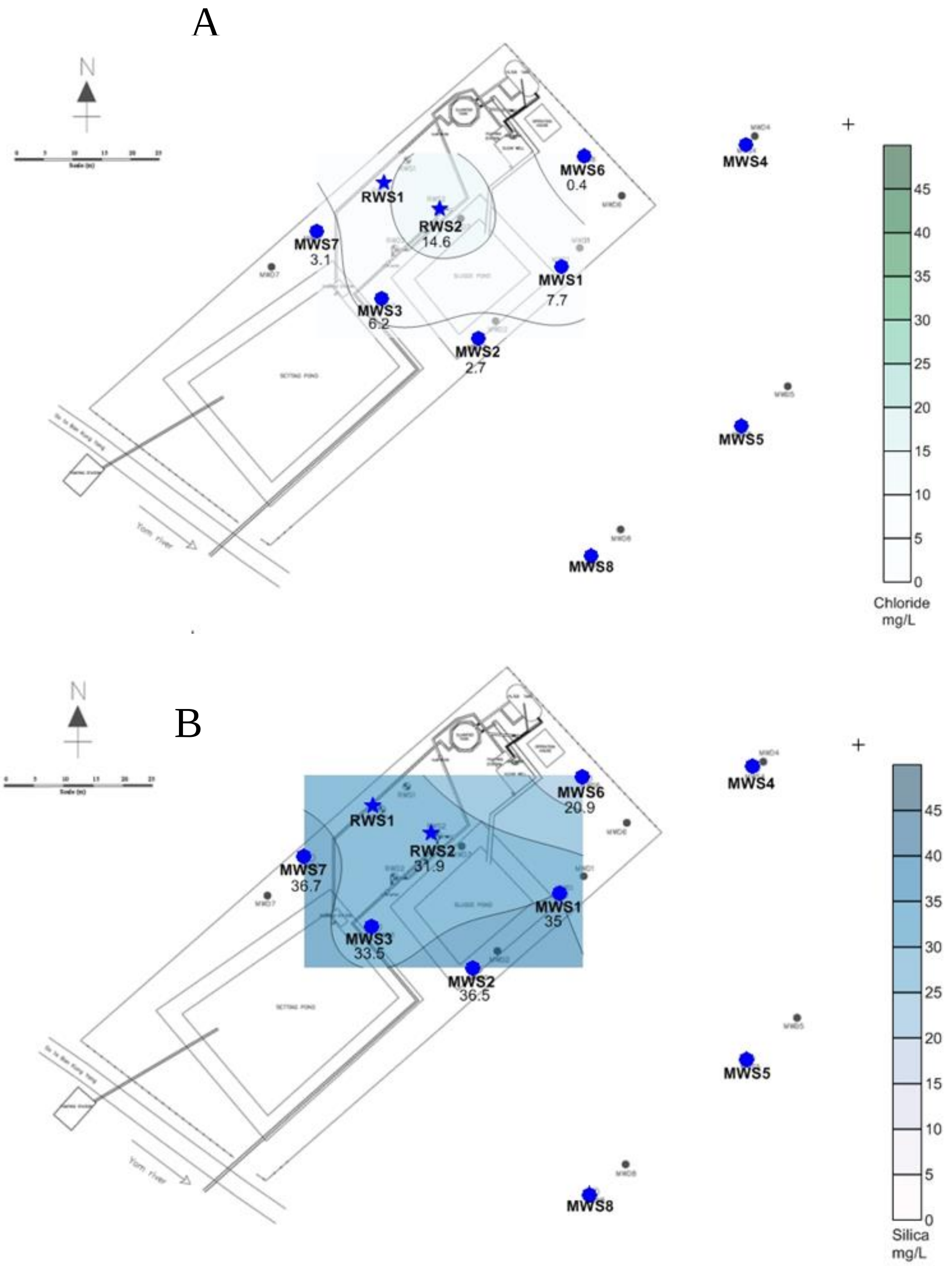

Figure 22. Chloride (A) and silica (B) distributions in the shallow aquifer after 2 to 5 days of recovery during the short-term injection test (October 13-15, 2012)

### 5.1.2.3 Long-term Injection and Recovery Test

Long-term injection testing in the shallow aquifer began on January 6, 2013. The concentration of chloride was higher in the injection water than during the short term injection test. Differences in the chloride and silica distributions within the shallow aquifer approximately 20 days after initial injection are minimal (Figure 23). The concentration of chloride in the injection water was elevated from an initial concentration of 45.1 mg/l on January 6, to 55.1 mg/l on January 12. The concentration of silica in the injection water was fairly consistent throughout the injection. The alteration of chloride concentration in the injection water is responsible for the higher differential gradient which is observed in the chloride map (Figure 23). The monitoring wells were sampled on February 4, which was after approximately 30 days of recharge (Figure 24). Discrepancy in the distribution gradient for chloride and silica can be attributed to the alteration of chloride concentration the injection water during January.

Recovery began on February 10, 2013, 15 days after the cessation of injection; sampling at the monitoring wells began the following day. The gradient is similar for both the silica and chloride in the shallow aquifer (Figure 25). The ion concentrations return to background levels more quickly at MWS1 than the nearby MWS2 and MWS3. Preferential flow is apparent in the shallow aquifer during injection (Figures 23 and 24) and in the recovery (Figure 25). The distribution patterns suggest that there may have been problems with MWS1 either during well development or damage to the aquifer during well installation, or general aquifer heterogeneity may exist in this area because the injection water arrived at MWS1 earlier (Figure 23) than other, nearby monitoring

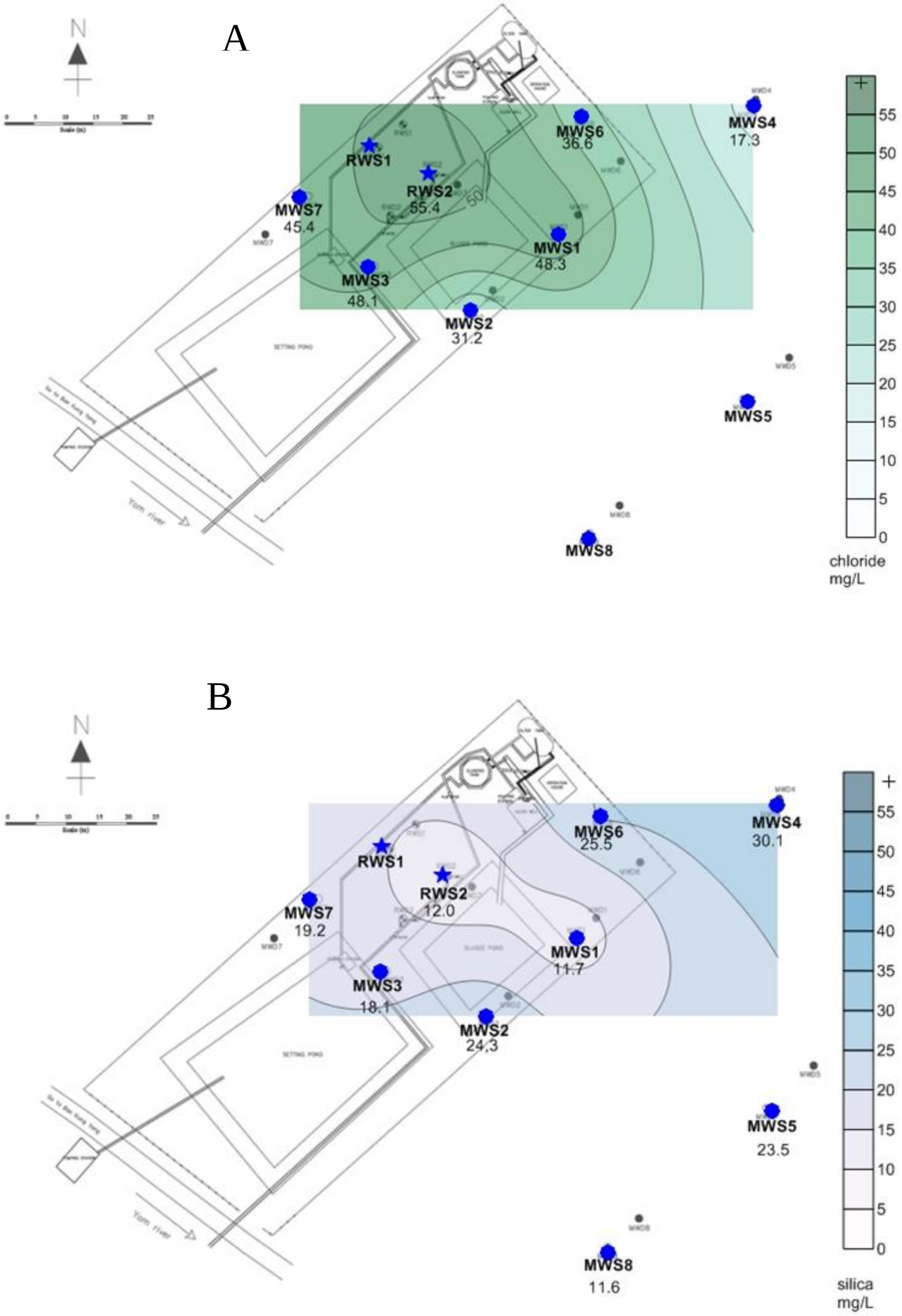

Figure 23. Chloride (A) and silica (B) distributions in the shallow aquifer after 15 days of injection during the long-term injection test (January 20, 2013).

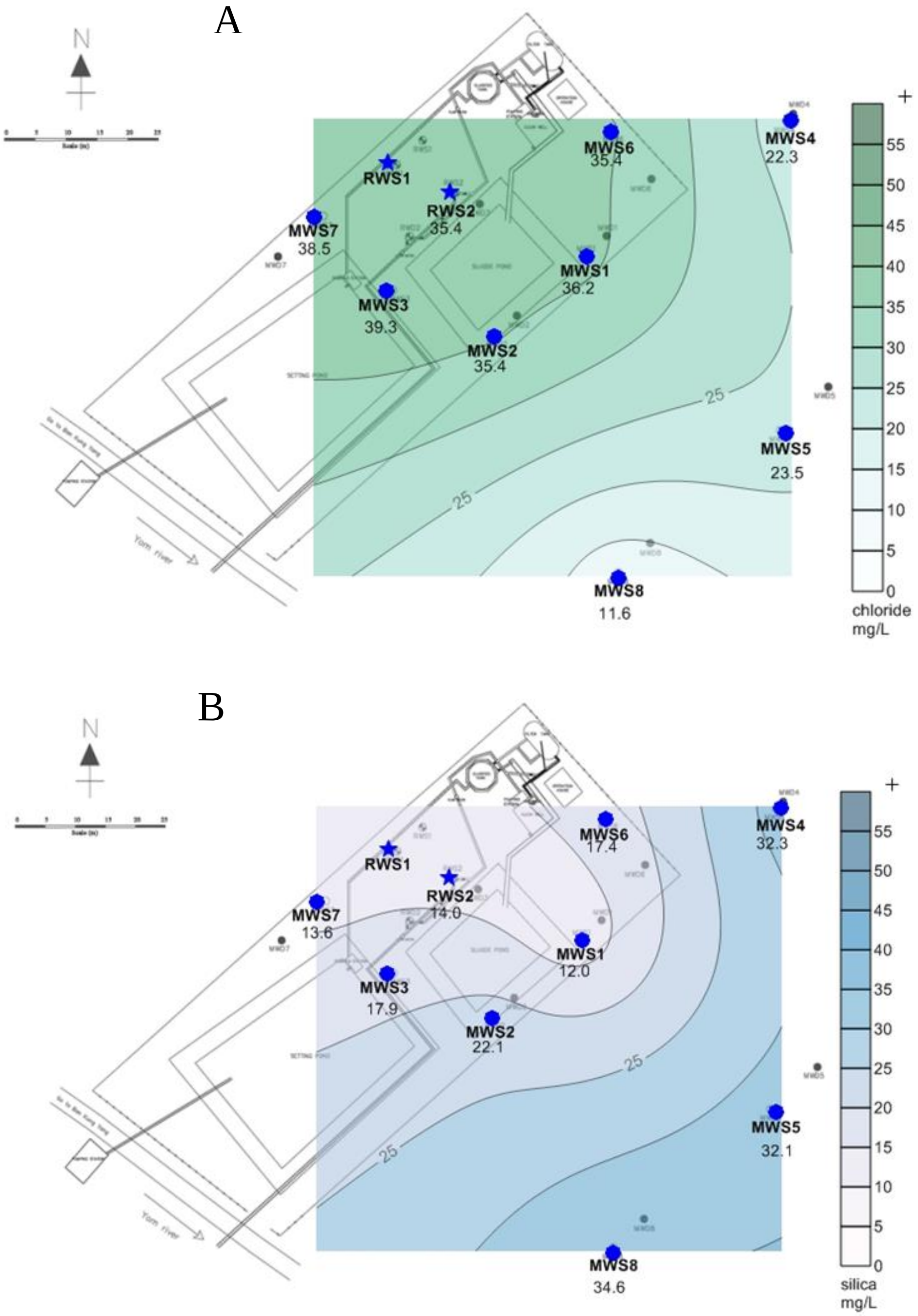

Figure 24. Chloride (A) and silica (B) distributions in the shallow aquifer after 30 days of injection during the long-term injection test (February 4, 2013).

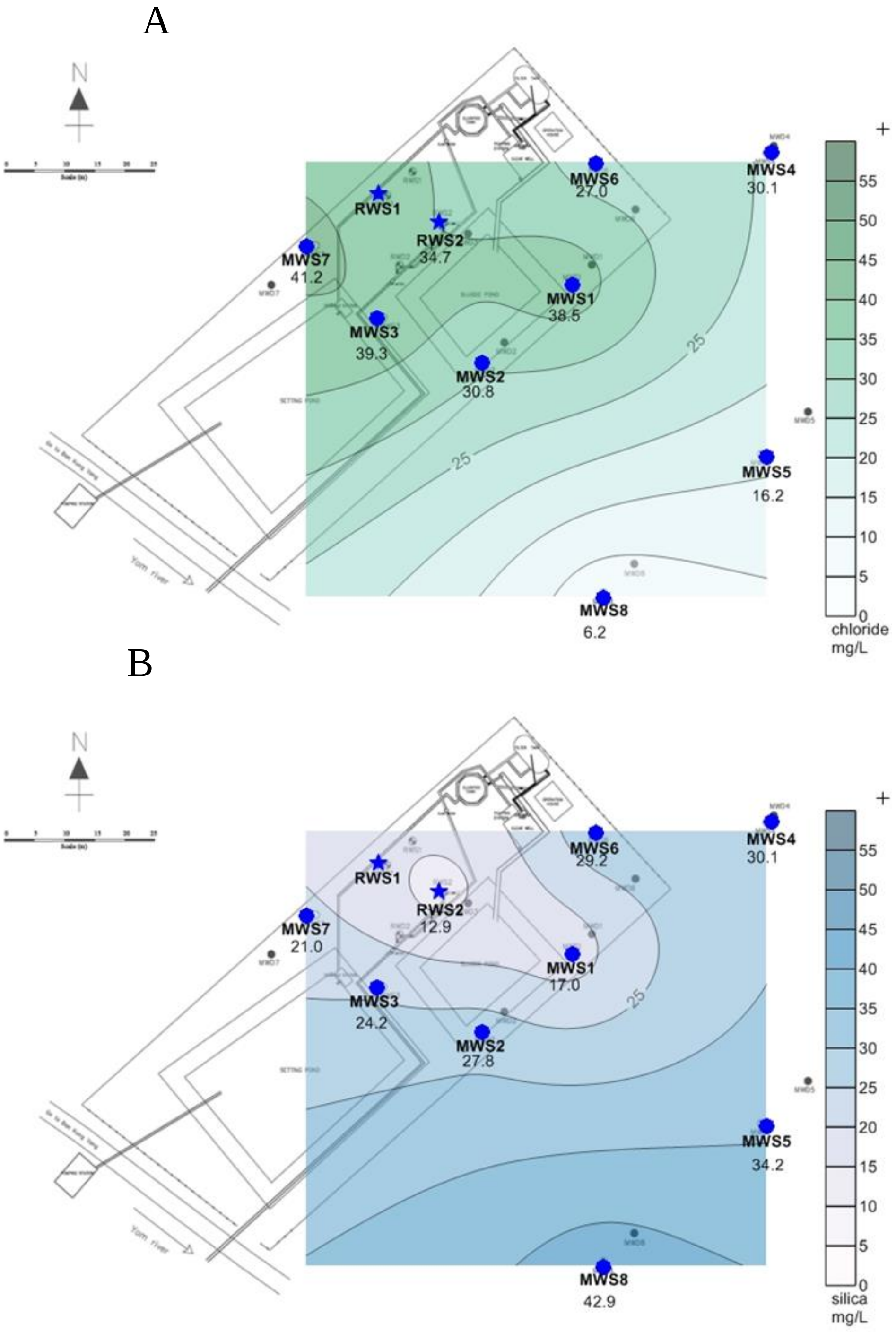

Figure 25. Chloride (A) and silica (B) distributions in the shallow aquifer after 2 days of recovery during the long-term test (February11, 2013).

wells and the recovery concentrations lagged (Figure 25) when compared to the same nearby monitoring wells.

Chloride and silica distributions in the upper aquifer are similar to those in the lower aquifer, suggesting similar flow characteristics in both aquifers. A steeper chemical gradient is observed for chloride during the long-term injection in the upper aquifer, due to a wider range in injection concentration than in silica. The diffusive process upon injection is pronounced in both the upper and lower aquifers. The dispersion due to injection is stronger than the diffusive southeasterly advective flow from the natural groundwater gradient in the aquifers. There is more pronounced advective flow to the southeast in the upper aquifer than in the lower aquifer, but the flow is evident in both aquifers after long-term injection.

### 5.2 Ion Concentration during Recovery: Tracer Dispersivity and ASR Efficiency

The four cycle (two short-term and two long-term, in both the upper and lower aquifers) tests were compared to native groundwater conditions prior to injection. As discussed in section 4.2.2, concentrations of silica and chloride in the injected water varied during the seven months of testing. The variation in injected water chemistry required multiple calculations based on:

- highest injected water ion concentration and highest background aquifer ion concentration
- average injected water ion concentration and the average background aquifer ion concentration
- lowest injected water ion concentration and the lowest background aquifer ion concentration

- highest background concentration and the lowest injected water concentration
- lowest background concentration and the highest injected water concentration.

Calculations used to define each curve are based on the equation presented in section 3.2.3, and are included in Appendix F. Recovery levels for the widest range of injection and background concentrations are presented for the short and long-term tests in both the upper and lower aquifers. The relative concentrations are then plotted against the percentage of injected water that was recovered at the time of sampling from the recharge/recovery well. In a study on the upper aquifer downstream of this site in Phitsanulok, Thailand, the silica concentrations ranged from 20 to 31mg/l during the dry season and 20 to 23 mg/l during the rainy season (Promma, 2007). Similarly, the chloride concentrations ranged from 2 to 20 mg/l during the dry season, and from 2 to 15 mg/l during the rainy season. There may be similar variation in background concentration at the Sukhothai site. Additional collection of background data during the dry season would help to substantiate similar conditions at this site. These concentration variations could be relevant to this analysis as some of the testing occurs several months after the native groundwater levels were established. If a similar seasonal variation exists at the Sukhothai site as it does at the Phitsanulok site, the collection of additional background concentrations closer to the periods prior to cycle testing would be prudent.

### 5.2.1 Short-Term Deep Aquifer Recovery Curve

The short-term deep aquifer test was the initial cycle test conducted during this project. Testing began on September 12, 2012 and ended on September 20, 2012. In general, the silica relative ion concentration curves are higher than chloride (Figure 26). Concentrations collected in the first three sampling periods indicate that higher concentrations of silica are recovered than for chloride. In the fourth sample, the concentration of silica recovered was the same as the third sample. The chloride concentration increased significantly from the third to the fourth sample during recovery. Date comparison on the 4th and 5th sampling seem to indicate that chloride concentration was nearly even, while the silica concentration was much higher on the 5th sample than on the 4th.

An additional period indicated in the field notes as injection under gravity on 9/20/2012 to 9/21/2012 occurred after recovery commenced. The additional injection period makes this data difficult to interpret. As discussed in section 4.2.2, both the chloride and the silica concentrations in the injection water were held fairly steady during this short-term injection test. Silica concentration ranged from 9.4 to 12.2 mg/l, and chloride ranged from 35.4 to 37 mg/l.

A more even temporal sampling distribution would have provided better data for analysis. For optimal understanding of how the recovery actually proceeded, it would have been advantageous if the sampling had occurred throughout the recovery test and not collected closely in time followed by a longer period before additional sampling. The personnel collecting the samples were being trained during testing, which likely contributed to some of the issues encountered. It is unclear why the chloride concentration increased so rapidly between the 3rd and 4th samples while the silica concentration remained steady. It is also unclear why the concentration of chloride would then be essentially flat on the final collection while the silica resumed its earlier increase in concentration. The most likely explanation is collection error. Since the short-term recovery did not continue past 100% recovery to near the 140% level of the other three tests, these data were not considered in the overall analysis of aquifer efficiency compiled in this thesis.

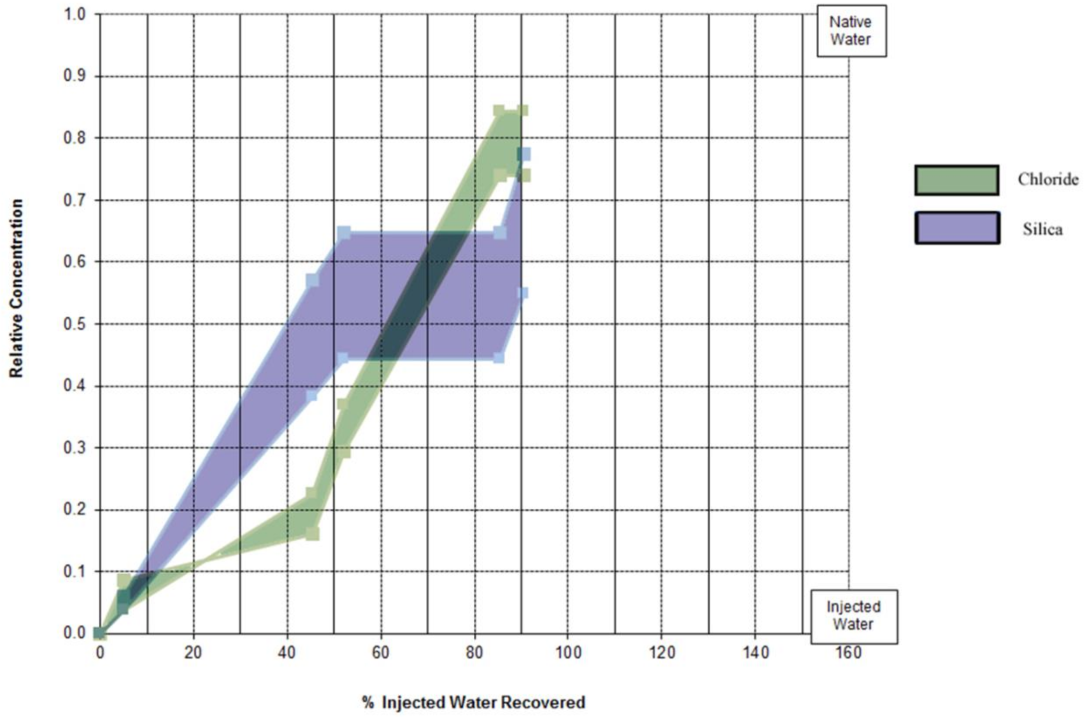

Figure 26. Deep aquifer, short-term test recovery curves (September 17 – 19, 2012).

### 5.2.2 Long-term Deep Aquifer Recovery Curve

The long-term deep aquifer injection and recovery test began October 18, 2012 and ended December 9, 2012. Variations in the expected recovery for both chloride and silica indicate a similar reduction in relative concentration at around the 60% recovery period (Figure 27). From 40 to 90% recovery, silica concentrations were higher than for chloride. The recovery curves are very similar after the 100% injected volume is reached.

As discussed in section 4.2.2, the chloride concentration during injection varied between 37.7 and 45 mg/l, and the silica concentration was 11.2 to 13.1 mg/l. The variation in chloride concentration during injection may be responsible for the lower levels of chloride recovery than silica. During this injection phase of this test, multiple injection and back-flushing cycles were performed to alleviate well clogging. From the period of 10/18/2012 to 11/20/2012 there were 49 backflushing events. The recovery phase was completed without backflushing; however it is not clear how the backflushing affected the movement of the injection water prior to recovery. Since the samples were collected for this test near the end of the rainy season in October, it is possible that variations in background concentrations may have occurred that could skew the recovery curve data comparisons.

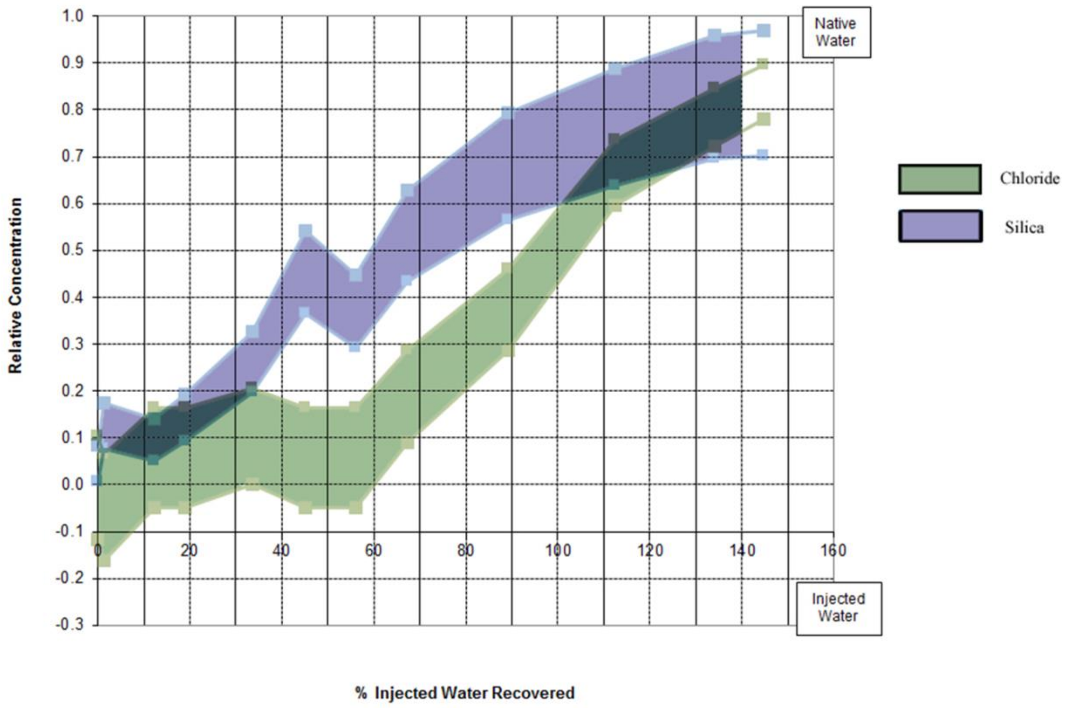

Figure 27. Deep aquifer, long-term test recovery curves (November 25 – December 8, 2012).

### 5.2.3 Short-term Shallow Aquifer Recovery Curve

The short-term upper aquifer injection and recovery test was performed between October 7 and 15, 2012, approximately month after the background data conditions were established. Chloride and the silica recovery at three of the five sampling times (Figure 28) are similar. After 20% recovery, a higher relative amount of silica was recovered than chloride. After approximately 40% of the water recovery, the chloride and silica concentrations are similar. Higher silica than chloride concentrations exist until approximately the 140% recovery volume where the ion concentrations of silica and chloride are both at nearly 90% recovered. The sampling at the Sukhothai site was collected toward the end of the rainy season in October. It is possible that the variations could be due to the time differences between the background testing concentrations and the collection of the injection data a month later if the background concentrations were substantially altered between the establishment of the background levels and the performance of the tests.

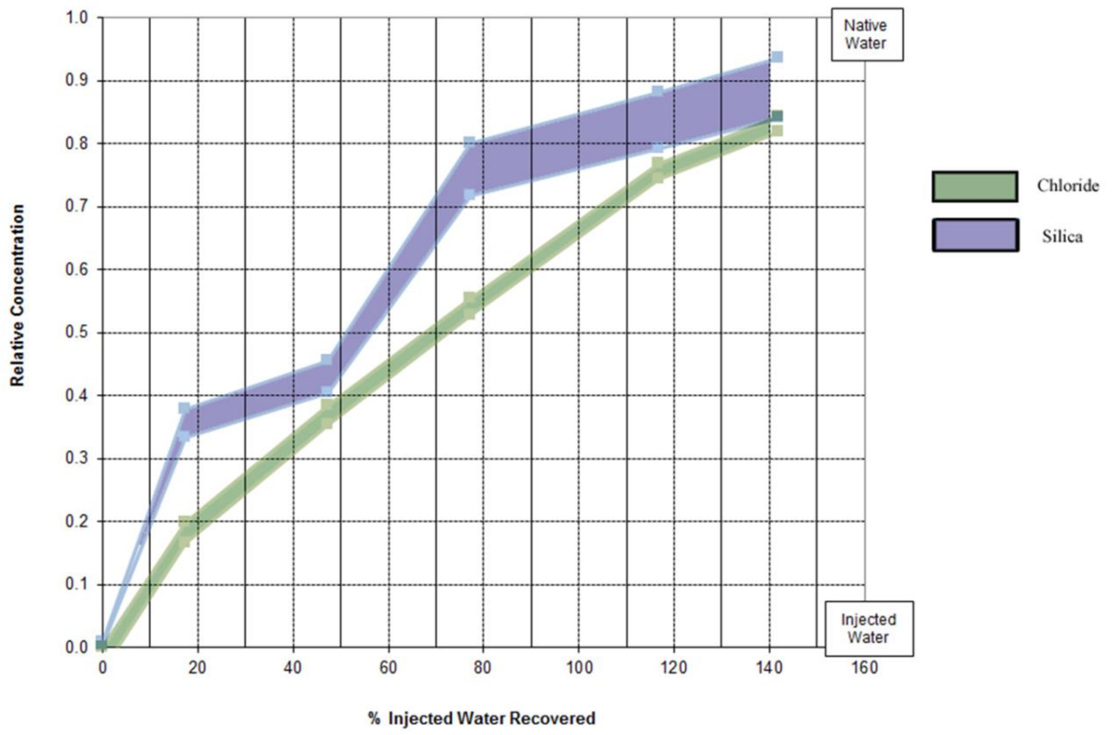

Figure 28. Shallow aquifer, short-term test recovery curves (October 12 – October 14, 2012).

### 5.2.4 Long-Term Shallow Aquifer Recovery Curve

The long-term test began on January 5, 2013 and ended February 25, 2013. The silica concentrations overlap the chloride concentrations for most of the recovery period, but the silica concentrations are slightly higher during the 40 to 80 percent recovery period (Figure 29). The background concentrations used to construct these curves were obtained during September, 2012 and the cycle tests were conducted in January and February of 2013.

As discussed in section 4.2.2, larger amounts of PACl were added to the injection water during the long-term shallow aquifer test resulting in increased concentrations of chloride ions. The chloride concentration in the injection water was initially 45.1 mg/l, was then increased to 55 mg/l on January 12, and then lowered to 36 mg/l on January 30. This wide range of chloride concentration accounts for the variation seen in Figure 28. The negative relative concentration values are attributable to the variation in concentrations of chloride in the injection water when compared to background concentrations. In some scenarios, when comparing the highest background concentration to lowest injection concentration, the calculations of ionic concentrations were negative. The situation is theoretical and is provided to include the widest possible range of values which could occur. The theoretical situation where the injection was at its lowest and the background was at its highest did not actually occur at the period of recovery.

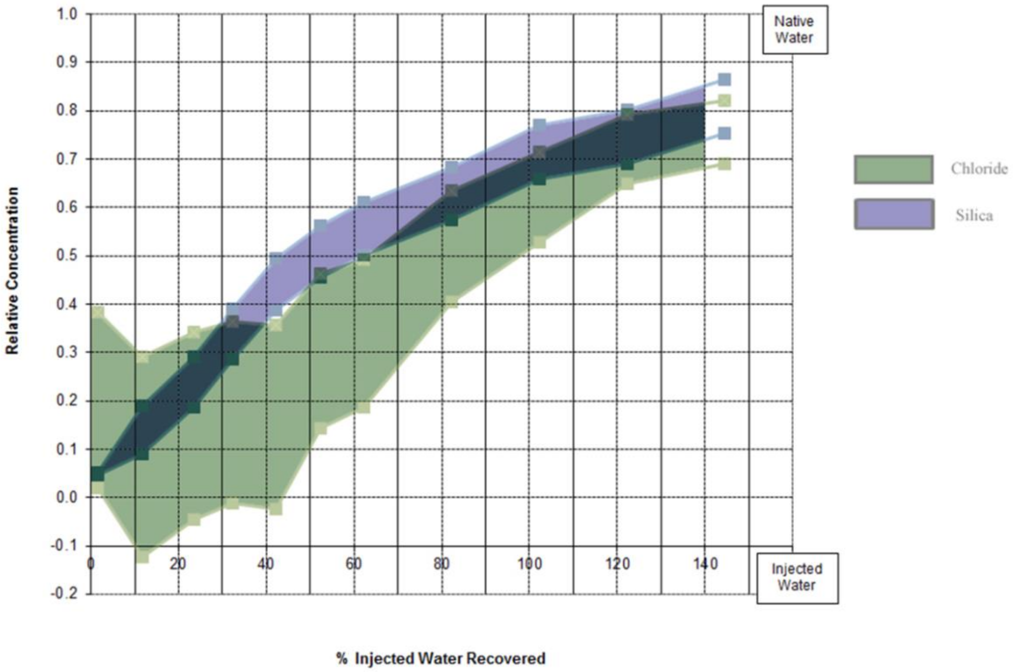

Figure 29. Shallow aquifer, long-term test recovery curves (February 10 – February 24, 2013).

In summary, discrepancies in relative ion concentrations for silica and chloride were observed in all four recovery curves. Different chemical gradients observed within the aquifers as noted on concentration maps likely influenced the differences observed between the two ion concentrations on the recovery curves. Backflushing events and variations in the ion concentrations during injection tests likely also affected the concentrations obtained throughout the recovery tests. The long-term tests in both the upper and the lower aquifers showed a stronger correlation between chloride and silica concentrations recovered than the short-term cycle tests. Although it is not possible to say that silica concentrations completely overlapped those of chloride throughout the tests, there is a very strong correlation in concentrations recovered for both ions at the 140% recovery periods for each of the three tests that continued to that point. These curves indicate that silica behaves conservatively as does chloride during these tests which supports the hypothesis that silica will behave in a similar manner to chloride.

### 5.3 Overall Recovery Efficiency

Aquifer recovery efficiency is defined as the percentage of the water volume that is stored which is recovered, while meeting target water quality in the recovered water (Pyne, 1995). Recovery efficiency is often based on a percentage recovery of the tracer being used. Recovery concentrations may be calculated at different times during the recovery process for various volumes. To evaluate overall performance for this ASR project the percent recovery was calculated based upon ion concentration at the end of each cycle test.

Recovery efficiencies for the ASR in the two long-term and one, shallow aquifer short-term tests are between 69 to 97% (Table 5). Similar silica and chloride recovery concentrations during the 4 cycle tests support previous indications of conservative behavior of both ions. The high percent recoveries suggest that little dispersion occurs during both short and long-term tests, and indicate efficient ASR recovery. Where percent recoveries of the two tracers differ, aquifer chemical heterogeneity and/or variations in injected chloride concentrations are likely explanations for the differences.

| % of tracer recovered | | | |
|---|---|---|---|
| Tracer | Short-term shallow test | Long-term shallow test | Long-term deep test |
| Chloride | 83-84 | 69 - 82 | 78-90 |
| Silica | 84-93 | 75 - 87 | 70-97 |

Table 5. Recovery efficiency at 140% of injection water recovered

# CHAPTER 6. CONCLUDING REMARKS

The purpose of this study was to evaluate the use of dissolved silica as an alternative, low cost, non-reactive, traceable element to monitor the infiltration and mixing of ASR recharge water within the Chao Phraya aquifer. Silica was considered an effective alternative if its spatial distribution was similar to that of chloride during injection, and if the relative silica levels in the recovered water were within those of chloride given the variation in injection and background concentrations. Chloride was selected for the comparison because it is the most commonly used tracer element in monitoring ASR processes. The lack of reactive quartz and highly weathered feldspar in sediments suggests that little silica will be added to or removed from groundwater during ASR tests.

Four injection and recovery tests were performed: a short-term and a long-term test in the lower aquifer, and a short-term and long-term test in the upper aquifer. Comparisons were made between dissolved silica and chloride concentrations during the injection and recovery tests.

The spatial distributions of chloride and silica during the injection, storage and recovery were similar. The bulls-eye patterns observed during injection and recovery centered on the ASR wells RWS2 and RWD2. The movement of silica and chloride concentrations after injection in both the upper and lower aquifers was comparable. Chloride and silica distributions were consistent with each other indicating that they both behaved conservatively during testing; however there was a higher chemical gradient for the chloride during injection and recovery due to the higher concentrations of chloride injected. Diffusive flow was predominant after initial injection as indicated by the bulls-eye patterns centered on the recharge wells. The advective flow of both silica and chloride was expected to be in a southeasterly direction due to the regional flow gradient, and these advective flow patterns did emerge during the long-term injection tests in both the upper and lower aquifers for both silica and chloride. Concentration maps for both silica and chloride displayed similar areas of physical heterogeneity within the aquifer. The background concentration levels of silica indicated more chemical heterogeneity for silica in the deep aquifer than the shallow aquifer, while chloride concentration levels within the deep aquifer were more evenly distributed. Silica and chloride native groundwater concentrations in the shallow aquifer did not indicate a large amount of chemical heterogeneity.

The recovery data supports the use of silica as a tracer. In both the long-term deep and shallow aquifer tests, considerable similarity was found in the final recovery concentrations of chloride and silica while the interim concentration levels of silica and chloride were not well matched. The wide variation in chloride injected during the long-term shallow aquifer test resulted in a wide recovery concentration levels for the recovery percentages for chloride. Longer-term tests indicated a closer relationship between the silica and the chloride than the shorter term tests.

Comparisons for the recovery curves were made based on background data obtained in September, 2012. In future testing, it is recommended that background testing at the monitoring wells be performed between tests, closer to the period before the injection commencement. Recovery percentages would be more accurate when compared to more current existing conditions within the aquifer than comparison to background concentrations that were possibly altered during short-term testing.

Similar silica and chloride concentrations during injection and recovery demonstrate the conservative behavior of both species, and provided information about aquifer heterogeneity, and ASR efficiency. Additional data gained during future cycle testing at the Sukhothai site, and more frequent sample collection throughout the testing periods would help to substantiate these results.

The results of this study suggest that silica may be used as a tracer in other ASR aquifers where groundwater and source water chemistries are similar and silica-rich groundwater conditions exist.  As ASR projects continue to expand into the more tropical regions of the world where similar conditions occur, the use of silica as a tracer may prove to be a valuable tool for ASR monitoring.

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# APPENDIX A. NATIVE GROUNDWATER CHEMISTRY

Table A.1. Upper Aquifer Groundwater Chemistry Background Sampling (May 18 – Sept. 6, 2012)

|  | Well | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW S6 | MW S7 | MW | MW | RW | RW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | No. | S6 | S6 | S7 | S1 | S1 | S2 | S2 | S3 | S3 | S4 | S4 | S5 | S5 |  |  | S8 | S8 | S2 | S2 |
|  | Date | 5/18/2012 | 5/23/2012 | 5/24/2012 | 8/31/2012 | 9/3/2012 | 8/31/2012 | 9/3/2012 | 8/30/2012 | 9/4/2012 | 9/1/2012 | 9/6/2012 | 8/31/2012 | 9/5/2012 | 8/29/2012 | 8/30/2012 | 8/31/2012 | 9/5/2012 | 8/28/2012 | 9/6/2012 |
| pH |  | 6.19 | 6.19 | 6.12 | 6.27 | 6.22 | 6.23 | 6.12 | 6.19 | 6.17 | 6.25 | 6.21 | 6.25 | 6.23 | 6.25 | 6.25 | 6.31 | 6.17 | 6.38 | 6.21 |
| E.C. | mS/cm | 239 | 263 | 254 | 224 | 217 | 217 | 197 | 214 | 211 | 233 | 217 | 232 | 227 | 234 | 240 | 235 | 208 | 232 | 219 |
| Ca | mg/l | 14 | 18 | 14 | 12 | 11.2 | 12.8 | 12.8 | 15.2 | 15.2 | 11.2 | 11.2 | 12 | 12 | 12.8 | 12.8 | 12.8 | 13.6 | 13 | 12.8 |
| K | mg/l | 0.59 | 0.7 | 0 | 1.7 | 2 | 1.5 | 1.8 | 1.5 | 1.8 | 1.7 | 1.9 | 1.7 | 1.9 | 1.4 | 1.5 | 1.5 | 1.7 | 1.6 | 1.9 |
| Na | mg/l | 33 | 35 | 37 | 31.1 | 29.9 | 20.7 | 25.9 | 20.1 | 23 | 33.4 | 31.6 | 33.4 | 31.1 | 33.4 | 32.8 | 32.2 | 25.9 | 32 | 28.8 |
| Mg | mg/l | 5.9 | 6.3 | 6.8 | 4.9 | 5.4 | 5.4 | 4.9 | 7.3 | 6.3 | 5.8 | 5.4 | 6.3 | 6.3 | 5.4 | 6.3 | 6.3 | 5.8 | 5.9 | 5.8 |
| Fe | mg/l | 10 | 11.9 | 10.5 | 13.28 | 12.86 | 11.46 | 11.32 | 7.76 | 7.3 | 12.61 | 12.08 | 11.77 | 11.11 | 11.23 | 11.53 | 11.18 | 10.57 | 7.69 | 2.8 |
| FeT | mg/l | - | 12 | 12.5 | 13.59 | 13.5 | 12.18 | 11.94 | 7.83 | 7.63 | 13.27 | 13.01 | 12.27 | 12.17 | 11.67 | 11.92 | 11.66 | 11.64 | 9.06 | 11.79 |
| Cu | mg/l | 0 | 0.01 | 0.01 | 0.06 | 0.07 | 0.07 | 0.04 | 0.03 | 0.03 | 0.07 | 0.05 | 0.07 | 0.07 | 0.07 | 0.08 | 0.12 | 0.04 | 0.08 | 0.05 |
| Mn | mg/l | - | 0.42 | 0.43 | 0.21 | 0.36 | 0.15 | 0.36 | 0.32 | 0.35 | 0.32 | 0.4 | 0.32 | 0.42 | 0.35 | 0.28 | 0.28 | 0.4 | 0.42 | 0.37 |
| SiO2 | mg/l | 36 | 36 | 37 | 36.8 | 36.6 | 36.4 | 35.8 | 36.1 | 35.5 | 37.5 | 36.9 | 36.4 | 36.1 | 38.2 | 37.4 | 36 | 35.6 | 33 | 34.8 |
| Cl | mg/l | 1.5 | 2.7 | 1.5 | 0.8 | 0.4 | 0.4 | 1.5 | 0.4 | 0.4 | 0.4 | 0.8 | 2.3 | 0.8 | 0.4 | 1.2 | 0.4 | 0.4 | 0.8 | 0.8 |
| SO4 | mg/l | 10 | 10 | 9.6 | 5.1 | 6.8 | 8.2 | 5.8 | 4.7 | 7.6 | 5.2 | 6 | 5.8 | 5.2 | 6.3 | 5.5 | 9.5 | 6.3 | 12 | 8 |
| HCO3 | mg/l | 146 | 164 | 161 | 137 | 134 | 112 | 125 | 131 | 131 | 146 | 140 | 146 | 146 | 146 | 149 | 146 | 134 | 140 | 134 |
| Carb. Alk. | mg/kg CaCO$_3$ | 120 | 135 | 132 | 112 | 110 | 92 | 102 | 107 | 107 | 120 | 115 | 120 | 120 | 120 | 122 | 120 | 110 | 115 | 110 |
| NO2 | mg/l | 0.01 | 0.01 | 0.01 | 0.026 | 0.012 | 0.02 | 0.011 | 0.006 | 0.023 | 0.004 | 0.016 | 0.004 | 0.018 | 0.024 | 0.021 | 0.023 | 0.017 | 0.005 | 0.036 |
| NO3 | mg/l | 1.1 | 0.7 | 0.6 | 0.47 | 0.5 | 0.25 | 0.1 | 0.18 | 0.3 | 1.08 | 0.6 | 0.6 | 0.3 | 0.58 | 0.34 | 0.47 | 0.2 | 0.6 | 0.7 |
| F | mg/l | 0.2 | 0.1 | 0.1 | 0.2 | 0.16 | 0.2 | 0.17 | 0.2 | 0.17 | 0.24 | 0.14 | 0.22 | 0.17 | 0.2 | 0.2 | 0.2 | 0.14 | 0.2 | 0.16 |
| HPO4 | mg/l | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ni | mg/l | NA | NA | NA | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Zn | mg/l | NA | NA | NA | 0.08 | 0.4 | 0.018 | 0 | 0.13 | 0.6 | 0 | 0.6 | 0.38 | 0.9 | 0.58 | 0.78 | 0.13 | 3.3 | 0.32 | 0.33 |
| Cr | mg/l | NA | NA | NA | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| As | mg/l | NA | NA | NA | 0.027 | 0.025 | 0.027 | 0.022 | 0.019 | 0.018 | 0.026 | 0.022 | 0.026 | 0.024 | 0.026 | 0.008 | 0.025 | 0.024 | <0.0028 | <0.0028 |
| Pb | mg/l | NA | NA | NA | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 |
| C.B. | % | 0.06 | 0.45 | 0.41 | 0.34 | 0.05 | 0.00 | 0.02 | 0.28 | 0.04 | 0.05 | 0.53 | 0.48 | 0.20 | 0.52 | 0.50 | 0.26 | 0.35 | 0.19 | 0.42 |

Table A.2. Lower aquifer groundwater chemistry during background sampling (May 18 – Sept 2, 2012)

|  | Well No. | MW D6 | MW D7 | MW D1 | MW D1 | MW D2 | MW D2 | MW D3 | MW D3 | MW D4 | MW D4 | MW D5 | MW D5 | MW D6 | MW D6 | MW D7 | MW D8 | MW D8 | RW D2 | RW D2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Date | 5/18/2012 | 5/24/2012 | 9/1/2012 | 9/3/2012 | 8/30/2012 | 9/3/2012 | 8/30/2012 | 9/3/2012 | 9/1/2012 | 9/6/2012 | 8/31/2012 | 9/5/2012 | 9/3/2012 | 8/29/2012 | 8/30/2012 | 8/31/2012 | 9/5/2012 | 8/31/2012 | 9/6/2012 |
| pH |  | 6.06 | 6.16 | 6.36 | 6.26 | 6.09 | 6.1 | 6.25 | 6.24 | 6.18 | 6.14 | 6.32 | 6.24 | 6.25 | 6.17 | 6.2 | 6.26 | 6.2 | 6.24 | 6.25 |
| E.C. | uS/cm | 241 | 292 | 241 | 221 | 201 | 207 | 227 | 233 | 241 | 233 | 228 | 216 | 225 | 205 | 247 | 242 | 237 | 223 | 239 |
| Ca | mg/l | 21 | 26 | 14.4 | 16 | 16.8 | 16.8 | 17.6 | 20.8 | 16.8 | 16.8 | 12 | 13.6 | 17.6 | 17.6 | 17.6 | 18.4 | 19.2 | 18 | 18.4 |
| K | mg/l | 0.4 | 1.1 | 2.3 | 2.6 | 2.2 | 2.6 | 2.1 | 2.5 | 2.3 | 2.4 | 2.1 | 2.4 | 2.6 | 2.1 | 2.3 | 2.2 | 2.5 | 2.5 | 2.6 |
| Na | mg/l | 26 | 25 | 28.8 | 24.2 | 15.5 | 19.6 | 23 | 20.1 | 24.2 | 27 | 29.9 | 27.6 | 24.2 | 17.3 | 24.2 | 24.7 | 24.2 | 26 | 26.5 |
| Mg | mg/l | 6.3 | 7.3 | 6.8 | 5.9 | 5.9 | 5.4 | 6.9 | 6.8 | 7.3 | 6.3 | 6.3 | 4.9 | 5.9 | 6.3 | 7.8 | 6.8 | 6.3 | 5.4 | 6.3 |
| Fe | mg/l | 7.7 | 7.7 | 15.1 | 13.6 | 8.97 | 8.43 | 7.6 | 7.16 | 6.7 | 6.2 | 13.6 | 12.9 | 7.02 | 7.2 | 7.5 | 6.1 | 5.66 | 6.66 | 7.33 |
| FeT | mg/l | 7.8 | 7.7 | 16.1 | 13.9 | 9.2 | 8.84 | 7.8 | 7.61 | 7 | 6.53 | 13.93 | 13.6 | 7.29 | 7.3 | 7.9 | 6.21 | 5.81 | 7.17 | 8.16 |
| Cu | mg/l | 0 | 0 | 0.08 | 0.03 | 0.03 | 0.02 | 0.04 | 0.04 | 0.08 | 0.05 | 0.11 | 0.08 | 0.03 | 0.01 | 0.05 | 0.08 | 0.02 | 0.03 | 0.06 |
| Mn | mg/l | 0.13 | 0.23 | 0.13 | 0.35 | 0.22 | 0.34 | 0.23 | 0.29 | 0.21 | 0.24 | 0.11 | 0.25 | 0.28 | 0.2 | 0.1 | 0.13 | 0.27 | 0.23 | 0.32 |
| SiO2 (aq) | mg/l | 35 | 43 | 36 | 36.5 | 41.6 | 40.1 | 39.5 | 29.9 | 44.6 | 43.6 | 42 | 41.4 | 38.5 | 38.7 | 43.9 | 43.9 | 43.5 | 40 | 36 |
| Cl | mg/l | 9.2 | 7.7 | 6.6 | 5 | 5.7 | 5 | 7.3 | 5.8 | 6.9 | 7.7 | 5.4 | 4.2 | 6.6 | 5.8 | 6.9 | 7.3 | 5.4 | 5.8 | 6.6 |
| SO4 | mg/l | 29 | 17 | 21.4 | 21.7 | 17.9 | 20.3 | 26.6 | 20.8 | 17.9 | 19.8 | 28.1 | 28.4 | 27.8 | 24.8 | 14 | 18.1 | 18.2 | 23 | 16.4 |
| HCO3 | mg/l | 112 | 152 | 119 | 109 | 91 | 100 | 100 | 119 | 119 | 119 | 103 | 97 | 103 | 91 | 128 | 122 | 125 | 112 | 128 |
| Carb. Alk | mg/kg $CaCO_3$ | 92 | 125 | 97 | 90 | 75 | 82 | 82 | 97 | 97 | 97 | 85 | 80 | 85 | 75 | 105 | 100 | 102 | 92 | 105 |
| NO2 | mg/l | 0.01 | 0.01 | 0.02 | 0.018 | 0.004 | 0.012 | 0.003 | 0.016 | 0.004 | 0.014 | 0.004 | 0.015 | 0.01 | 0.004 | 0.003 | 0.004 | 0.016 | 0.045 | 0.012 |
| NO3 | mg/l | 0.7 | 0.4 | 0.65 | 0.5 | 0.13 | 0.1 | 0.31 | 0.1 | 0.43 | 0.3 | 0.67 | 0.5 | 0.5 | 0.22 | 0.31 | 0.31 | 0.2 | 0.3 | 0.7 |
| F | mg/l | 0.2 | 0.3 | 0.22 | 0.1 | 0.2 | 0.14 | 0.2 | 0.14 | 0.23 | 0.14 | 0.25 | 0.17 | 0.13 | 0.2 | 0.2 | 0.2 | 0.16 | 0.1 | 0.11 |
| HPO4 | mg/l | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ni | mg/l | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Zn | mg/l | NA | NA | 0.18 | 1 | 0.23 | 0 | 1.38 | 1.4 | 0.023 | 2.4 | 0.23 | 0.7 | 3.1 | 0.13 | 0.78 | 1.78 | 0.9 | 0.32 | 0.01 |
| Cr | mg/l | NA | NA | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| As | mg/l | NA | NA | 0.011 | 0.012 | 0.015 | 0.01 | 0.008 | 0.007 | 0.015 | 0.014 | 0.014 | 0.012 | 0.01 | 0.011 | 0.017 | 0.016 | 0.024 | <0.0028 | 0.012 |
| Pb | mg/l | NA | NA | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 |
| C.B. | % | 0.06 | 0.91 | 0.06 | 0.32 | 0.66 | 0.06 | 1.96 | 0.26 | 0.50 | 0.15 | 0.71 | 0.77 | 0.43 | 0.63 | 0.81 | 0.40 | 0.19 | 1.08 | 0.35 |

# APPENDIX B. RIVER WATER CHEMISTRY

## Table B.1. River Water Chemistry

| | | Background | | | Short-term Lower | | | Short-term Upper | | Long-term Lower | | | | | | Long-term Upper (2013) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5/18/2012 | 8/31/2012 | 9/6/2012 | 9/12/2012 | 9/15/2012 | 9/21/2012 | 10/8/2012 | 10/11/2012 | 10/23/2012 | 10/26/2012 | 10/31/2012 | 11/6/2012 | 11/12/2012 | 11/20/2012 | 1/6/2013 | 1/13/2013 | 1/20/2013 | 1/27/2013 | 2/4/2013 |
| pH | | 6.55 | 7.56 | 7.37 | 7.35 | 7.08 | 7.42 | 7.28 | 7.21 | 7.57 | 7.49 | 7.44 | 7.68 | 7.68 | 7.24 | 7.47 | 7.48 | 7.46 | 7.78 | 8.11 |
| E.C. | µS/cm | 224 | 206 | 176 | 190 | 215 | 245 | 232 | 220 | 295 | 295 | 289 | 306 | 287 | 282 | 314 | 334 | 341 | 346 | 347 |
| Ca | mg/l | 27 | 24 | 20.8 | 23.2 | 25.6 | 30.4 | 28 | 28.8 | 36.8 | 37.6 | 37.6 | 38.4 | 36 | 34.4 | 39.2 | 39.2 | 40 | 38.4 | 37.6 |
| K | mg/l | 0.8 | 1.5 | 1.8 | 1.7 | 1.7 | 1.8 | 1.9 | 1.8 | 1.5 | 1.5 | 1.6 | 2.3 | 2 | 2.5 | 2 | 2.2 | 2.7 | 2.7 | 2.4 |
| Na | mg/l | 12 | 19.6 | 11.5 | 13.2 | 11.5 | 9.2 | 9.6 | 9.5 | 12.1 | 12.1 | 10 | 16.1 | 9.8 | 10.4 | 11.5 | 15 | 15 | 16.7 | 19 |
| Mg | mg/l | 6.4 | 7.3 | 6.3 | 6.8 | 7.8 | 8.8 | 7.3 | 6.8 | 9.3 | 8.8 | 9.8 | 8.8 | 9.3 | 8.3 | 9.3 | 9.8 | 9.8 | 10.7 | 10.3 |
| Fe | mg/l | 0.03 | 0.18 | 0.23 | 0.11 | 0.15 | 0.16 | 0.07 | 0.11 | 0.04 | 0.04 | 0.05 | 0.11 | 0.03 | 0.01 | 0.03 | 0.05 | 0.03 | 0.02 | 0.02 |
| FeT | mg/l | 0.96 | 1.3 | 1.65 | 1.63 | 2.66 | 1.08 | 1.12 | 1.86 | 0.27 | 0.18 | 0.23 | 0.39 | 0.37 | 0.32 | 0.23 | 0.27 | 0.25 | 0.32 | 0.14 |
| Cu | mg/l | 0.02 | 0.14 | 0.1 | 0.11 | 0.05 | 0.05 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0 | 0 |
| Mn | mg/l | 0.03 | 0 | 0.34 | 0.28 | 0.49 | 0.05 | 0.08 | 0.33 | 0.1 | 0.21 | 0.05 | 0.06 | 0 | 0.03 | 0.02 | 0.06 | 0.08 | 0.11 | 0.02 |
| SiO2 | mg/l | 18 | 14.9 | 13.7 | 14.9 | 15.8 | 15.1 | 14.9 | 15.4 | 18.1 | 18.3 | 17.9 | 18.7 | 18 | 18.6 | 17.7 | 15.6 | 16.1 | 17.4 | 18.7 |
| Cl | mg/l | 0.8 | 0.4 | 0.8 | 2.3 | 0.4 | 0 | 1.2 | 0.4 | 0.8 | 0.8 | 0.4 | 3.9 | 0.4 | 0.8 | 3.5 | 5.8 | 5.4 | 3.9 | 4.2 |
| SO4 | mg/l | 29 | 23 | 22 | 23.2 | 16.8 | 19.1 | 14.6 | 14.6 | 16 | 15.6 | 16.4 | 17.4 | 16.3 | 17 | 18.5 | 20.7 | 22.9 | 23.5 | 24.3 |
| HCO3 | mg/l | 109 | 134 | 97 | 109 | 125 | 137 | 128 | 131 | 170 | 170 | 170 | 176 | 161 | 155 | 171 | 177 | 177 | 183 | 180 |
| Carb alk | mg/kg CaCO3 | 90 | 110 | 80 | 90 | 102 | 112 | 105 | 107 | 140 | 140 | 140 | 144 | 132 | 127 | 140 | 145 | 145 | 150 | 148 |
| NO2 | mg/l | 0.13 | 0.026 | 0.37 | 0.082 | 0.033 | 0.045 | 0.027 | 0.032 | 0.053 | 0.057 | 0.045 | 0.041 | 0.014 | 0.018 | 0.01 | 0.01 | 0.02 | 0 | 0.01 |
| NO3 | mg/l | 1.9 | 1.43 | 2.1 | 0.4 | 1.5 | 1.3 | 0.4 | 0.3 | 1.4 | 0.5 | 0.7 | 2.2 | 0.1 | 0.1 | 0 | 0 | 0.2 | 0.1 | 2.5 |
| F | mg/l | 0.3 | 0.2 | 0.09 | 0 | 0.13 | 0.12 | 0.21 | 0.21 | 0.25 | 0.24 | 0.25 | 0.25 | 0.27 | 0.25 | 0.22 | 0.22 | 0.21 | 0.18 | 0.23 |
| HPO4 | mg/l | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.3 | 0 | 0.1 | 0 | 0.1 | 0 | 0.1 | 0.4 | 0 | 0 | 0.3 | 0.1 |
| Ni | mg/l | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Zn | mg/l | | 0.23 | 0.1 | 0.1 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Cr | mg/l | | 0.03 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| As | mg/l | | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | | 0.003 | <.002 | <.002 | 0.006 | 0.003 | 0.003 | 0.005 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 | <.002 |
| Charge Balance | % | 0.56 | 0.38 | 0.05 | 0.13 | 0.59 | 0.43 | 0.44 | 0.23 | 0.02 | 0.37 | 0.13 | 0.10 | 0.79 | 0.05 | 0.22 | 0.35 | 0.14 | 0.12 | 0.05 |

# APPENDIX C. GROUNDWATER CHEMISTRY DURING INJECTION TESTS

Table C.1. Short-term, injection under pressure test in Lower Aquifer (Sept 12 – Sept 20, 2012)

| | | Recharge | | | | | | | | Recovery | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | MW | MW | MW | MW | MW | RW | RW | RW | RW | RW | RW | RW | MW | MW | MW | MW | MW |
| | No. | D2 | D2 | D1 | D2 | D3 | D6 | D7 | D2 | D2 | D2 | D2 | D2 | D2 | D2 | D2 | D7 | D6 | D1 | D3 |
| | Date | 9/12/2012 | 9/14/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/16/2012 | 9/17/2012 | 9/18/2012 | 9/18/2012 | 9/19/2012 | 9/19/2012 | 9/24/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 |
| | Time | 15:45 | 14:25 | 18:15 | 15:30 | 21:40 | 18:15 | 15:30 | 2:30 | 15:45 | 16:00 | 20:00 | 16:00 | 19:00 | 6:00 | | 15:30 | 19:30 | 19:30 | 24:30:00 |
| pH | | 7.97 | 7.86 | 6.21 | 6.05 | 6.2 | 6.1 | 6.11 | 7.71 | 7.13 | 6.59 | 6.45 | 6.32 | 6.35 | 6.31 | 6.03 | 6.05 | 6.1 | 6.05 | 6.15 |
| E.C. | mS/cm | 301 | 325 | 201 | 197 | 251 | 218 | 226 | 322 | 317 | 273 | 265 | 244 | 242 | 295 | 204 | 223 | 211 | 201 | 234 |
| Ca | mg/l | 23.2 | 24 | 16.8 | 16 | 16.8 | 19.2 | 16.8 | 24.8 | 22.4 | 19.2 | 19.2 | 20 | 20 | 20 | 17.6 | 18.4 | 18.4 | 16.8 | 21.8 |
| K | mg/l | 1.9 | 1.8 | 2.6 | 2.6 | 2.5 | 2.6 | 2.5 | 1.9 | 2.1 | 2.5 | 2.5 | 2.7 | 2.9 | 2.7 | 2.8 | 2.8 | 2.6 | 2.6 | 2.8 |
| Na | mg/l | 31.1 | 30.5 | 15.5 | 16.1 | 20.7 | 15 | 18.4 | 27.6 | 31.1 | 28.8 | 26.2 | 20.7 | 21.9 | 30.5 | 12.7 | 18.4 | 16.7 | 15.5 | 16.1 |
| Mg | mg/l | 6.3 | 6.6 | 6.3 | 5.9 | 6.3 | 6.3 | 6.3 | 7.8 | 6.8 | 5.9 | 5.9 | 6.3 | 6.3 | 6.8 | 7.8 | 6.3 | 5.9 | 5.9 | 6.8 |
| Fe | mg/l | 0.01 | 0.03 | 12.12 | 6.79 | 5.28 | 7.18 | 7.38 | 0.05 | 0.07 | 0.15 | 0.19 | 0.35 | 0.33 | 0.23 | 8.07 | 7.85 | 5.88 | 10.55 | 6.49 |
| FeT | mg/l | 0.04 | 0.03 | 12.86 | 8.71 | 5.82 | 7.85 | 7.81 | 0.05 | 0.1 | 0.19 | 0.22 | 0.35 | 0.37 | 0.27 | 9.17 | 7.86 | 7.49 | 12.75 | 7.82 |
| Cu | mg/l | 0 | 0 | | | | | | 0.01 | 0.01 | | 0.01 | | 0.01 | 0.01 | | | | | |
| Mn | mg/l | 0.05 | 0.08 | 0.35 | 0.35 | | 0.25 | 0.32 | 0.08 | 0 | | 0.05 | 0.13 | 0.14 | 0.01 | | 0.18 | 0.22 | 0.33 | 0.26 |
| SiO2 | mg/l | 10.6 | 9.4 | 34.4 | 38 | 19.5 | 37.4 | 37.8 | 12.2 | 11 | 24.6 | 26.6 | 26.6 | 30 | 28.2 | 42.5 | 39 | 39.8 | 39.6 | 30.9 |
| Cl | mg/l | 35.4 | 37 | 6.6 | 8.9 | 33.1 | 5.8 | 22.3 | 37 | 38.1 | 30.4 | 26.2 | 12.3 | 12.3 | 28.1 | 7.3 | 8.5 | 5.8 | 4.2 | 6.6 |
| SO4 | mg/l | 9.7 | 9.6 | 20.5 | 21.3 | 14.4 | 20.8 | 11.9 | 8.7 | 15.3 | 13.4 | 13.3 | 15.5 | 15.3 | 16.2 | 16.9 | 12.2 | 23.9 | 19.8 | 18.1 |
| HCO3 | mg/l | 112 | 112 | 88 | 76 | 64 | 97 | 79 | 116 | 100 | 94 | 97 | 109 | 112 | 109 | 94 | 109 | 88 | 91 | 106 |
| Carb. Alk. | mg/kg CaCO3 | 92 | 92 | 72 | 62 | 52 | 80 | 65 | 95 | 82 | 77 | 80 | 90 | 92 | 90 | 77 | 90 | 72 | 75 | 87 |
| NO2 | mg/l | 0.003 | 0.002 | | | | | | 0.004 | 0.003 | | 0.004 | | 0.003 | 0.002 | | | | | |
| NO3 | mg/l | 0.9 | 1 | 0.04 | 3.6 | 1.1 | 0 | 0.4 | 0.5 | 0.1 | 1 | 0.2 | | 0.3 | 0.4 | 1.7 | | | | |
| F | mg/l | 0.14 | 0.21 | | | | | | 0.15 | 0.12 | | 0.12 | | 0.12 | 0.13 | | | | | |
| HPO4 | mg/l | 0 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0.3 | 0.9 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 | 0.3 | 0.3 | 0 |
| Ni | mg/l | <0.01 | <0.01 | | | | | | <0.01 | <0.01 | | 0.024 | | 0.022 | 0.016 | | | | | |
| Zn | mg/l | 0.1 | 0.1 | | | | | | 0.1 | 0.1 | | 0.1 | | 0.1 | 0.2 | | | | | |
| Cr | mg/l | <0.01 | <0.01 | | | | | | <0.01 | <0.01 | | <0.01 | | <0.01 | <0.01 | | | | | |
| As | mg/l | <.0028 | <.0028 | 0.009 | 0.007 | <.0028 | 0.008 | 0.008 | <.0028 | <.0028 | <.0028 | 0.003 | 0.004 | 0.005 | <.0028 | 0.01 | 0.015 | 0.01 | 0.011 | 0.007 |
| Pb | mg/l | <0.002 | <0.002 | | | | | | <0.002 | <0.002 | | <0.002 | | <0.002 | <0.002 | | | | | |
| C.B. | % | 0.49 | 0.55 | 0.85 | 1.29 | 0.45 | 0.20 | 0.97 | 0.09 | 0.81 | 1.22 | 0.72 | 0.60 | 0.73 | 0.51 | 0.42 | 0.61 | 2.16 | 1.03 | 2.52 |

Table C.2. Short-term, injection under pressure test in the Upper Aquifer (Oct. 7 – Oct. 15, 2012)

| | | Recharge | | | | | | | | Recovery | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | RW | MW | MW | MW | MW | MW | RW | RW | RW | RW | RW | MW | MW | MW | MW | MW |
| | No. | S2 | S2 | S2 | S3 | S7 | S6 | S1 | S2 | S2 | S2 | S2 | S2 | S2 | S1 | S2 | S3 | S6 | S7 |
| | Date | 10/8/2012 | 10/10/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/12/2012 | 10/13/2012 | 10/13/2012 | 10/14/2012 | 10/15/2012 | 10/14/2012 | 10/14/2012 | 10/14/2012 | 10/15/2012 | 10/14/2012 |
| | Time | 16:00 | 14:00 | 10:15 | 7:00 | 7:30 | 11:15 | 13:45 | 10:30 | 22:00 | 10:00 | 22:00 | 14:00 | 0:00 | 10:00 | 21:30 | 19:30 | 0:30 | 19:00 |
| pH | | 8.15 | 8.18 | 8.07 | 7.07 | 6.1 | 6.29 | 6.16 | 6.23 | 6.44 | 6.34 | 6.27 | 6.26 | 6.24 | 6.34 | 6.22 | 6.22 | 6.23 | 6.27 |
| E.C. | mS/cm | 387 | 407 | 396 | 361 | 247 | 257 | 283 | 227 | 332 | 293 | 267 | 253 | 241 | 233 | 230 | 230 | 238 | 242 |
| Ca | mg/l | 27.2 | 29.6 | 28 | 24.8 | 12.8 | 13.6 | 10.4 | 12.8 | 21.6 | 19.2 | 17.6 | 16.8 | 16 | 11.2 | 11.2 | 16 | 12 | 12 |
| K | mg/l | 2.3 | 2.1 | 2 | 2.1 | 2 | 2 | 2.1 | 2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.1 | 2 | 1.9 | 1.9 | 2 |
| Na | mg/l | 43.1 | 42.6 | 44.1 | 38.5 | 26.5 | 26.8 | 36.5 | 24.5 | 37.4 | 33.9 | 33.4 | 28.2 | 27.6 | 29.3 | 31.1 | 27 | 32.8 | 32.8 |
| Mg | mg/l | 7.3 | 7.3 | 7.3 | 6.8 | 5.8 | 5.8 | 4.4 | 5.4 | 5.9 | 5.4 | 5.4 | 5.9 | 5.9 | 5.8 | 5.8 | 5.9 | 6.8 | 6.8 |
| Fe | mg/l | 0.03 | 0.03 | 0.02 | 0.03 | 12.15 | 11.62 | 11.58 | 11.79 | 0.49 | 0.77 | 1.86 | 2.46 | 2.92 | 12.82 | 11.58 | 2.96 | 9.87 | 11.57 |
| FeT | mg/l | 0.03 | 0.03 | 0.04 | 0.24 | 12.46 | 12.08 | 11.86 | 12.19 | 1.62 | 0.98 | 2.09 | 2.57 | 3.04 | 13.98 | 11.91 | 3.1 | 10.16 | 11.82 |
| Cu | mg/l | 0 | 0 | 0 | | | | | | 0.01 | | 0.02 | | 0.03 | | | | | |
| Mn | mg/l | 0.06 | 0.01 | 0.06 | 0.02 | 0.39 | 0.34 | 0.32 | 0.32 | 0.07 | 0.1 | 0.06 | 0.21 | 0.29 | 0.35 | 0.39 | 0.26 | 0.44 | 0.39 |
| SiO2 | mg/l | 10.2 | 10.5 | 10.4 | 14.5 | 28.1 | 26.6 | 13.8 | 29 | 19.5 | 21.4 | 29.9 | 31.9 | 33.2 | 35 | 36.5 | 33.5 | 20.9 | 36.7 |
| Cl | mg/l | 56.6 | 55.8 | 57.8 | 48.5 | 35 | 39.7 | 52.8 | 23.5 | 46.6 | 36.2 | 26.6 | 14.6 | 10.4 | 7.7 | 2.7 | 6.2 | 0.4 | 3.1 |
| SO4 | mg/l | 9.5 | 10.2 | 9.3 | 9 | 7.3 | 7.5 | 9.2 | 5.6 | 10 | 8.5 | 7.7 | 8.3 | 7.7 | 5.5 | 5.4 | 5.1 | 9.6 | 6.4 |
| HCO3 | mg/l | 125 | 131 | 128 | 119 | 73 | 67 | 49 | 85 | 103 | 103 | 116 | 122 | 128 | 122 | 137 | 134 | 146 | 146 |
| Car. Alk. | mg/kg CaCO3 | 102 | 107 | 105 | 97 | 60 | 55 | 40 | 70 | 85 | 85 | 95 | 100 | 105 | 100 | 112 | 110 | 120 | 120 |
| NO2 | mg/l | 0 | 0.001 | 0.002 | | | | | | 0.02 | | 0.01 | | 0.006 | | | | | |
| NO3 | mg/l | 0.9 | 1.5 | 0.8 | 0.8 | 0.3 | 0.6 | 3.1 | 0.5 | 2.6 | 1.4 | 1.5 | 0.3 | 0.5 | 3.2 | 1 | 1.2 | 0.8 | 0.6 |
| F | mg/l | 0.15 | 0.18 | 0.14 | | | | | | 0.06 | | 0.1 | | 0.09 | | | | | |
| HPO4 | mg/l | 0.1 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0.3 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ni | mg/l | <.01 | <.01 | <.01 | | | | | | 0.01 | | <.01 | | <.01 | | | | | |
| Zn | mg/l | 0 | 0 | 0 | | | | | | 0.1 | | 0 | | 0.3 | | | | | |
| Cr | mg/l | <.01 | <.01 | <.01 | | | | | | 0.005 | | <.01 | | <.01 | | | | | |
| As | mg/l | <.0028 | <.0028 | <.0028 | <.0028 | 0.016 | 0.018 | 0.008 | 0.019 | 0.003 | <.0028 | 0.003 | 0.005 | 0.008 | 0.024 | 0.026 | 0.01 | 0.024 | 0.022 |
| Pb | mg/l | <.002 | <.002 | 0.003 | | | | | | <.002 | | <.002 | | 0.003 | | | | | |
| C.B. | % | 0.43 | 0.33 | 0.41 | 0.09 | 0.45 | 0.24 | 0.23 | 0.44 | 0.10 | 0.41 | 0.08 | 0.34 | 0.38 | 0.40 | 0.21 | 0.20 | 0.31 | 0.24 |

Table C.3. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012)

| | | Recharge | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well | | RW | RW | RW | MW | MW | MW | MW | MW | MW | RW | RW |
| No. | | D2 | D2 | D2 | D2 | D7 | D6 | D1 | D4 | D3 | D2 | D2 |
| Date | | 10/23/2012 | 10/26/2012 | 10/31/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/6/2012 | 11/12/2012 |
| Time | | 16:45 | 16:00 | 14:00 | 7:00 | 7:15 | 10:55 | 11:00 | 17:50 | 18:00 | 14:00 | 10:00 |
| pH | | 8.53 | 8.09 | 8.16 | 6.65 | 6.2 | 6.19 | 6.1 | 6.17 | 6.64 | 7.91 | 8.12 |
| E.C. | mS/cm | 421 | 404 | 397 | 325 | 271 | 269 | 214 | 288 | 343 | 413 | 414 |
| Ca | mg/l | 34.4 | 37.6 | 36.8 | 18.4 | 22.4 | 18.4 | 17.6 | 19.2 | 24 | 37.6 | 36 |
| K | mg/l | 34.4 | 37.6 | 36.8 | 2.8 | 2.8 | 2.7 | 2.4 | 2.9 | 2.7 | 1.9 | 2 |
| Na | mg/l | 43.1 | 37.4 | 33.4 | 40.8 | 28.4 | 24.2 | 19 | 28.4 | 37.4 | 37.4 | 37.4 |
| Mg | mg/l | 9.3 | 9.3 | 8.8 | 5.9 | 8.3 | 6.3 | 5.9 | 6.3 | 6.3 | 8.8 | 8.3 |
| Fe | mg/l | 0.05 | 0.04 | 0.05 | 8 | 9.26 | 11.8 | 5.95 | 9.71 | 5 | 0.09 | 0.02 |
| FeT | mg/l | 0.05 | 0.04 | 2.96 | 8.07 | 9.3 | 12.1 | 6.01 | 9.95 | 5.17 | 0.09 | 0.02 |
| Cu | mg/l | 0 | 0.01 | 0.01 | | | | | | | 0 | 0.01 |
| Mn | mg/l | 0.07 | 0.06 | 0.26 | 0.27 | 0.28 | 0.29 | 0.17 | 0.11 | 0.23 | 0.02 | 0 |
| SiO2 | mg/l | 11.2 | 13.1 | 12.1 | 20 | 32.8 | 30.1 | 43.9 | 28.3 | 11.6 | 12.9 | 12.1 |
| Cl | mg/l | 45.4 | 41.6 | 37.7 | 41.6 | 33.1 | 33.5 | 7.3 | 43.5 | 37.7 | 42 | 41.6 |
| SO4 | mg/l | 15.3 | 15.3 | 14 | 23.5 | 20.3 | 22.1 | 18.4 | 22 | 22.3 | 16.2 | 14.1 |
| HCO3 | mg/l | 161 | 164 | 164 | 91 | 79 | 70 | 97 | 67 | 112 | 167 | 151 |
| Carb. Alk. | mg/kg CaCO3 | 137 | 135 | 135 | 75 | 65 | 57 | 80 | 55 | 92 | 137 | 132 |
| NO2 | mg/l | 0.004 | 0.005 | 0.004 | | | | | | | 0.004 | 0 |
| NO3 | mg/l | 2.3 | 8 | 0.9 | 3.8 | 0.3 | 0.9 | 3.8 | 0.3 | 0.7 | 1.4 | 1.1 |
| F | mg/l | 0.22 | 0.2 | 0,21 | | | | | | | 0.24 | 0.21 |
| HPO4 | mg/l | 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.1 | 0 | 0 |
| Ni | mg/l | <0.01 | <0.01 | <0.01 | | | | | | | <0.01 | <0.01 |
| Zn | mg/l | 0 | 0 | 0 | | | | | | | 0 | 0 |
| Cr | mg/l | <0.01 | <0.01 | <0.01 | | | | | | | <0.01 | <0.01 |
| As | mg/l | <0.028 | <0.028 | <0.028 | 0.003 | 0.005 | 0.007 | 0.016 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | <0.002 | <0.002 | <0.002 | | | | | | | <0.002 | <0.002 |
| C.B. | % | 1.44 | 0.03 | 0.02 | 0.53 | 0.31 | 0.17 | 0.25 | 0.04 | 0.54 | 0.07 | 0.40 |

Table C.3. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012) continued

| | | Recharge | | | | | | | | | Recovery | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | MW | MW | MW | MW | MW | MW | MW | MW | RW | RW | RW |
| | No. | D2 | D5 | D8 | D6 | D1 | D7 | D2 | D3 | D4 | D2 | D2 | D2 |
| | Date | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/25/2012 | 11/26/2012 | 11/27/2012 |
| | Time | 15:15 | 16:30 | 16:30 | 6:30 | 6:50 | 9:20 | 9:40 | 12:30 | 12:50 | 21:00 | 20:40 | 11:20 |
| pH | | 6.98 | 6.23 | 6.18 | 6.11 | 6.08 | 6.36 | 6.2 | 6.65 | 6.16 | 7.15 | 6.89 | 6.96 |
| E.C. | mS/cm | 345 | 179 | 232 | 274 | 269 | 323 | 283 | 353 | 223 | 381 | 388 | 385 |
| Ca | mg/l | 37.6 | 12.8 | 19.2 | 22.4 | 18.4 | 19.2 | 16.8 | 24 | 17.6 | 40 | 32.8 | 31.2 |
| K | mg/l | 2.1 | 2.4 | 2.7 | 3 | 2.8 | 3 | 2.9 | 2.8 | 2.6 | 2.6 | 2.5 | 2.5 |
| Na | mg/l | 14.4 | 15 | 17.2 | 17.2 | 24.2 | 32.8 | 27.6 | 34.5 | 16.7 | 20.2 | 33.4 | 33.4 |
| Mg | mg/l | 8.8 | 4.9 | 6.8 | 7.3 | 5.9 | 6.8 | 5.9 | 7.8 | 6.8 | 9.8 | 8.3 | 8.8 |
| Fe | mg/l | 0 | 8.35 | 5.94 | 8.57 | 12.67 | 7.37 | 8.65 | 4.87 | 5.97 | 0.11 | 0.1 | 0.1 |
| FeT | mg/l | 0 | 8.66 | 6.06 | 8.69 | 12.95 | 7.43 | 9.04 | 5.05 | 6.1 | 0.18 | 0.18 | 0.13 |
| Cu | mg/l | 0.01 | | | | | | | | | 0 | | |
| Mn | mg/l | 0.03 | 0.19 | 0.24 | 0.29 | 0.31 | 0.23 | 0.26 | 0.24 | 0.21 | 0 | 0 | 0 |
| SiO2 | mg/l | 15.4 | 42.2 | 42.2 | 33 | 31.6 | 25 | 29.4 | 13.6 | 43.6 | 15.5 | 14.7 | 16 |
| Cl | mg/l | 41.6 | 3.1 | 8.5 | 29.7 | 35.8 | 37 | 38.5 | 40.8 | 6.6 | 43.1 | 39.3 | 39.3 |
| SO4 | mg/l | 14.3 | 34 | 17.9 | 19.5 | 17.4 | 21.2 | 18.2 | 21.6 | 16.6 | 22.1 | 19.6 | 20.2 |
| HCO3 | mg/l | 106 | 58 | 103 | 79 | 69 | 91 | 67 | 109 | 103 | 125 | 143 | 140 |
| Carb. Alk. | mg/kg CaCO3 | 87 | 47 | 85 | 65 | 56 | 75 | 55 | 90 | 85 | 102 | 117 | 115 |
| NO2 | mg/l | 0.001 | | | | | | | | | 0.001 | | |
| NO3 | mg/l | 2.8 | 0.1 | 0.2 | 0 | 1.6 | 1.5 | 0.3 | 0.1 | 0.5 | 1 | 0 | 0.5 |
| F | mg/l | 0.17 | | | | | | | | | 0.1 | | |
| HPO4 | mg/l | 0.6 | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.7 | 0.5 | 0.2 | 0 | 0.6 | 0 |
| Ni | mg/l | <0.01 | | | | | | | | | <0.01 | | |
| Zn | mg/l | 0.01 | | | | | | | | | 0 | | |
| Cr | mg/l | <0.01 | | | | | | | | | <0.01 | | |
| As | mg/l | <.0028 | 0.015 | 0.015 | 0.008 | 0.008 | 0.011 | 0.008 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | <0.002 | | | | | | | | | <0.002 | | |
| C.B. | % | 0.41 | 0.23 | 0.66 | 0.09 | 0.02 | 0.33 | 0.59 | 0.33 | 0.06 | 0.09 | 0.32 | 0.45 |

Table C.3. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012) continued

|  |  | Recovery |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | Well | MW | MW | MW | MW | MW | MW | MW | RW | RW | RW | RW |
|  | No. | D3 | D7 | D2 | D6 | D1 | D5 | D8 | D2 | D2 | D2 | D2 |
|  | Date | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/27/2012 | 11/28/2012 | 11/29/2012 | 11/30/2012 |
|  | Time | 7:50 | 8:10 | 10:30 | 10:50 | 13:00 | 13:25 | 15:45 | 11:20 | 18:30 | 19:20 | 18:30 |
| pH |  | 6.68 | 6.36 | 6.13 | 6.08 | 6.03 | 6.17 | 6.17 | 6.96 | 6.85 | 6.59 | 6.64 |
| E.C. | mS/cm | 353 | 321 | 283 | 271 | 269 | 189 | 239 | 385 | 373 | 349 | 362 |
| Ca | mg/l | 23.2 | 19.2 | 17.6 | 21.6 | 18.4 | 14.4 | 19.2 | 31.2 | 30.4 | 27.2 | 28 |
| K | mg/l | 3.2 | 3.4 | 3.2 | 3.3 | 3.5 | 2.8 | 3.1 | 2.5 | 2.1 | 2.2 | 2.2 |
| Na | mg/l | 35.6 | 32.8 | 26.4 | 18.4 | 22.4 | 17.2 | 18.4 | 33.4 | 35.1 | 35.7 | 35.1 |
| Mg | mg/l | 7.8 | 6.8 | 5.9 | 7.3 | 6.3 | 5.4 | 7.3 | 8.8 | 7.3 | 6.8 | 7.3 |
| Fe | mg/l | 5.09 | 7.47 | 8.84 | 8.9 | 13.68 | 12.11 | 5.97 | 0.1 | 0.1 | 0.13 | 0.15 |
| FeT | mg/l | 5.41 | 7.8 | 9.15 | 9.82 | 13.86 | 12.41 | 6.72 | 0.13 | 0.11 | 0.13 | 0.15 |
| Cu | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| Mn | mg/l | 0.2 | 0.25 | 0.22 | 0.27 | 0.24 | 0.25 | 0.27 | 0 | 0 | 0.02 | 0.03 |
| SiO2 | mg/l | 43.9 | 18.7 | 15.5 | 42.6 | 42.6 | 40.9 | 42.3 | 16 | 19.3 | 24.6 | 22.3 |
| Cl | mg/l | 40 | 37.7 | 41.6 | 27 | 35.8 | 3.5 | 9.2 | 39.3 | 37.7 | 39.3 | 39.3 |
| SO4 | mg/l | 22.7 | 21.5 | 18 | 18.9 | 17.5 | 28.7 | 17.2 | 20.2 | 19.9 | 18.3 | 18.9 |
| HCO3 | mg/l | 109 | 88 | 64 | 85 | 67 | 73 | 109 | 140 | 134 | 122 | 128 |
| Carb. Alk. | mg/kg CaCO3 | 90 | 72 | 52 | 70 | 55 | 60 | 90 | 115 | 110 | 100 | 105 |
| NO2 | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| NO3 | mg/l | 1.2 | 2.5 | 0 | 0.3 | 0.9 | 4.6 | 0.7 | 0.5 | 0 | 0.3 | 0 |
| F | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| HPO4 | mg/l | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0.3 |
| Ni | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| Zn | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| Cr | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| As | mg/l | 0.006 | 0.018 | 0.01 | 0.009 | 0.009 | 0.015 | 0.017 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l |  |  |  |  |  |  |  |  |  |  |  |
| C.B. | % | 0.33 | 0.62 | 0.07 | 0.20 | 0.27 | 0.40 | 0.47 | 0.45 | 0.32 | 0.45 | 0.27 |

Table C.3. Long-term, injection under pressure the Lower Aquifer (Oct 18 – Dec 9, 2012) continued

| | | Recovery | | | | | | Post injection | |
|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | RW | RW | MW | RW | RW | RW |
| | No. | D2 | D2 | D2 | D2 | D4 | D2 | D2 | D2 |
| | Date | 12/1/2012 | 12/3/2012 | 12/5/2012 | 12/7/2012 | 12/8/2012 | 12/8/2012 | 1/6/2013 | 1/12/2013 |
| | Time | 18:30 | 17:30 | 19:30 | 18:00 | 15:30 | 17:00 | 18:00 | 17:00 |
| pH | | 6.45 | 6.37 | 6.25 | 6.24 | 6.15 | 6.28 | 7.74 | 7.92 |
| E.C. | mS/cm | 335 | 301 | 277 | 259 | 233 | 251 | 421 | 471 |
| Ca | mg/l | 25.6 | 23.2 | 22.4 | 20.8 | 16 | 20.8 | 36 | 39.2 |
| K | mg/l | 2.3 | 2.3 | 2.4 | 2.5 | 2.3 | 2.5 | 2 | 2.3 |
| Na | mg/l | 30.5 | 28.2 | 23.6 | 22.4 | 23.6 | 21.3 | 39.1 | 42 |
| Mg | mg/l | 6.8 | 6.8 | 6.3 | 6.8 | 6.8 | 5.9 | 8.3 | 10.3 |
| Fe | mg/l | 0.18 | 0.31 | 0.5 | 0.8 | 6.81 | 1.02 | 0.02 | 0.02 |
| FeT | mg/l | 0.18 | 0.36 | 0.52 | 0.83 | 6.88 | 1.05 | 0.02 | 0.03 |
| Cu | mg/l | 0.01 | | | | | 0.02 | 0.01 | 0.01 |
| Mn | mg/l | 0.05 | 0.05 | 0.03 | 0.13 | 0.13 | 0.04 | 0.01 | 0.02 |
| SiO2 | mg/l | 26.8 | 30.9 | 33.2 | 35 | 43.8 | 35.2 | 12.2 | 12.2 |
| Cl | mg/l | 34.7 | 28.1 | 17.7 | 13.5 | 6.6 | 11.6 | 45.1 | 55.1 |
| SO4 | mg/l | 17.4 | 16.2 | 15.8 | 16.3 | 21.2 | 16.1 | 17.2 | 18.6 |
| HCO3 | mg/l | 116 | 116 | 116 | 116 | 109 | 112 | 159 | 165 |
| Carb. Alk. | mg/kg CaCO3 | 95 | 95 | 95 | 95 | 90 | 92 | 130 | 135 |
| NO2 | mg/l | 0 | | | | | 0 | 0 | 0 |
| NO3 | mg/l | 0.3 | 0.3 | 0.7 | 0.5 | 1.7 | 0.4 | 0 | 0.1 |
| F | mg/l | 0.11 | | | | | 0.11 | 0.18 | 0.15 |
| HPO4 | mg/l | 0.3 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 |
| Ni | mg/l | <0.01 | | | | | <0.01 | <0.01 | <0.01 |
| Zn | mg/l | 0.1 | | | | | 0 | 0.1 | 0.1 |
| Cr | mg/l | <0.01 | | | | | <0.01 | <0.01 | <0.01 |
| As | mg/l | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | <0.002 | | | | | <0.002 | <0.002 | <0.002 |
| C.B. | % | 0.39 | 0.56 | 0.31 | 0.12 | 0.03 | 0.18 | 0.06 | 0.45 |

Table C.4.  Long-term, recharge under pressure the Upper Aquifer (Jan. 5 – Feb. 25, 2013)

| | | Recharge | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well No. | RW | MW | MW | MW | MW | MW | MW | RW | RW | MW | MW | MW | MW | MW | RW | MW | MW | MW |
| | | S2 | S6 | S3 | S7 | S4 | S2 | S1 | S2 | S2 | S1 | S6 | S7 | S5 | S3 | S2 | S8 | S4 | S2 |
| | Date | 1/19/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/24/2013 | 1/30/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 |
| | Time | 10:30 | 6:00 | 9:00 | 9:30 | 12:40 | 13:20 | 18:00 | 18:00 | 14:00 | 6:00 | 7:00 | 10:10 | 13:10 | 13:50 | 15:00 | 16:15 | 17:00 | 19:30 |
| pH | | 8.08 | 6.96 | 6.68 | 6.16 | 6 | 6.05 | 6.41 | 8.06 | 8.3 | 6.56 | 6.37 | 6.85 | 6 | 6.71 | 8.42 | 6.08 | 6.03 | 6.1 |
| E.C. | mS/cm | 474 | 309 | 406 | 309 | 173 | 273 | 339 | 481 | 444 | 336 | 307 | 324 | 247 | 390 | 432 | 227 | 244 | 294 |
| Ca | mg/l | 37.6 | 15.2 | 32 | 14.4 | 10.4 | 14.4 | 16 | 38.4 | 37.6 | 17.6 | 16 | 16 | 13.6 | 27.2 | 30.4 | 13.6 | 12.8 | 14.4 |
| K | mg/l | 2.7 | 2 | 2.4 | 2.2 | 2.2 | 2 | 2.2 | 2.7 | 2.6 | 2.4 | 2 | 2.3 | 2.1 | 2.3 | 2.3 | 1.9 | 2.1 | 2 |
| Na | mg/l | 44.9 | 28.2 | 34.5 | 32.8 | 17.8 | 30.5 | 41.8 | 41.4 | 40.3 | 38 | 36.2 | 37.4 | 25.9 | 40.8 | 41.4 | 24.2 | 29.3 | 34.5 |
| Mg | mg/l | 9.8 | 7.3 | 9.3 | 8.3 | 4.9 | 5.4 | 5.9 | 10.7 | 10.3 | 6.3 | 5.4 | 6.8 | 5.8 | 8.3 | 10.2 | 5.8 | 4.9 | 6.8 |
| Fe | mg/l | 0.02 | 4.88 | 0.18 | 13.25 | 12.84 | 13.06 | 13.1 | 0.01 | 0.01 | 11.16 | 12.01 | 12.55 | 13.18 | 0.17 | 0.02 | 12.43 | 13.59 | 12.99 |
| FeT | mg/l | 0.05 | 5.1 | 0.49 | 13.48 | 13.66 | 13.22 | 13.33 | 0.02 | 0.01 | 11.78 | 13.03 | 12.95 | 13.76 | 0.46 | 0.05 | 12.68 | 13.78 | 13.66 |
| Cu | mg/l | 0.01 | | | | | | | 0 | 0 | | | | | | 0 | | | |
| Mn | mg/l | 0.03 | 0.4 | 0.09 | 0.45 | 0.4 | 0.33 | 0.44 | 0 | 0 | 0.36 | 0.39 | 0.48 | 0.34 | 0.08 | 0.01 | 0.35 | 0.36 | 0.39 |
| SiO2 | mg/l | 11.7 | 25.5 | 18.1 | 19.2 | 30.1 | 24.3 | 11.7 | 12 | 13.6 | 12 | 17.4 | 13.6 | 32.1 | 17.9 | 14 | 34.6 | 32.3 | 22.1 |
| Cl | mg/l | 55.4 | 36.6 | 48.1 | 45.4 | 17.3 | 31.2 | 49.3 | 53.5 | 36.6 | 36.2 | 35.4 | 38.5 | 23.5 | 39.3 | 35.4 | 11.6 | 22.3 | 35.4 |
| SO4 | mg/l | 20.3 | 14.9 | 19.3 | 17.3 | 8 | 13.6 | 20.2 | 21.4 | 22.3 | 24 | 20 | 23.2 | 12.2 | 23.1 | 22.7 | 7.5 | 13.2 | 20.2 |
| HCO3 | mg/l | 165 | 79 | 131 | 73 | 67 | 62 | 79 | 168 | 168 | 98 | 89 | 90 | 85 | 137 | 156 | 107 | 89 | 82 |
| Carb. Alk | mg/kg CaCO$_3$ | 135 | 65 | 108 | 60 | 55 | 68 | 65 | 138 | 153 | 80 | 73 | 74 | 70 | 113 | 138 | 88 | 73 | 68 |
| NO2 | mg/l | 0 | | | | | | | 0 | 0 | | | | | | 0 | | | |
| NO3 | mg/l | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.1 | 0.1 | 0.2 | 0.5 | 0.3 | 0.2 | 0.2 | 0.7 | 0.5 | 0.3 | 2 |
| F | mg/l | 0.11 | | | | | | | 0.22 | 0.15 | | | | | | 0.21 | | | |
| HPO4 | mg/l | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0 | 0 | 0.3 |
| Ni | mg/l | <0.01 | | | | | | | <0.01 | <0.01 | | | | | | <0.01 | | | |
| Zn | mg/l | 0.2 | | | | | | | 0.2 | 0.1 | | | | | | 0.1 | | | |
| Cr | mg/l | <0.01 | | | | | | | <0.01 | <0.01 | | | | | | <0.01 | | | |
| As | mg/l | <.0028 | 0.022 | 0.012 | 0.02 | 0.025 | 0.023 | 0.02 | <.0028 | <.0028 | 0.02 | 0.022 | 0.012 | 0.023 | 0.01 | <.0028 | 0.022 | 0.012 | 0.021 |
| Pb | mg/l | <.002 | | | | | | | <.002 | <.002 | | | | | | <0.002 | | | |
| C.B. | % | 0.14 | 0.07 | 0.19 | 0.76 | 0.10 | 0.56 | 0.75 | 0.47 | 0.10 | 0.31 | 0.23 | 0.09 | 0.49 | 0.46 | 0.28 | 0.26 | 0.05 | 0.61 |

Table C.4. Long-term, recharge under pressure the Upper Aquifer (Jan. 5 – Feb. 25, 2013) continued

| | | Recovery | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well No. | RW<br>S2 | MW<br>S2 | MW<br>S6 | MW<br>S1 | RW<br>S2 | MW<br>S3 | MW<br>S7 | MW<br>S5 | MW<br>S8 | RW<br>S2 | RW<br>S2 | RW<br>S2 | RW<br>S2 |
| | Date | 2/10/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/12/2013 | 2/13/2013 | 2/14/2013 | 2/15/2013 |
| | Time | 12:15 | 9:00 | 9:00 | 9:00 | 12:30 | 14:15 | 14:20 | 16:40 | 17:00 | 16:15 | 13:15 | 13:15 | 13:15 |
| pH | | 7.36 | 6.26 | 6.2 | 6.31 | 6.93 | 6.52 | 6.31 | 6.1 | 6.2 | 6.57 | 6.59 | 6.46 | 6.42 |
| E.C. | mS/cm | 432 | 266 | 272 | 307 | 411 | 333 | 310 | 230 | 242 | 394 | 376 | 351 | 335 |
| Ca | mg/l | 33.6 | 13.6 | 14.4 | 16 | 30.4 | 21.6 | 14.4 | 13.6 | 20 | 27.2 | 25.6 | 23.2 | 22.4 |
| K | mg/l | 2 | 1.5 | 1.5 | 1.9 | 2.1 | 1.8 | 1.7 | 1.6 | 2.2 | 2 | 1.9 | 1.9 | 1.9 |
| Na | mg/l | 40.8 | 31.6 | 33.4 | 38.5 | 40.8 | 34.5 | 37.4 | 24.7 | 17.8 | 37.6 | 35.6 | 36.2 | 34.2 |
| Mg | mg/l | 9.8 | 5.4 | 5.8 | 6.3 | 8.8 | 7.3 | 6.8 | 5.8 | 7.3 | 7.8 | 7.8 | 7.3 | 6.8 |
| Fe | mg/l | 0.02 | 12.46 | 10.93 | 11.15 | 0.13 | 0.75 | 11.82 | 13.07 | 5.89 | 0.2 | 0.24 | 0.37 | 0.6 |
| FeT | mg/l | 1.54 | 12.71 | 12.03 | 11.81 | 0.2 | 0.85 | 12.41 | 13.51 | 6.23 | 0.23 | 0.31 | 0.42 | 0.66 |
| Cu | mg/l | 0 | | | | | | | | | | | | |
| Mn | mg/l | 0.05 | 0.34 | 0.38 | 0.37 | 0.03 | 0.19 | 0.41 | 0.35 | 0.31 | 0.06 | 0.08 | 0.11 | 0.17 |
| SiO2 | mg/l | 12.9 | 27.8 | 29.2 | 17 | 16.1 | 24.2 | 21 | 34.2 | 42.9 | 18.4 | 20.7 | 23.1 | 24.7 |
| Cl | mg/l | 34.7 | 30.8 | 27 | 38.5 | 39.7 | 39.3 | 41.2 | 16.2 | 6.2 | 37 | 35.8 | 36.2 | 30.4 |
| SO4 | mg/l | 24 | 13.3 | 12.7 | 19.5 | 21.6 | 16.6 | 19.5 | 7.5 | 12 | 18.7 | 17.5 | 15.3 | 14.1 |
| HCO3 | mg/l | 171 | 85 | 101 | 95 | 153 | 107 | 82 | 101 | 122 | 137 | 131 | 125 | 125 |
| Carb. Alk | mg/kg $CaCO_3$ | 140 | 70 | 83 | 78 | 125 | 88 | 68 | 83 | 100 | 113 | 108 | 103 | 103 |
| NO2 | mg/l | 0 | | | | | | | | | | | | |
| NO3 | mg/l | 0.6 | 0.2 | 0.2 | 0.3 | 0.1 | 0.2 | 0.4 | 0.4 | 0.3 | 0.1 | 0.1 | 0.1 | 0.1 |
| F | mg/l | 0.15 | | | | | | | | | | | | |
| HPO4 | mg/l | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0 | 0 |
| Ni | mg/l | <0.01 | | | | | | | | | | | | |
| Zn | mg/l | 0.1 | | | | | | | | | | | | |
| Cr | mg/l | <0.01 | | | | | | | | | | | | |
| As | mg/l | <.0028 | 0.022 | 0.012 | 0.023 | <.0028 | 0.01 | 0.021 | 0.025 | 0.022 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | <0.002 | | | | | | | | | | | | |
| C.B. | % | 0.21 | 0.13 | 0.04 | 0.23 | 0.12 | 0.22 | 0.50 | 0.09 | 0.00 | 0.02 | 0.14 | 0.16 | 0.11 |

Table C.4. Long-term, recharge under pressure the Upper Aquifer (Jan. 5 – Feb. 25, 2013) continued

| | | Recovery | | | | |
|---|---|---|---|---|---|---|
| | Well No. | RW S2 | RW S2 | RW S2 | RW S2 | RW S2 |
| | Date | 2/16/2013 | 2/18/2013 | 2/20/2013 | 2/22/2013 | 2/24/2013 |
| | Time | 13:15 | 13:15 | 13:15 | 13:15 | 18:15 |
| pH | | 6.44 | 6.34 | 6.28 | 6.27 | 6.22 |
| E.C. | mS/cm | 323 | 305 | 286 | 273 | 263 |
| Ca | mg/l | 21.6 | 19.2 | 18.4 | 17.6 | 16.8 |
| K | mg/l | 1.8 | 1.7 | 1.6 | 1.6 | 1.6 |
| Na | mg/l | 33.9 | 31.6 | 28.2 | 27.9 | 26.3 |
| Mg | mg/l | 6.8 | 6.3 | 6.3 | 6.3 | 6.3 |
| Fe | mg/l | 0.9 | 1.82 | 2.44 | 2.77 | 3.18 |
| FeT | mg/l | 0.93 | 1.95 | 2.5 | 2.93 | 3.35 |
| Cu | mg/l | 0 | | | | 0.01 |
| Mn | mg/l | 0.19 | 0.21 | 0.22 | 0.23 | 0.27 |
| SiO2 | mg/l | 25.8 | 27.5 | 29.5 | 30.2 | 31.7 |
| Cl | mg/l | 28.9 | 21.2 | 16.9 | 12.7 | 11.2 |
| SO4 | mg/l | 13.9 | 10.9 | 10.2 | 9.3 | 7.9 |
| HCO3 | mg/l | 125 | 125 | 122 | 128 | 125 |
| Carb. Alk | mg/kg CaCO$_3$ | 103 | 103 | 100 | 105 | 103 |
| NO2 | mg/l | 0.1 | | | | 0.006 |
| NO3 | mg/l | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 |
| F | mg/l | 0.18 | | | | 0.18 |
| HPO4 | mg/l | 0 | 0.2 | 0 | 0 | 0 |
| Ni | mg/l | <0.01 | | | | <0.01 |
| Zn | mg/l | 0.1 | | | | 0.2 |
| Cr | mg/l | <0.01 | | | | <0.01 |
| As | mg/l | <.0028 | <.0028 | <.0028 | <.0028 | <.0028 |
| Pb | mg/l | <0.002 | | | | <0.002 |
| C.B. | % | 0.00 | 0.29 | 1.03 | 0.97 | 1.55 |

# APPENDIX D. TREATED WATER SAMPLES

Table D. 1 Injection Water during four recharge tests

| | Sample Date/Time | Cl | SO4 | Si | Fe | Na | Ca | Alk | Mg | K | NO3 | ph | Cond | temp | DO | ORP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RWD2 | 9/12/2012 0:00 | 35.4 | 9.7 | 10.6 | 0.04 | 31.1 | 23.2 | 92 | 6.3 | 1.9 | 0.9 | 8.29 | 308 | 29.44 | 6.07 | 547 |
| | 9/14/2012 14:25 | 37 | 9.6 | 9.4 | 0.03 | 30.5 | 24 | 92 | 6.8 | 1.8 | 0.002 | 8.3 | 323 | 29.14 | 5.92 | 444.5 |
| | 9/16/2012 0:00 | 37 | 8.7 | 12.2 | 0.05 | 27.6 | 24.8 | 95 | 7.8 | 1.9 | 0.05 | 8.16 | 297 | 28.9 | 7.5 | 448.1 |
| | 9/24/2012 0:00 | 28.1 | 16.2 | 28.2 | 0.27 | 30.5 | 20 | 90 | 6.8 | 2.7 | 0.4 | 6.27 | 299 | 29.73 | 0 | -223.6 |
| | AVERAGE | 36.47 | 9.33 | 10.73 | 0.04 | 29.73 | 24 | 93 | 6.97 | 1.87 | 0.32 | 8.25 | 309.33 | 29.16 | 6.5 | 479.87 |
| RWS2 | 10/8/2012 | 56.6 | 9.5 | 10.2 | 0.03 | 43.1 | 27.2 | 125 | 7.3 | 2.3 | 0.9 | 8.38 | 397 | 29.69 | 7.45 | 531.5 |
| | 10/10/2012 0:00 | 55.8 | 10.2 | 10.5 | 0.03 | 42.6 | 29.6 | 107 | 7.3 | 2.1 | 1.5 | 8.23 | 411 | 30.44 | 8.32 | 221 |
| | 10/11/2012 10:15 | 57.8 | 9.3 | 10.4 | 0.04 | 44.1 | 28 | 128 | 7.3 | 2 | 0.002 | 8.22 | 402 | 29 | 8.12 | 224.3 |
| | AVERAGE | 56.73 | 9.67 | 10.37 | 0.03 | 43.27 | 28.27 | 120 | 7.3 | 2.13 | 0.8 | 8.28 | 403.33 | 29.71 | 7.96 | 325.6 |
| RW2D | 10/23/2012 16:45 | 45.5 | 15.3 | 11.2 | 0.05 | 43.1 | 34.4 | 161 | 9.3 | 1.7 | 2.3 | 8.41 | 404 | 32.48 | 5.87 | 112 |
| | 10/26/2013 16:00 | 41.6 | 15.3 | 13.1 | 0.04 | 37.4 | 37.6 | 164 | 9.3 | 1.7 | 8 | 8.13 | 394 | 32.54 | 1.07 | 59.7 |
| | 10/31/2012 14:00 | 37.7 | 14 | 12.1 | 0.05 | 33.4 | 36.8 | 164 | 8.8 | 1.8 | 0.9 | 8.36 | 369 | 30.8 | 0.65 | -40.2 |
| | 11/6/2012 14:00 | 42 | 16.2 | 12.9 | 0.09 | 37.4 | 37.6 | 167 | 8.8 | 1.9 | 1.4 | 8.32 | 385 | 31.07 | 0.66 | -102.2 |
| | 11/12/2012 10:00 | 41.3 | 14.1 | 12.1 | 0.02 | 37.4 | 36 | 161 | 8.3 | 2 | 1.1 | 8.4 | 352 | 30.69 | 0.24 | -104 |
| | 11/20/2012 15:15 | 41.6 | 14.3 | 15.4 | 0 | 14.4 | 37.6 | 106 | 8.8 | 2.1 | 2.8 | 6.98 | 287 | 32.02 | 4.18 | -77.2 |
| | AVERAGE | 41.62 | 14.98 | 12.8 | 0.05 | 37.74 | 36.48 | 163.4 | 8.9 | 1.82 | 2.74 | 8.324 | 380.8 | 31.516 | 1.698 | -14.94 |
| RWS2 | 1/6/2013 0:00 | 45.1 | 17.2 | 12.2 | 0.02 | 39.1 | 36 | 159 | 8.3 | 2 | 0 | 7.26 | 386 | 28.11 | 10 | 219.6 |
| | 1/12/2013 17:00 | 55.1 | 18.8 | 12.2 | 0.03 | 42 | 39.2 | 165 | 10.3 | 2.3 | 0.01 | 8.04 | 408 | 27.83 | 9.59 | 133.7 |
| | 1/19/2013 10:30 | 55.4 | 20.3 | 11.7 | 0.05 | 44.9 | 37.6 | 165 | 9.8 | 2.7 | 0.1 | 8.26 | 374 | 26.34 | 8.2 | -59 |
| | 1/24/2013 18:00 | 53.5 | 21.4 | 12 | 0.02 | 41.4 | 38.4 | 168 | 10.7 | 2.7 | 0.1 | 8.27 | 356 | 28.08 | 7.34 | -129.3 |
| | 1/30/2013 14:00 | 36.6 | 22.3 | 13.6 | 0.01 | 40.3 | 37.6 | 168 | 10.3 | 2.6 | 0.1 | 8.26 | 288 | 28.68 | 5.84 | -160.9 |
| | 4/2/2013 15:00 | 35.4 | 22.7 | 14 | 0.02 | 41.4 | 30.4 | 156 | 10.2 | 2.3 | 0.7 | 8.42 | 297 | 29.32 | 4.35 | -176.2 |
| | AVERAGE | 46.85 | 20.45 | 12.62 | 0.03 | 41.52 | 36.53 | 163.5 | 9.93 | 2.43 | 0.17 | 7.85 | 389.33 | 27.43 | 9.26 | 98.1 |

# APPENDIX E. DATA VALIDATION

Table E.1. Upper aquifer groundwater chemistry during background sampling (May 18 – Sept. 6, 2012)

| | Well | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | RW | RW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. | S6 | S6 | S7 | S1 | S1 | S2 | S2 | S3 | S3 | S4 | S4 | S5 | S5 | S6 | S7 | S8 | S8 | S2 | S2 |
| | Date | 5/18/12 | 5/23/12 | 5/24/12 | 8/31/12 | 9/3/12 | 8/31/12 | 9/3/12 | 8/30/12 | 9/4/12 | 9/1/12 | 9/6/12 | 8/31/12 | 9/5/12 | 8/29/12 | 8/30/12 | 8/31/12 | 9/5/12 | 8/3/12 | 9/6/12 |
| pH | | 6.19 | 6.19 | 6.12 | 6.27 | 6.22 | 6.23 | 6.12 | 6.19 | 6.17 | 6.25 | 6.21 | 6.25 | 6.23 | 6.25 | 6.25 | 6.31 | 6.17 | 6.38 | 6.21 |
| E.C. | µS/cm | 239 | 263 | 254 | 224 | 217 | 217 | 197 | 214 | 211 | 233 | 217 | 232 | 227 | 234 | 240 | 235 | 208 | 232 | 219 |
| TDS | mg/l | 185 | 204 | 198 | 161 | 160 | 142 | 150 | 151 | 156 | 169 | 164 | 171 | 167 | 171 | 173 | 172 | 157 | 169 | 160 |
| $TDS_{calc}$ | mg/l | 174.2 | 190.5 | 185.8 | 160.3 | 159.0 | 141.1 | 150.0 | 149.9 | 154.5 | 168.5 | 163.5 | 170.7 | 165.9 | 170.7 | 171.2 | 171.4 | 155.6 | 168.1 | 159.8 |
| $TDS_{calc}/EC$ | | 0.73 | 0.72 | 0.73 | 0.72 | 0.73 | 0.65 | 0.76 | 0.70 | 0.73 | 0.72 | 0.75 | 0.74 | 0.73 | 0.73 | 0.71 | 0.73 | 0.75 | 0.72 | 0.73 |
| $TDS/TDS_{calc}$ | | 1.06 | 1.07 | 1.07 | 1.00 | 1.01 | 1.01 | 1.00 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.01 | 1.00 | 1.01 | 1.01 | 1.00 |
| cation-anion | meq/l | 0.03 | 0.03 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.03 | 0.03 | 0.01 | 0.03 | 0.03 | 0.01 | 0.02 | 0.01 | 0.02 |

Table E.2. Lower aquifer groundwater chemistry during background sampling (May 18 – Sept 2, 2012)

| | Well | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | MW | RW | RW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. | D6 | D7 | D1 | D1 | D2 | D2 | D3 | D3 | D4 | D4 | D5 | D5 | D6 | D6 | D7 | D8 | D8 | D2 | D2 |
| | Date | 5/18/12 | 5/24/12 | 9/1/12 | 9/3/12 | 8/30/12 | 9/3/12 | 8/30/12 | 9/3/12 | 9/1/12 | 9/6/12 | 8/31/12 | 9/5/12 | 9/3/12 | 8/29/12 | 8/30/12 | 8/31/12 | 9/5/12 | 8/3/12 | 9/6/12 |
| pH | | 6.06 | 6.16 | 6.36 | 6.26 | 6.09 | 6.1 | 6.25 | 6.24 | 6.18 | 6.14 | 6.32 | 6.24 | 6.25 | 6.17 | 6.2 | 6.26 | 6.2 | 6.24 | 6.25 |
| E.C. | µS/cm | 241 | 292 | 241 | 221 | 201 | 207 | 227 | 233 | 241 | 233 | 228 | 216 | 225 | 205 | 247 | 242 | 237 | 223 | 239 |
| TDS | mg/l | 191 | 211 | 178 | 168 | 151 | 160 | 174 | 167 | 180 | 183 | 178 | 172 | 178 | 158 | 182 | 184 | 185 | 177 | 177 |
| $TDS_{calc}$ | mg/l | 183.1 | 202.8 | 175.4 | 166.5 | 150.9 | 159.2 | 172.7 | 165.1 | 178.9 | 182.2 | 177.7 | 171.2 | 174.8 | 158.0 | 180.2 | 181.9 | 180.9 | 176.3 | 176.6 |
| $TDS_{calc}/EC$ | | 0.76 | 0.69 | 0.73 | 0.75 | 0.75 | 0.77 | 0.76 | 0.71 | 0.74 | 0.78 | 0.78 | 0.79 | 0.78 | 0.77 | 0.73 | 0.75 | 0.76 | 0.79 | 0.74 |
| $TDS/TDS_{calc}$ | | 1.04 | 1.04 | 1.01 | 1.01 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.02 | 1.00 | 1.01 | 1.01 | 1.02 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.00 | 0.06 | 0.00 | 0.02 | 0.03 | 0.00 | 0.10 | 0.01 | 0.03 | 0.01 | 0.03 | 0.04 | 0.02 | 0.03 | 0.04 | 0.02 | 0.01 | 0.05 | 0.02 |

Table E.3.  River water chemistry during background conditions and injection tests

| | | Background | | | Short-term Lower | | | Short-term Upper | | Long-term Lower | | | | | | Long-term Upper (2013) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5/18/2012 | 8/31/2012 | 9/6/2012 | 9/12/2012 | 9/15/2012 | 9/21/2012 | 10/8/2013 | 10/11/2012 | 10/23/2012 | 10/26/2012 | 10/31/2012 | 11/6/2012 | 11/12/2012 | 11/20/2012 | 1/6/2013 | 1/13/2013 | 1/20/2013 | 1/27/2013 | 2/4/2013 |
| pH | | 6.55 | 7.56 | 7.37 | 7.35 | 7.08 | 7.42 | 7.28 | 7.21 | 7.57 | 7.49 | 7.44 | 7.68 | 7.68 | 7.24 | 7.47 | 7.48 | 7.46 | 7.78 | 8.11 |
| E.C. | µS/cm | 224 | 206 | 176 | 190 | 215 | 245 | 232 | 220 | 295 | 295 | 289 | 306 | 287 | 282 | 314 | 334 | 341 | 346 | 347 |
| TDS | mg/l | 150 | 159 | 128 | 140 | 143 | 153 | 142 | 144 | 180 | 180 | 179 | 195 | 171 | 169 | 186 | 196 | 200 | 204 | 208 |
| $TDS_{calc}$ | mg/l | 150.2 | 158.3 | 127.1 | 139.7 | 142.4 | 153.0 | 141.1 | 142.0 | 180.3 | 179.4 | 178.7 | 194.5 | 171.4 | 168.6 | 185.9 | 195.5 | 199.3 | 203.6 | 208.0 |
| $TDS_{calc}/EC$ | | 0.67 | 0.77 | 0.72 | 0.74 | 0.66 | 0.62 | 0.61 | 0.65 | 0.61 | 0.61 | 0.62 | 0.64 | 0.60 | 0.60 | 0.59 | 0.59 | 0.58 | 0.59 | 0.60 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.03 | 0.02 | 0.00 | 0.01 | 0.03 | 0.02 | 0.02 | 0.01 | 0.00 | 0.02 | 0.01 | 0.01 | 0.05 | 0.00 | 0.01 | 0.02 | 0.01 | 0.04 | 0.00 |

Table E.4. Short-term, injection under pressure test in Lower Aquifer (Sept 12 – Sept 20, 2012)

| | | Recharge | | | | | | | | Recovery | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | MW | MW | MW | MW | MW | RW | RW | RW | RW | RW | RW | RW | MW | MW | MW | MW | MW |
| | No. | D2 | D2 | D1 | D2 | D3 | D6 | D7 | D2 | D2 | D2 | D2 | D2 | D2 | D2 | D2 | D7 | D6 | D1 | D3 |
| | Date | 9/12/2012 | 9/14/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/15/2012 | 9/16/2012 | 9/17/2012 | 9/18/2012 | 9/18/2012 | 9/19/2012 | 9/19/2012 | 9/24/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 | 9/19/2012 |
| | Time | 15:45 | 14:25 | 18:15 | 15:30 | 21:40 | 18:15 | 15:30 | 2:30 | 15:45 | 16:00 | 20:00 | 16:00 | 19:00 | 6:00 | | 15:30 | 19:30 | 19:30 | 12:30 AM |
| pH | | 7.97 | 7.86 | 6.21 | 6.05 | 6.2 | 6.1 | 6.11 | 7.71 | 7.13 | 6.59 | 6.45 | 6.32 | 6.35 | 6.31 | 6.03 | 6.05 | 6.1 | 6.05 | 6.15 |
| E.C. | µS/cm | 301 | 325 | 201 | 197 | 251 | 218 | 226 | 322 | 317 | 273 | 265 | 244 | 242 | 295 | 204 | 223 | 211 | 201 | 234 |
| TDS | mg/l | 175 | 176 | 148 | 150 | 148 | 158 | 159 | 179 | 177 | 172 | 168 | 159 | 165 | 187 | 156 | 162 | 181 | 152 | 161 |
| $TDS_{calc}$ | mg/l | 174.4 | 175.5 | 146.3 | 149.6 | 169.6 | 155.1 | 155.4 | 159.7 | 188.2 | 169.0 | 168.2 | 158.1 | 164.3 | 187.0 | 146.5 | 159.6 | 156.3 | 149.4 | 155.3 |
| $TDS_{calc}/EC$ | | 0.58 | 0.54 | 0.73 | 0.76 | 0.68 | 0.71 | 0.69 | 0.50 | 0.59 | 0.62 | 0.63 | 0.65 | 0.68 | 0.63 | 0.72 | 0.72 | 0.74 | 0.74 | 0.66 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.01 | 1.00 | 0.87 | 1.02 | 1.02 | 1.12 | 0.94 | 1.02 | 1.00 | 1.01 | 1.00 | 1.00 | 1.06 | 1.02 | 1.16 | 1.02 | 1.0 |
| cation-anion | meq/l | 0.03 | 0.03 | 0.04 | 0.05 | 0.02 | 0.01 | 0.04 | 0.01 | 0.05 | 0.07 | 0.04 | 0.03 | 0.04 | 0.03 | 0.02 | 0.03 | 0.09 | 0.04 | 0.12 |

Table E.5. Short-term, injection under pressure test in the Upper Aquifer (Oct. 7 – Oct. 15, 2012)

| | | Recharge | | | | | | | | Recovery | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | RW | MW | MW | MW | MW | MW | RW | RW | RW | RW | RW | MW | MW | MW | MW | MW |
| | No. | S2 | S2 | S2 | S3 | S7 | S6 | S1 | S2 | S2 | S2 | S2 | S2 | S2 | S1 | S2 | S3 | S6 | S7 |
| | Date | 10/8/2012 | 10/10/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/11/2012 | 10/12/2012 | 10/13/2012 | 10/13/2012 | 10/14/2012 | 10/15/2012 | 10/14/2012 | 10/14/2012 | 10/14/2012 | 10/15/2012 | 10/14/2012 |
| | Time | 16:00 | 14:00 | 10:15 | 7:00 | 7:30 | 11:15 | 13:45 | 10:30 | 22:00 | 10:00 | 22:00 | 14:00 | 0:00 | 10:00 | 21:30 | 19:30 | 0:30 | 19:00 |
| pH | | 8.15 | 8.18 | 8.07 | 7.07 | 6.1 | 6.29 | 6.16 | 6.23 | 6.44 | 6.34 | 6.27 | 6.26 | 6.24 | 6.34 | 6.22 | 6.22 | 6.23 | 6.27 |
| E.C. | µS/cm | 387 | 407 | 396 | 361 | 247 | 257 | 283 | 227 | 332 | 293 | 267 | 253 | 241 | 233 | 242 | 230 | 238 | 242 |
| TDS | % | 219 | 224 | 223 | 204 | 156 | 158 | 157 | 146 | 197 | 179 | 181 | 169 | 167 | 161 | 164 | 163 | 159 | 173 |
| $TDS_{calc}$ | mg/l | 218.5 | 224.0 | 222.8 | 203.2 | 153.8 | 155.6 | 156.3 | 145.3 | 196.9 | 179.2 | 181.4 | 168.2 | 166.6 | 159.8 | 162.9 | 162.8 | 157.2 | 172.4 |
| $TDS_{calc}/EC$ | | 0.56 | 0.55 | 0.56 | 0.56 | 0.62 | 0.61 | 0.55 | 0.64 | 0.59 | 0.61 | 0.68 | 0.66 | 0.69 | 0.69 | 0.67 | 0.71 | 0.66 | 0.71 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.00 | 1.01 | 1.00 |
| cation-anion | meq/l | 0.03 | 0.03 | 0.03 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.02 | 0.00 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 |

Table E.6. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012)

| | | Recharge | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | RW | MW | MW | MW | MW | MW | MW | RW | RW |
| | No. | D2 | D2 | D2 | D2 | D7 | D6 | D1 | D4 | D3 | D2 | D2 |
| | Date | 10/23/2012 | 10/26/2012 | 10/31/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/2/2012 | 11/6/2012 | 11/12/2012 |
| | Time | 16:45 | 16:00 | 14:00 | 7:00 | 7:15 | 10:55 | 11:00 | 17:50 | 18:00 | 14:00 | 10:00 |
| pH | | 8.53 | 8.09 | 8.16 | 6.65 | 6.2 | 6.19 | 6.1 | 6.17 | 6.64 | 7.91 | 8.12 |
| E.C. | µS/cm | 421 | 404 | 397 | 325 | 271 | 269 | 214 | 288 | 343 | 413 | 414 |
| TDS | mg/l | 245 | 245 | 227 | 203 | 180 | 174 | 168 | 185 | 199 | 241 | 232 |
| $TDS_{calc}$ | mg/l | 245.1 | 245.2 | 226.7 | 201.8 | 177.4 | 172.4 | 166.3 | 183.9 | 197.9 | 240.6 | 232.0 |
| $TDS_{calc}/EC$ | | 0.58 | 0.61 | 0.57 | 0.62 | 0.65 | 0.64 | 0.78 | 0.64 | 0.58 | 0.58 | 0.56 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.00 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.12 | 0.00 | 0.00 | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.04 | 0.01 | 0.03 |

Table E.6. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012) continued

| | | Recharge | | | | | | | | | Recovery | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | MW | MW | MW | MW | MW | MW | MW | MW | RW | RW | RW |
| | No. | D2 | D5 | D8 | D6 | D1 | D7 | D2 | D3 | D4 | D2 | D2 | D2 |
| | Date | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/20/2012 | 11/25/2012 | 11/26/2012 | 11/27/2012 |
| | Time | 15:15 | 16:30 | 16:30 | 6:30 | 6:50 | 9:20 | 9:40 | 12:30 | 12:50 | 21:00 | 20:40 | 11:20 |
| pH | | 6.98 | 6.23 | 6.18 | 6.11 | 6.08 | 6.36 | 6.2 | 6.65 | 6.16 | 7.15 | 6.89 | 6.96 |
| E.C. | µS/cm | 345 | 179 | 232 | 274 | 269 | 323 | 283 | 353 | 223 | 381 | 388 | 385 |
| TDS | mg/l | 190.0 | 144.0 | 169.0 | 174.0 | 172.0 | 194.0 | 174.0 | 201.0 | 165.0 | 216.0 | 222.0 | 221.0 |
| $TDS_{calc}$ | mg/l | 189.4 | 142.7 | 165.7 | 171.3 | 171.3 | 191.5 | 172.6 | 199.2 | 162.2 | 215.5 | 237.0 | 235.9 |
| $TDS_{calc}/EC$ | | 0.55 | 0.80 | 0.71 | 0.63 | 0.64 | 0.59 | 0.61 | 0.56 | 0.73 | 0.57 | 0.61 | 0.61 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.01 | 1.02 | 1.02 | 1.00 | 1.01 | 1.01 | 1.01 | 1.02 | 1.00 | 0.94 | 0.94 |
| cation-anion | meq/l | 0.03 | 0.01 | 0.03 | 0.00 | 0.00 | 0.02 | 0.03 | 0.02 | 0.0 | 0.01 | 0.02 | 0.03 |

Table E.6. Long-term, injection under pressure the Lower Aquifer (Oct. 18 – Dec. 9, 2012) continued

| | | Recovery | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | MW | MW | MW | MW | MW | MW | MW | RW | RW | RW | RW |
| | No. | D3 | D7 | D2 | D6 | D1 | D5 | D8 | D2 | D2 | D2 | D2 |
| | Date | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/26/2012 | 11/27/2012 | 11/28/2012 | 11/29/2012 | 11/30/2012 |
| | Time | 7:50 | 8:10 | 10:30 | 10:50 | 13:00 | 13:25 | 15:45 | 11:20 | 18:30 | 19:20 | 18:30 |
| pH | | 6.68 | 6.36 | 6.13 | 6.08 | 6.03 | 6.17 | 6.17 | 6.96 | 6.85 | 6.59 | 6.64 |
| E.C. | µS/cm | 353 | 321 | 283 | 271 | 269 | 189 | 239 | 385 | 373 | 349 | 362 |
| TDS | mg/l | 233 | 188 | 160 | 185 | 181 | 155 | 175 | 221 | 218 | 214 | 216 |
| $TDS_{calc}$ | mg/l | 231.6 | 185.8 | 159.4 | 181.4 | 180.4 | 161.3 | 182.8 | 235.9 | 217.8 | 214.4 | 216.1 |
| $TDS_{calc}/EC$ | | 0.66 | 0.58 | 0.56 | 0.67 | 0.67 | 0.85 | 0.76 | 0.61 | 0.58 | 0.61 | 0.60 |
| $TDS/TDS_{calc}$ | | 1.01 | 1.01 | 1.00 | 1.02 | 1.00 | 0.96 | 0.96 | 0.94 | 1.00 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.02 | 0.04 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 |

Table E.6. Long-term, injection under pressure the Lower Aquifer (Oct 18 – Dec 9, 2012) continued

| | | Recovery | | | | | | Post injection samples | |
|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | RW | RW | RW | MW | RW | RW | RW |
| | No. | D2 | D2 | D2 | D2 | D4 | D2 | D2 | D2 |
| | Date | 12/1/2012 | 12/3/2012 | 12/5/2012 | 12/7/2012 | 12/8/2012 | 12/8/2012 | 1/6/2013 | 1/12/2013 |
| | Time | 18:30 | 17:30 | 19:30 | 18:00 | 15:30 | 17:00 | 18:00 | 17:00 |
| pH | | 6.45 | 6.37 | 6.25 | 6.24 | 6.15 | 6.28 | 7.74 | 7.92 |
| E.C. | µS/cm | 335 | 301 | 277 | 259 | 233 | 251 | 421 | 471 |
| TDS | mg/l | 202 | 193 | 180 | 175 | 176 | 169 | 238 | 261 |
| $TDS_{calc}$ | mg/l | 201.5 | 193.1 | 179.1 | 174.8 | 176.1 | 169.1 | 238.1 | 261.0 |
| $TDS_{calc}/EC$ | | 0.60 | 0.64 | 0.65 | 0.67 | 0.76 | 0.67 | 0.57 | 0.55 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.02 | 0.03 | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.04 |

## Table E.7. Long-term, recharge under pressure the Upper Aquifer (Jan. 5 – Feb. 25, 2013)

| | | Recharge | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | MW | MW | MW | MW | MW | MW | RW | RW | MW | MW | MW | MW | MW | RW | MW | MW | MW |
| | No. | S2 | S6 | S3 | S7 | S4 | S2 | S1 | S2 | S2 | S1 | S6 | S7 | S5 | S3 | S2 | S8 | S4 | S2 |
| | Date | 1/19/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/20/2013 | 1/24/2013 | 1/30/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 | 2/4/2013 |
| | Time | 10:30 | 6:00 | 9:00 | 9:30 | 12:40 | 13:20 | 18:00 | 18:00 | 14:00 | 6:00 | 7:00 | 10:10 | 13:10 | 13:50 | 15:00 | 16:15 | 17:00 | 19:30 |
| pH | | 8.08 | 6.96 | 6.68 | 6.16 | 6 | 6.05 | 6.41 | 8.06 | 8.3 | 6.56 | 6.37 | 6.85 | 6 | 6.71 | 8.42 | 6.08 | 6.03 | 6.1 |
| E.C. | µS/cm | 474 | 309 | 406 | 309 | 173 | 273 | 339 | 481 | 444 | 336 | 307 | 324 | 247 | 390 | 432 | 227 | 244 | 294 |
| TDS | mg/l | 264 | 170 | 229 | 177 | 124 | 163 | 187 | 263 | 255 | 184 | 182 | 184 | 158 | 255 | 240 | 153 | 161 | 179 |
| $TDS_{calc}$ | mg/l | 263.6 | 168.9 | 228.7 | 175.8 | 123.9 | 162.5 | 186.4 | 263.2 | 255.4 | 184.7 | 176.7 | 182.5 | 157.4 | 250.9 | 240.1 | 152.5 | 161.0 | 178.2 |
| $TDS_{calc}/EC$ | | 0.56 | 0.55 | 0.56 | 0.57 | 0.72 | 0.60 | 0.55 | 0.55 | 0.58 | 0.55 | 0.58 | 0.56 | 0.64 | 0.64 | 0.56 | 0.67 | 0.66 | 0.61 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.01 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.03 | 1.01 | 1.00 | 1.02 | 1.00 | 1.00 | 1.00 | 1.00 |
| cation-anion | meq/l | 0.01 | 0.00 | 0.01 | 0.04 | 0.00 | 0.03 | 0.05 | 0.04 | 0.01 | 0.02 | 0.01 | 0.01 | 0.02 | 0.04 | 0.02 | 0.01 | 0.00 | 0.03 |

## Table E.7. Long-term, recharge under pressure the Upper Aquifer (Jan. 5 – Feb. 25, 2013) continued

| | | Recovery | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Well | RW | MW | MW | MW | MW | MW | MW | MW | RW | RW | RW | RW | RW | RW | RW | RW | RW | RW |
| | No. | S2 | S2 | S6 | S1 | S3 | S7 | S5 | S8 | S2 | S2 | S2 | S2 | S2 | S2 | S2 | S2 | S2 | S2 |
| | Date | 2/10/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/11/2013 | 2/12/2013 | 2/13/2013 | 2/14/2013 | 2/15/2013 | 2/16/2013 | 2/18/2013 | 2/20/2013 | 2/22/2013 | 2/24/2013 |
| | Time | 12:15 | 9:00 | 9:00 | 9:00 | 14:15 | 14:20 | 16:40 | 17:00 | 12:30 | 16:15 | 13:15 | 13:15 | 13:15 | 13:15 | 13:15 | 13:15 | 13:15 | 18:15 |
| pH | | 7.36 | 6.26 | 6.2 | 6.31 | 6.52 | 6.31 | 6.1 | 6.2 | 6.93 | 6.57 | 6.59 | 6.46 | 6.42 | 6.44 | 6.34 | 6.28 | 6.27 | 6.22 |
| E.C. | µS/cm | 432 | 266 | 272 | 307 | 333 | 310 | 230 | 242 | 411 | 394 | 376 | 351 | 335 | 323 | 305 | 286 | 273 | 263 |
| TDS | mg/l | 243 | 167 | 174 | 186 | 199 | 184 | 154 | 170 | 235 | 217 | 210 | 206 | 197 | 195 | 181 | 172 | 170 | 164 |
| $TDS_{calc}$ | mg/l | 242.6 | 166.2 | 174.0 | 184.8 | 198.3 | 183.2 | 153.8 | 168.7 | 234.6 | 216.5 | 209.7 | 205.1 | 196.6 | 194.8 | 180.4 | 172.2 | 170.1 | 165.5 |
| $TDS_{calc}/EC$ | | 0.56 | 0.62 | 0.64 | 0.60 | 0.60 | 0.59 | 0.67 | 0.70 | 0.57 | 0.55 | 0.56 | 0.58 | 0.59 | 0.60 | 0.59 | 0.60 | 0.62 | 0.63 |
| $TDS/TDS_{calc}$ | | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.0 |
| cation-anion | meq/l | 0.02 | 0.01 | 0.00 | 0.01 | 0.01 | 0.03 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.02 | 0.06 | 0.05 | 0.08 |

# APPENDIX F. RECOVERY CURVE DATA

# Table F. 1 Recovery Curve Data Long-term Deep

Long-term Recovery Under Pressure - Deep Aquifer

| | | | |
|---|---|---|---|
| Start Date | 11/25/2012 | StartTime | 6:30:00 PM |
| End Date | 12/9/2012 | End Time | 4:00:00 AM |

| | | Chloride ion conc. mg/l | Silica ion conc. mg/l |
|---|---|---|---|
| 🟨 Background Sample: | Highest Background Level Recorded in September | 7.7 | 44.6 |
| 🟨 Treated Water: | Lowest Level Recorded During the Test | 37.7 | 11.2 |
| 🟥 Background Sample: | Lowest Background Level Recorded in September | 4.2 | 36 |
| 🟥 Treated Water: | Highest Level Recorded During the Test | 45.5 | 13.1 |
| 🟪 Background Sample: | Highest Background Level Recorded in September | 7.7 | 44.6 |
| 🟪 Treated Water: | Highest Level Recorded During the Test | 45.5 | 13.1 |
| 🟦 Background Sample: | Lowest Background Level Recorded in September | 4.2 | 36 |
| 🟦 Treated Water: | Lowest Level Recorded During the Test | 37.7 | 11.2 |
| 🟩 Background Sample: | Average of all of the Background Readings in September | 6 | 40 |
| 🟩 Treated Water: | Average of all of the Treated Water Injected During Test | 41.6 | 12.28 |

* Relative Ion Concentration =

$$\frac{\text{Rec. Ion concentration - treated water ion injection conc.}}{\text{treated water ion inj. conc. - bckgrnd conc. before injection}}$$

Volume Injected: 18949 $m^3$

| Recovery Sample collection time | % Recovered | Vol Recovered m3 | Elapsed time Min | Rec. Chloride ion conc. mg/l | Rec. Silica ion conc. mg/l | 🟨 Relative chloride * | 🟨 Relative silica * | 🟥 Relative chloride * | 🟥 Relative silica * | 🟪 Relative chloride * | 🟪 Relative silica * | 🟦 Relative chloride * | 🟦 Relative silica * | 🟩 Relative chloride * | 🟩 Relative silica * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/25/12 18:30 | 0 | 0 | 0 | 41.62 | 13.28 | -0.13 | 0.06 | 0.09 | 0.01 | 0.1 | 0.01 | -0.12 | 0.08 | 0 | 0.04 |
| 11/25/12 21:00 | 1.17 | 221 | 150 | 43.1 | 15.5 | -0.18 | 0.13 | 0.06 | 0.10 | 0.06 | 0.08 | -0.16 | 0.17 | -0.04 | 0.12 |
| 11/26/12 20:40 | 12.21 | 2312.88 | 1570 | 39.3 | 14.7 | -0.05 | 0.1 | 0.15 | 0.07 | 0.16 | 0.05 | -0.05 | 0.14 | 0.06 | 0.09 |
| 11/27/12 11:20 | 19.05 | 3609.27 | 2450 | 39.3 | 16 | -0.05 | 0.14 | 0.15 | 0.13 | 0.16 | 0.09 | -0.05 | 0.19 | 0.06 | 0.13 |
| 11/28/12 18:30 | 33.59 | 6364.11 | 4320 | 37.7 | 19.3 | 0 | 0.24 | 0.19 | 0.27 | 0.21 | 0.20 | 0 | 0.33 | 0.11 | 0.25 |
| 11/29/12 19:20 | 45.17 | 8559.13 | 5810 | 39.3 | 24.6 | -0.05 | 0.4 | 0.15 | 0.50 | 0.16 | 0.37 | -0.05 | 0.54 | 0.06 | 0.44 |
| 11/30/12 18:30 | 55.98 | 10606.84 | 7200 | 39.3 | 22.3 | -0.05 | 0.33 | 0.15 | 0.40 | 0.16 | 0.29 | -0.05 | 0.45 | 0.06 | 0.36 |
| 12/1/12 18:30 | 67.17 | 12728.21 | 8640 | 34.7 | 26.8 | 0.1 | 0.47 | 0.26 | 0.60 | 0.29 | 0.43 | 0.09 | 0.63 | 0.19 | 0.52 |
| 12/3/12 17:30 | 89.09 | 16882.56 | 11460 | 28.1 | 30.9 | 0.32 | 0.59 | 0.42 | 0.78 | 0.46 | 0.57 | 0.29 | 0.79 | 0.38 | 0.67 |
| 12/5/12 19:30 | 112.42 | 21302.08 | 14460 | 17.7 | 33.2 | 0.67 | 0.66 | 0.67 | 0.88 | 0.74 | 0.64 | 0.6 | 0.89 | 0.67 | 0.75 |
| 12/7/12 18:00 | 134.11 | 25412.23 | 17250 | 13.5 | 35 | 0.81 | 0.71 | 0.77 | 0.96 | 0.85 | 0.70 | 0.72 | 0.96 | 0.79 | 0.82 |
| 12/8/12 17:00 | 144.84 | 27445.21 | 18630 | 11.6 | 35.2 | 0.87 | 0.72 | 0.82 | 0.97 | 0.9 | 0.70 | 0.78 | 0.97 | 0.84 | 0.83 |

# Table F.2. Recovery Curve Data Short-term Deep

Short-term Recovery Under Pressure - Deep Aquifer

| | | | |
|---|---|---|---|
| Start Date | 9/17/2012 | StartTime | 12:45:00 PM |
| End Date | 9/20/2012 | End Time | 12:45:00 AM |

| | | Chloride ion conc. mg/l | Silica ion conc. mg/l |
|---|---|---|---|
| Background Sample: | Highest Background Level Recorded in September | 7.7 | 44.6 |
| Treated Water: | Lowest Level Recorded During the Test | 35.4 | 9.4 |
| Background Sample: | Lowest Background Level Recorded in September | 4.2 | 36 |
| Treated Water: | Highest Level Recorded During the Test | 37 | 12.2 |
| Background Sample: | Highest Background Level Recorded in September | 7.7 | 44.6 |
| Treated Water: | Highest Level Recorded During the Test | 37 | 12.2 |
| Background Sample: | Lowest Background Level Recorded in September | 4.2 | 36 |
| Treated Water: | Lowest Level Recorded During the Test | 35.4 | 9.4 |
| Background Sample: | Average of all of the Background Readings in September | 6 | 40 |
| Treated Water: | Average of all of the Treated Water Injected During Test | 36.5 | 10.7 |

* Relative Ion Concentration =

$$\frac{\text{Rec. Ion concentration - treated water ion injection conc.}}{\text{treated water ion inj. conc. - bckgrnd conc. before injection}}$$

| | |
|---|---|
| Volume injected | 4029 $m^3$ |
| m3/day | 2260.08 |
| m3/hour | 94.17 |
| m3/min | 1.57 |

| Recovery Sample collection time | % Recovered | Vol Recovered m3 | Elapsed time Min | Rec. Chloride ion conc. mg/l | Rec. Silica ion conc. mg/l | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9/17/12 12:45 | 0 | 0 | | | | | | | | | | | | | |
| 9/17/12 15:45 | 5 | 235.41 | 3 | 38.1 | 11 | 0.1 | 0.05 | 0.03 | 0.05 | 0.04 | 0.04 | 0.09 | 0.06 | 0.05 | 0.01 |
| 9/18/12 16:00 | 45.42 | 2138.31 | 27.25 | 30.4 | 24.6 | 0.18 | 0.43 | 0.2 | 0.52 | 0.23 | 0.38 | 0.16 | 0.57 | 0.2 | 0.47 |
| 9/18/12 20:00 | 52.08 | 2452.19 | 31.25 | 26.2 | 26.6 | 0.33 | 0.49 | 0.33 | 0.61 | 0.37 | 0.44 | 0.29 | 0.65 | 0.34 | 0.54 |
| 9/19/12 16:00 | 85.42 | 4021.59 | 51.25 | 12.3 | 26.6 | 0.83 | 0.49 | 0.75 | 0.61 | 0.84 | 0.44 | 0.74 | 0.65 | 0.79 | 0.54 |
| 9/19/12 19:00 | 90.42 | 4257 | 54.25 | 12.3 | 30 | 0.83 | 0.59 | 0.75 | 0.75 | 0.84 | 0.55 | 0.74 | 0.77 | 0.79 | 0.66 |
| 9/20/12 0:45 | 100 | 4708.2 | 60 | | | | | | | | | | | | |

# Table F.3. Recovery Curve Data Long-term Shallow

Long-term Recovery Under Pressure - Shallow Aquifer

| | | | |
|---|---|---|---|
| Start Date | 2/10/2013 | StartTime | 8:15:00 PM |
| End Date | 2/25/2013 | End Time | 8:45:00 AM |

| | | | Chloride ion conc. mg/l | Silica ion conc. mg/l |
|---|---|---|---|---|
| 🟨 | Background Sample: | Highest Background Level Recorded in September | 1.5 | 37.5 |
| 🟨 | Treated Water: | Lowest Level Recorded During the Test | 35.4 | 11.7 |
| 🟥 | Background Sample: | Lowest Background Level Recorded in September | 0.4 | 34.8 |
| 🟥 | Treated Water: | Highest Level Recorded During the Test | 55.4 | 14 |
| 🟪 | Background Sample: | Highest Background Level Recorded in September | 1.5 | 37.5 |
| 🟪 | Treated Water: | Highest Level Recorded During the Test | 55.4 | 14 |
| 🟦 | Background Sample: | Lowest Background Level Recorded in September | 0.4 | 34.8 |
| 🟦 | Treated Water: | Lowest Level Recorded During the Test | 35.4 | 11.7 |
| 🟩 | Background Sample: | Average of all of the Background Readings in September | 0.7 | 36.1 |
| 🟩 | Treated Water: | Average of all of the Treated Water Injected During Test | 46.9 | 12.6 |

* Relative Ion Concentration =

$$\frac{\text{Rec. Ion concentration - treated water ion injection conc.}}{\text{treated water ion inj. conc. - bckgrnd conc. before injection}}$$

Volume Injected: 18949 $m^3$

| Recovery Sample collection time | % Recovered | Vol Recovered m3 | Elapsed time Min | Rec. Chloride ion conc. mg/l | Rec. Silica ion conc. mg/l | 🟨 Relative chloride * | 🟨 Relative silica * | 🟥 Relative chloride * | 🟥 Relative silica * | 🟪 Relative chloride * | 🟪 Relative silica * | 🟦 Relative chloride * | 🟦 Relative silica * | 🟩 Relative chloride * | 🟩 Relative silica * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2/10/13 8:15 | 0 | 0 | 0 | | | | | | | | | | | | |
| 2/10/13 12:15 | 1.67 | 299.64 | 240 | 34.7 | 12.9 | 0.02 | 0.05 | 0.38 | 0.05 | 0.38 | 0.05 | 0.02 | 0.05 | 0.26 | 0.01 |
| 2/11/13 12:30 | 11.8 | 2116.19 | 1695 | 39.7 | 16.1 | -0.13 | 0.17 | 0.29 | 0.1 | 0.29 | 0.09 | -0.12 | 0.19 | 0.16 | 0.15 |
| 2/12/13 16:15 | 23.39 | 4194.93 | 3360 | 37 | 18.4 | -0.05 | 0.26 | 0.33 | 0.21 | 0.34 | 0.19 | -0.05 | 0.29 | 0.21 | 0.25 |
| 2/13/13 13:15 | 32.16 | 5768.02 | 4620 | 35.8 | 20.7 | -0.01 | 0.35 | 0.36 | 0.32 | 0.36 | 0.29 | -0.01 | 0.39 | 0.24 | 0.34 |
| 2/14/13 13:15 | 42.19 | 7565.85 | 6060 | 36.2 | 23.1 | -0.02 | 0.44 | 0.35 | 0.44 | 0.36 | 0.39 | -0.02 | 0.49 | 0.23 | 0.45 |
| 2/15/13 13:15 | 52.22 | 9363.68 | 7500 | 30.4 | 24.7 | 0.15 | 0.5 | 0.45 | 0.51 | 0.46 | 0.46 | 0.14 | 0.56 | 0.36 | 0.51 |
| 2/16/13 13:15 | 62.24 | 11161.5 | 8940 | 28.9 | 25.8 | 0.19 | 0.55 | 0.48 | 0.57 | 0.49 | 0.5 | 0.19 | 0.61 | 0.39 | 0.56 |
| 2/18/13 13:15 | 82.29 | 14757.15 | 11820 | 21.2 | 27.5 | 0.42 | 0.61 | 0.62 | 0.65 | 0.63 | 0.57 | 0.41 | 0.68 | 0.56 | 0.63 |
| 2/20/13 13:15 | 102.34 | 18352.8 | 14700 | 16.9 | 29.5 | 0.55 | 0.69 | 0.7 | 0.75 | 0.71 | 0.66 | 0.53 | 0.77 | 0.65 | 0.72 |
| 2/22/13 13:15 | 122.39 | 21948.46 | 17580 | 12.7 | 30.2 | 0.67 | 0.72 | 0.78 | 0.78 | 0.79 | 0.69 | 0.65 | 0.8 | 0.74 | 0.75 |
| 2/24/13 18:15 | 144.53 | 25918.65 | 20760 | 11.2 | 31.7 | 0.71 | 0.78 | 0.8 | 0.85 | 0.82 | 0.75 | 0.69 | 0.87 | 0.77 | 0.81 |

## Table F.4. Recovery Curve Data Long-term Shallow

Short-term Recovery Under Pressure - Shallow Aquifer

| | | | |
|---|---|---|---|
| Start Date | 10/11/2012 | StartTime | 12:45:00 AM |
| End Date | 10/15/2012 | End Time | 12:45:00 AM |

| | | Chloride ion conc. mg/l | Silica ion conc. mg/l |
|---|---|---|---|
| Background Sample: | Highest Background Level Recorded in September | 1.5 | 37.5 |
| Treated Water: | Lowest Level Recorded During the Test | 55.8 | 10.2 |
| Background Sample: | Lowest Background Level Recorded in September | 0.4 | 34.8 |
| Treated Water: | Highest Level Recorded During the Test | 57.8 | 10.5 |
| Background Sample: | Highest Background Level Recorded in September | 1.5 | 37.5 |
| Treated Water: | Highest Level Recorded During the Test | 57.8 | 10.5 |
| Background Sample: | Lowest Background Level Recorded in September | 0.4 | 35 |
| Treated Water: | Lowest Level Recorded During the Test | 55.8 | 10.2 |
| Background Sample: | Average of all of the Background Readings in September | 0.7 | 36.1 |
| Treated Water: | Average of all of the Treated Water Injected During Test | 56.7 | 10.4 |

* Relative Ion Concentration =

Rec. Ion concentration - treated water ion injection conc.

treated water ion inj. conc. - bckgrnd conc. before injection

| | |
|---|---|
| Volume Injected: | 4134 $m^3$ |
| $m^3$/day | 2260.08 |
| $m^3$/hour | 94.17 |
| $m^3$/min | 1.57 |

| Recovery Sample collection time | | 94.17 1.57 | Vol Recovered m3 | Elapsed time Min | Rec. Chloride ion conc. mg/l | Rec. Silica ion conc. mg/l | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * | Relative chloride * | Relative silica * |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10/11/12 10:15 | 0 | | | 0 | 57.8 | 10.4 | -0.04 | 0.01 | 0 | 0 | 0 | 0 | -0.04 | 0.01 | -0.02 | 0 |
| 10/12/12 22:00 | 17.42 | | 618.19 | 7 | 46.6 | 19.5 | 0.17 | 0.34 | 0.2 | 0.37 | 0.2 | 0.33 | 0.17 | 0.38 | 0.18 | 0.35 |
| 10/13/12 10:00 | 47.27 | | 1677.94 | 19 | 36.2 | 21.4 | 0.36 | 0.41 | 0.38 | 0.45 | 0.38 | 0.4 | 0.35 | 0.46 | 0.37 | 0.43 |
| 10/13/12 22:00 | 77.13 | | 2737.69 | 31 | 26.6 | 29.9 | 0.54 | 0.72 | 0.54 | 0.8 | 0.55 | 0.72 | 0.53 | 0.8 | 0.54 | 0.76 |
| 10/14/12 14:00 | 116.94 | | 4150.69 | 47 | 14.6 | 31.9 | 0.76 | 0.79 | 0.75 | 0.88 | 0.77 | 0.79 | 0.74 | 0.88 | 0.75 | 0.84 |
| 10/15/12 0:00 | 141.82 | | 5033.82 | 57 | 10.4 | 33.2 | 0.84 | 0.84 | 0.83 | 0.93 | 0.84 | 0.84 | 0.82 | 0.93 | 0.83 | 0.89 |

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Dissolved Silica as an Indicator of ASR
Performance in the Chao Phraya River
Valley Aquifer, Central Thailand

Title of Thesis

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Signature of Graduate School Staff

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