City of North Battleford Water Well Capture Zone Study

Harry Rohde, P.Eng. and Bob Stewart, P.Geol.
Agriculture and Agri-Food Canada – Prairie Farm Rehabilitation Administration, Regina, SK, Canada
Dr. John R. Lawrence, George Swerhone and Dr. Len Wassenaar
Environment Canada – National Water Research Institute, Saskatoon, SK, Canada
Dr. Darren Korber and Prabhakara Medihala
Department of Food and Bioproducts, College of Agriculture – University of Saskatchewan, Saskatoon, SK, Canada
Dr. Kerry MacQuarrie, P.Eng., Dennis Connor and Sylvie Morton
Department of Civil Engineering and Canadian Rivers Institute – University of New Brunswick, Fredericton, NB, Canada

ABSTRACT
The Water Well Capture Zone Study was initiated to determine the factors responsible for the deterioration of water well supplies and to evaluate an experimental technology designed to mitigate the effects of biofilm development around water wells. Previous laboratory studies with an impressed current system indicated that electrical currents directed toward a well screen could reverse the effects of biofilm development. However, this field evaluation proved unsuccessful and demonstrated that a more thorough understanding of the impressed current system is still required to properly evaluate whether this technology can be useful as preventative maintenance technique.

RÉSUMÉ
L’étude sur la zone de captage de l’eau de puits a été entreprise afin de déterminer les facteurs responsables de la détérioration des sources d’alimentation en eau des puits et d’évaluer une technologie expérimentale conçue pour atténuer les effets du développement de biofilm autours des puits. Des études préalablement menées en laboratoire sur un système de protection par courant imposé avaient révélé que des courants électriques dirigés sur un filtre pour puits pouvaient renverser les effets du développement de biofilm. La présente évaluation sur le terrain s’est toutefois révélée infructueuse et a démontré qu’il faudra améliorer notre compréhension du système par courant imprimé pour bien évaluer l’utilité de cette technologie comme technique d’entretien préventif.

1 INTRODUCTION

Groundwater is a key resource for the agricultural sector across Canada, providing water supplies to over 80% of rural Canadians (Bruce, J.P. et al, 2009). Although there is a high reliance on groundwater supplies, water wells are often managed with a “set and forget” attitude, which can lead to deterioration in performance and water quality over time. This generally leads to a poor understanding of the conditions that cause many of the problems encountered in the water well environment, and when problems do arise, inappropriate remedial actions are often applied. Therefore, there is a need to better understand the various factors that affect water well deterioration and to develop improved techniques to prevent premature well failure.

1.1 Study Area

The City of North Battleford is a rural community of 14,000 people located in northwestern Saskatchewan that utilizes groundwater withdrawn from six wells completed in an alluvial deposit along the north bank of the North Saskatchewan River (see Figure 1). The Water Well Capture Zone Study project site is located at the western end of the City of North Battleford well field. This well field is ideal for this type of study since the operational history is well documented and the existing level of knowledge provides a more effective opportunity as compared to individual farm wells which usually have little or no maintenance history or performance records. The City of North Battleford wells are also unique in their propensity for accelerated deterioration, typically experiencing a 40 to 50% decline in performance within 3 years. This provides an opportunity to complete a study in as little as 2 to 3 years, compared to an average well that may normally require an observation period of 10 to 15 years.

1.2 Project Objectives

To undertake this study, a multidisciplinary team was formed to investigate the impacts of the physical, chemical and biological changes that occur in this well field. The potential impacts and mechanisms responsible for the premature deterioration in well performance were investigated, along with potential diagnostic tools and preventative maintenance techniques that could be employed to forewarn or prevent this premature decline in well performance.

The project team included Environment Canada – National Water Research Institute (NWRI), Saskatoon, Saskatchewan – College of Agriculture, Saskatoon, Saskatchewan; the University of New Brunswick – Department of Civil Engineering, Fredericton, New Brunswick; and Agriculture and Agri-Food Canada – Prairie Farm Rehabilitation Administration (PFRA), Regina, Saskatchewan.

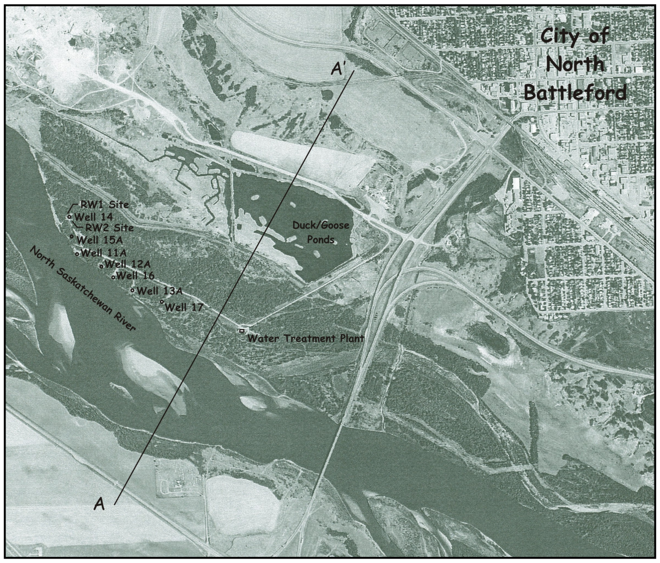

Figure 1. Study area location

The main objectives of this project include:

- Design and install two research wells and adjacent piezometers to facilitate performance monitoring and water quality sampling. One well will be equipped with an impressed current system and its potential in preventing biological plugging of the well intake area will be investigated.
- Collect and analyze soil and water samples to identify and quantify the mechanisms responsible for the deterioration of a water well supply.
- Characterize the biological, chemical and hydraulic properties in the well environment that effect water well operation.
- Develop methods for predicting long-term water well performance and service life.

For this study, the PFRA installed the research wells and piezometers used by the research team to monitor and evaluate the biological activity, water isotopes and geochemistry, surface and groundwater interactions, and the hydraulic properties and temperature variations within the aquifer environment. The PFRA also evaluated the effectiveness of the impressed current system, which is an experimental technology designed to mitigate the effects of biofilm development around the well intake area. A description of these project components will be provided, along with a brief summary of the results of the other study components

2 RESEARCH WELL SITES

In the fall of 2006, the two research wells for this study (RW1 & RW2) were installed near Well 14, which was inactive. RW1 was installed about 6 metres northwest of Well 14, while RW2 was installed about 55 metres southeast (Figure 2).

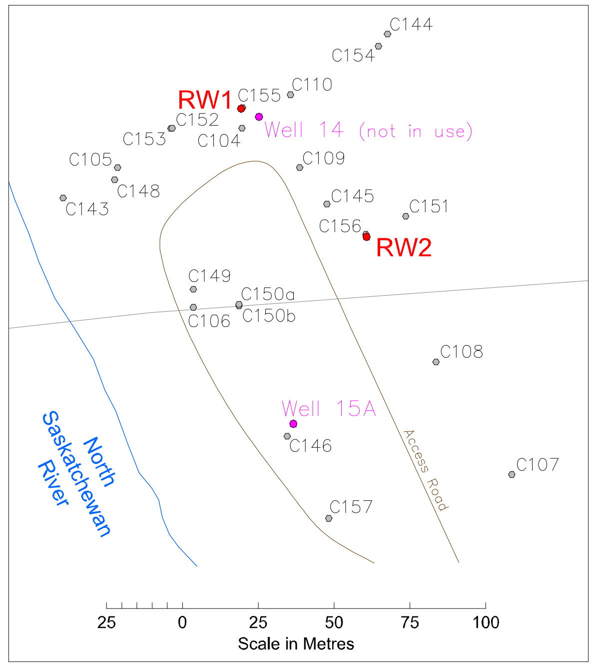

Figure 2. Research well sites

The aquifer material at the research well sites consists of alluvial deposits of fine sand, silt and clay, with minor amounts of gravel and organics, averaging about 20 metres in thickness (Figure 3).

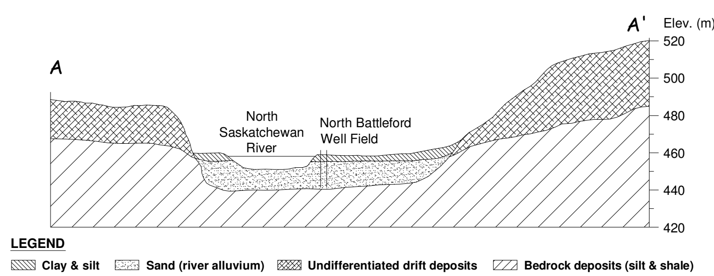

Figure 3. Generalized cross section of study area

Both well installations were similar, except that an impressed current system was installed around RW2 to evaluate its ability to mitigate the effects of biological plugging. In June 2007, the wells were placed into operation, and were pumped continuously, with very little interruption, until March 2009. The near-well zones of both wells were closely monitored to evaluate chemical, physical and biological changes that may contribute to premature deterioration in well performance.

A network of 98 piezometers was installed around the two research wells to monitor water levels, temperatures, chemistry and biological activity. This closely-spaced network of piezometers permitted a comprehensive assessment of the well capture zone area to be undertaken. Representative samples of aquifer media were also collected and analyzed for chemical and biological content.

Figure 4. Piezometer installations at RW1

3 IMPRESSED CURRENT SYSTEM

The impressed current system is an experimental technology that was evaluated as a potential preventative maintenance treatment to mitigate the effects of biofilm development around the well intake area. Preliminary laboratory studies jointly conducted by PFRA and Environment Canada (NWRI) have shown that the plugging effect of the biofilm can be significantly mitigated with an applied electrical field using an impressed current system (Globa, Lawrence and Rohde, 2004). Previous studies (PFRA and DBI, 1998-2000) have also shown that biological plugging appears to be a major factor in the fairly rapid deterioration in performance of the City of North Battleford wells, and this project provided a good opportunity to evaluate the ability of the impressed current system to mitigate the effect of biofilm development at a newly-installed well. If successful, this preventative treatment should reduce the frequency of extensive well treatments and prolong well life. The basic layout of the system is shown in Figure 5.

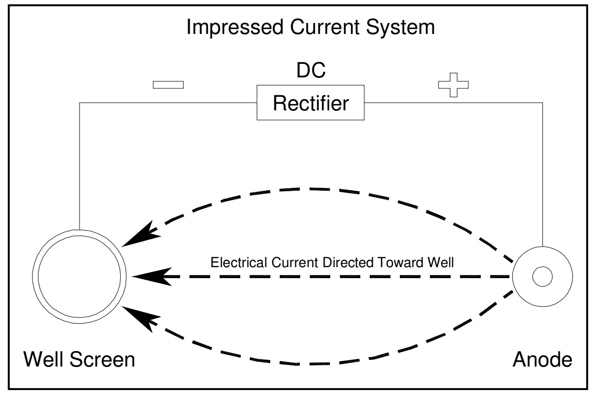

Figure 5. Schematic of Impressed Current System

3.1 Installation of Impressed Current System

In this field study, the impressed current system was installed at RW2. The installation consists of four anode strings attached to PVC piezometers (C139-C142) that were installed around RW2 at a radial distance of about 1.5 metres. Each anode string consists of five, 1.22-metre long anodes installed to a depth of about 18.2 metres, as shown in Figure 6. A rectifier is used to apply a direct current from the anodes toward the well screen (cathode).

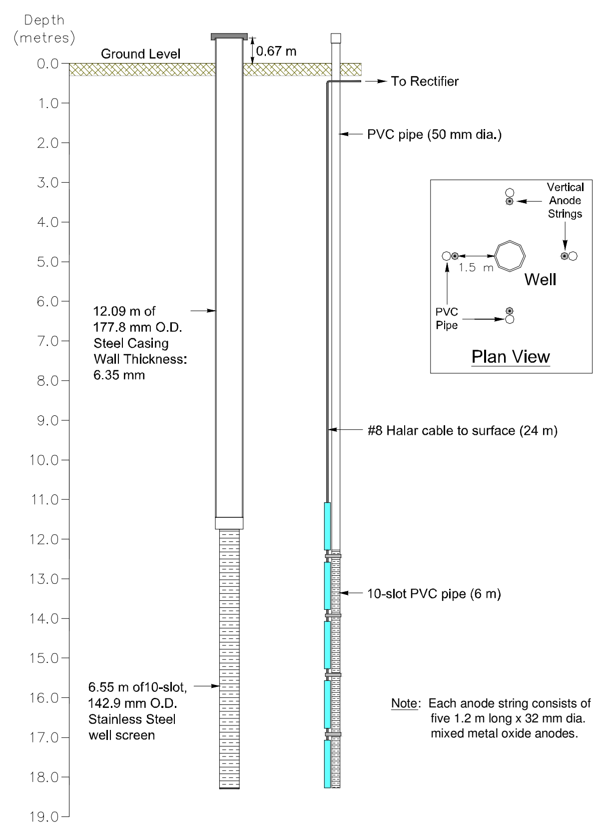

Figure 6. Anode installations at RW2

The impressed current system (see Figure 7) was activated when both research wells (RW1 and RW2) were placed into operation on June 13, 2007. The rectifier settings were adjusted to deliver 58.5 volts and 10 amps through the anodes towards the well screen at RW2. These initial settings were chosen as a starting point, based on previous results from both field and laboratory investigations. Although the lab studies were unable to precisely quantify the amount of current flux required to migrate biofouling effects, previous field trials at Well 17 had utilized settings of about 60-75 volts and 35 amps. Therefore, the initial settings for the RW2 site were considered a conservative starting point for initiating this experiment. Several readings taken from the rectifier over the next four months revealed a gradual drop in voltage from 58.5 to 28.5 volts, but the current flow remained steady at about 10 amps. In order to evaluate the effect of the impressed current system as compared to the RW1 site, periodic pump tests were conducted to monitor any changes to the specific capacities of the wells and biological testing monitored any changes in biological activity.

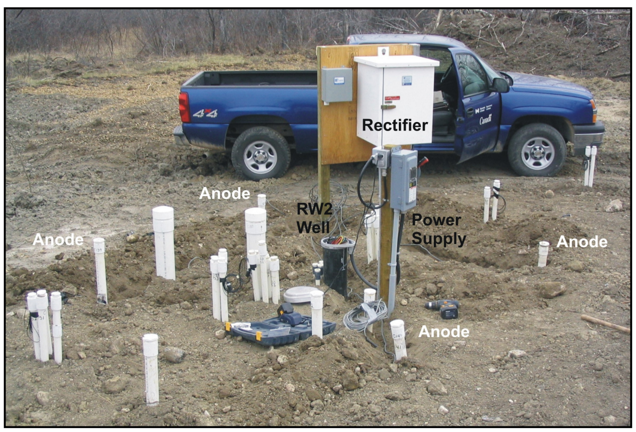

Figure 7. Set-up of impressed current system

3.2 Monitoring of Impressed Current System

One of the main methods to evaluate the effectiveness of the impressed current was to perform pump tests and record any changes in the specific capacity at each well. Pump tests were performed after the wells were initially installed in the fall of 2006, and again prior to placing them online June 2007. These first two sets of specific capacity measurements for each well were fairly similar, although both showed a slight increase in the spring of 2007. This was probably due to higher water levels experienced in the aquifer in the spring, resulting in an increased aquifer transmissivity.

In October 2007, a pump test performed on RW2 revealed that this well had experienced a 75 percent drop in specific capacity, while RW1 showed about a 15 per cent decline. This was unexpected since previously wells in this well field experienced a significant decline in specific capacity after about 3 years of operation. This premature decline in specific capacity for RW2 also reduced the well pumping rate to only 3.8 L/s (50 igpm). This lower pumping rate could compromise the study results, and therefore, a treatment was performed to restore the well capacity.

It was speculated that this very rapid decline in specific capacity was due to the plugging of the well intake area with mineral deposits, since this is one of the side effects of the impressed current system. Through electromigration, the electrical current causes ions in the water to move from the anode to the well screen (i.e. cathode), which are then reduced and deposited on the well screen. There is also an increase in pH at the well screen which shifts the carbonate equilibrium causing calcite to precipitate on the well screen. This mineral scale was observed on some of the temperature probes that had been installed at the RW2 site (see Figure 8) and consists primarily of carbonate deposits, and therefore, can readily be dissolved by a mineral acid, such as hydrochloric acid.

Figure 8. Mineral Scale on Temperature Probe

There was a concern by the project team that if an acid treatment penetrated some distance into the aquifer it would compromise the biological analyses of the aquifer environment and no longer allow a true comparison between the two well sites. Fortunately, this mineral scale was only expected to be deposited on the well screen, with minimal or no deposition within the aquifer matrix. Therefore, the acid treatment was applied solely within the well screen area, without allowing the acid to penetrate into the surrounding aquifer material. After treatment, the well capacity improved significantly; however, the impressed current system was deactivated until a more thorough assessment of the situation that led to this accelerated plugging of the well screen was performed, and the system remained inactive for the remainder of the study. At RW1, the specific capacity was still in an acceptable range and no treatment was required.

3.2.2 Specific Capacity Tests

Periodic short-term pump tests were conducted to monitor the specific capacity of each well. The specific capacity at RW1 had remained fairly steady, about 6 igpm/ft of drawdown, until about March 2008 when a gradual decline started. After June 2008, the well performance began an accelerated decline and reached a specific capacity of 1.5 igpm/ft of drawdown by February 2009 (Figure 9).

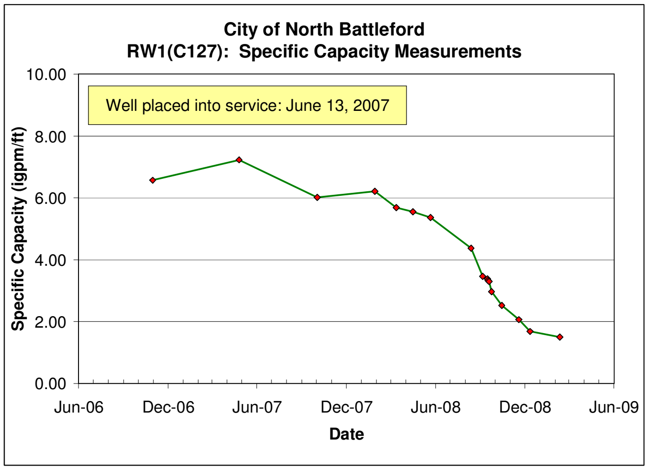

Figure 9. Specific capacity measurements at RW1

After the well treatment at RW2, the specific capacity remained fairly steady until March 2008, when the well performance also began a gradual decline and by February 2009 reached a specific capacity of 2.2 igpm/ft of drawdown (Figure 10).

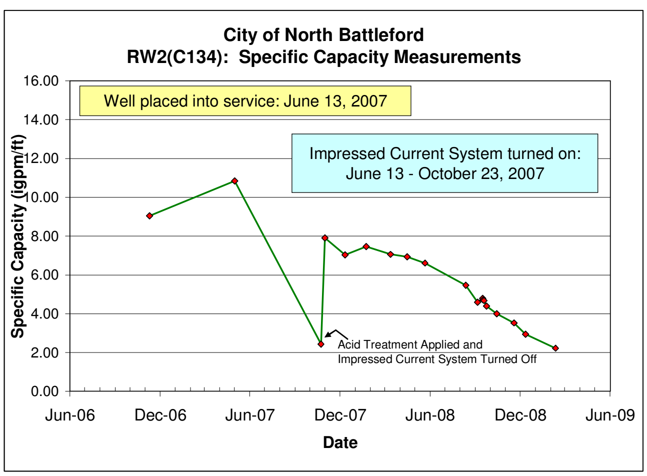

Figure 10. Specific capacity measurements at RW2

In order to calculate the specific capacity, pump tests were conducted at a rate of about 6.1 L/s (80 igpm) at each well; however, as the wells began to plug, the pumping rates were gradually reduced. In September 2009, the pumping rate was reduced to about 3.8 L/s (50 igpm) and as the plugging continued the pumping rates in both wells were reduced to about 1.5 L/s (20 igpm) by February 2009. At this point, the wells were barely operational and well treatments will have to be considered in the near future in order to restore the functionality of these wells.

4 SUMMARY OF STUDY RESULTS

Although one of the key study components, the evaluation of the impressed current system, was suspended, the results of the other study components provided valuable insight into some of the factors and mechanisms that may influence the rapid plugging of the City's wells. A brief summary of several of the main findings that relate directly to the aquifer plugging situation are provided in this section.

4.1 Microbiological Evaluations

The results of the microbiological investigations clearly revealed that the greatest increase in microbial populations in the water and biofilm material at both research well sites occurred within a radius of 1-2 metres from the wells (Lawrence et al. 2009). Observations from polycarbonate coupons installed at selected piezometer sites also indicated that considerable biomass accumulation was possible and that biofilm formation was often coincident with deposition of both oxidized and reduced forms of iron, and that this was spatially-dependent within the well field (Figure 11).

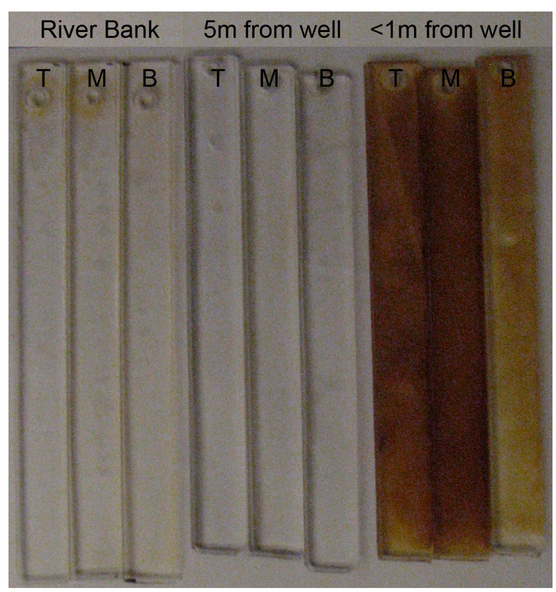

Figure 11. Biofilm accumulation on coupons at the RW1 site, with iron deposition in one-metre zone of the well (Lawrence et al. 2009)

Other biological analyses, including carbon utilization assays and biofilm thickness analysis, all suggest that both biomass and metabolic activity are stimulated within the one-metre water extraction zone surrounding each well. In addition, molecular analyses of these microbial communities revealed that pumping the wells resulted in a reduction in the microbial community biodiversity relative to the pre-pumping microbial conditions within the one-metre zone of the wells, but not at more distant sampling locations. Specifically, there was a selection for fewer specific, possibly specialized bacterial species, which contributed to the development of a microbial (biofouling) community in the immediate vicinity of the well.

4.2 Hydraulic Evaluation of the Aquifer

The characterization of the hydraulic conditions at both research well sites support the observation that the zone of plugging is generally concentrated within one metre of the well (MacQuarrie et al. 2009). In particular, the analysis of the hydraulic head difference (Δh) trends at piezometer sites close to RW1 and RW2 showed that head differences increased significantly at these locations after about 300 to 365 days of continuous pumping. This hydraulic head difference increase was consistent for locations within one metre of the wells (Figure 12). Since pumping rates were constant for this analysis, it suggests that the increases in Δh are an indication of aquifer plugging. (Note: In Figure 12, the sharp decline and increase in October 2007 is due to the well screen plugging and subsequent acid treatment at RW2.)

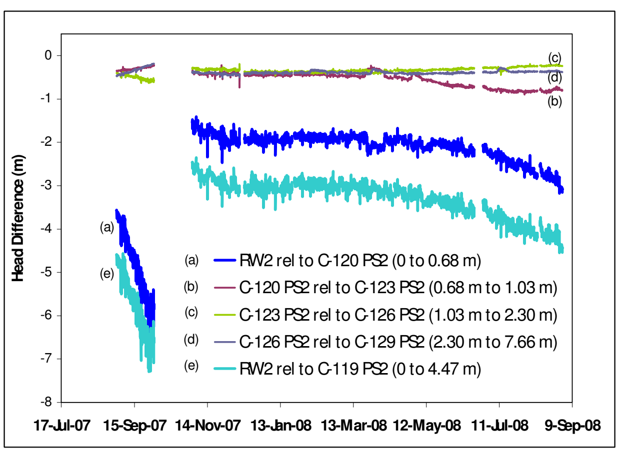

Figure 12. Hydraulic head differences at RW2 site (MacQuarrie et al. 2009)

Based on these observations, it appears that after about one year of continuous pumping, plugging of the aquifer around the production wells in the City of North Battleford well field will rapidly accelerate. Also, the results of the hydraulic head difference analysis suggest that this plugging may be limited in areal extent. Therefore, long-term monitoring of hydraulic heads at the production wells may be an effective means to signal the onset of plugging around the wells.

4.3 Water Isotopes and Geochemistry

Another component of the study examined the potential influence of the North Saskatchewan River and the adjacent Ducks Unlimited wetland on well plugging. Water isotopes and geochemical data were gathered to determine the groundwater flow velocities in the aquifer and the potential influx of surface water and accompanying nutrients into the well field (Wassenaar, 2009). The isotope data clearly showed that there was no influence from the duck ponds on the groundwater supply wells. In Figure 13, the crosses that represent the river and groundwater samples are concentrated in the centre of the line graph near the large circle that represents the mean rainfall; the two duck pond samples are located further along the line.

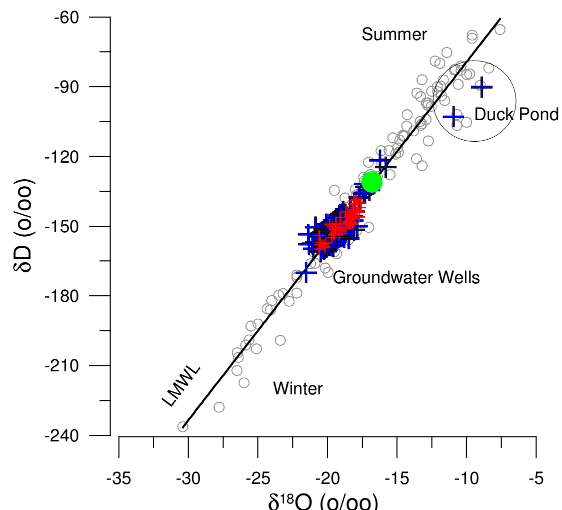

Figure 13. Water Isotope measurements (^{18}O vs. ^{2}H) (Wassenaar, 2009)

The isotope results also showed that there was recharge to the aquifer from the river and that the seasonal isotopic patterns appeared only at piezometer sites closest to the river, implying that the wells at the study site were drawing residual groundwater and that there would be no direct influx of nutrients from the river to contribute to the plugging process around the wells. However, the data were inconclusive in detecting the flux of river water required to determine groundwater flow rates to the wells.

Water samples collected from the river and selected piezometers indicate that the water can be characterized as a $Ca\text{-}HCO_3$ type. Groundwater in all areas within the aquifer was found to be anoxic and often smelled of hydrogen sulphate gas, indicative of sulphate-reducing conditions. Dissolved organic carbon concentrations were also generally high and wells furthest away from the river were high in iron and manganese.

4.3.1 Geochemistry of Sediment Samples

An analysis of the iron and manganese concentrations in the aquifer sediments was conducted to determine their potential influence in the plugging process (Connor and MacQuarrie, 2009). The aquifer sand samples were analyzed for total iron and manganese by Inductively Coupled Plasma Emission Spectrometry (ICP/ES). Manganese and iron oxides were found to be abundant in the aquifer sands. The manganese concentrations in the sand samples vary from 50 to 140 mg/kg, while the iron concentrations are higher and range from 230 to 1200 mg/kg (see Figures 14 and 15). Also, at most locations corresponding to the well screens depths, iron levels were lower in the later samples, indicating iron oxide disappearance over time. This could be the result of bacterial action which, under anaerobic conditions such as exist in the aquifer, convert the manganese and iron oxides to lower oxidation states which are water soluble.

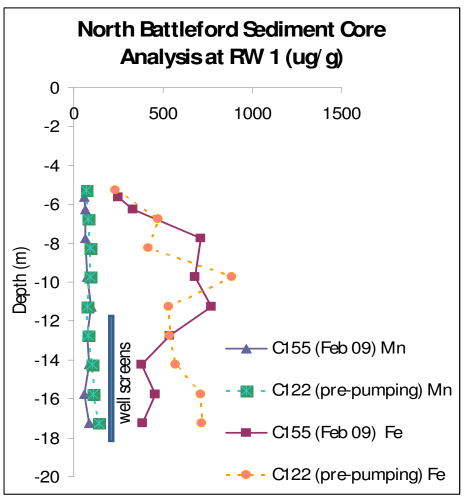

Figure 14. Iron and manganese concentrations in aquifer sediments near RW1 (Connor et al. 2009)

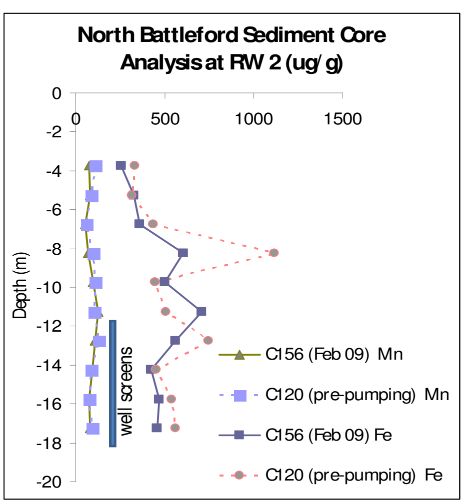

Figure 15. Iron and manganese concentrations in aquifer sediments near RW2 (Connor et al. 2009)

5 CONCLUSIONS

The two research wells and intensive network of piezometers enabled a comprehensive monitoring of water levels, temperatures, water isotopes and chemistry, and microbiological activity during the 2-year observation period, from June 2007 to March 2009. Unfortunately, the evaluation of the impressed current system was suspended due to operational complications; however, the study investigations were able to continue and the characterization of the biological, chemical and hydraulic properties of the aquifer environment was completed.

The study revealed that both research wells exhibited signs of plugging within the first year of operation and experienced a 75 percent decline in capacity by the end of the study in March 2009. During this observation period, the results of the biological and hydraulic investigations clearly indicated that the plugging is biological in nature and occurs within the one-metre zone of the well intake area. Although it is still difficult to directly quantify the mechanisms responsible for this rapid and severe plugging it has become evident that the river and duck ponds are not a source of nutrients and do not directly influence the plugging process around the well. Other factors that could possibly contribute to rapid biofilm growth are both the high organic content and iron concentrations in this alluvial aquifer, which represent potential nutrient and electron donor sources for the naturally-occurring nuisance bacteria in the water well environment.

The plugging seems to occur within the one-metre zone around the production wells, and therefore, improved well treatment techniques and technologies are needed to effectively treat this area. Traditional chemical treatments appear to be ineffective in reaching this zone, and therefore, an approach such as the impressed current system could be reassessed as a potential preventative treatment to arrest or prevent the biological plugging. However, occasional acid treatments may be required to prevent mineral scale development on the well screen.

There is still some ongoing monitoring that could be considered to improve the overall understanding of water well environment in the study area. This would include the collection of hydraulic head and well discharge data, as well as river stage data. A detailed flow and heat transport model could be developed for a more complete integration of the hydraulic and temperature data, and additional water isotope data could be collected to improve the interpretation of seasonal isotopic patterns and to determine groundwater flow rates to the wells. In addition, it may be instructive to identify the specific microorganisms that comprise the microbial (i.e.biofouling) community within the one-metre plugging zone around the well.

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