# Monitoring Changes in Near-Well Hydraulic Conditions as a Means to Assess Aquifer Clogging

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## Abstract:

To better understand and monitor the hydraulic effects caused by clogging near groundwater production wells, a study was conducted in the unconfined sand aquifer utilized by the City of North Battleford, Saskatchewan, Canada. Detailed investigations were carried out near one production well between the spring of 2007 and the fall of 2008. Results from four pumping tests conducted over this time period indicated no significant temporal changes in hydraulic conductivity within approximately two meters of the pumping well. In contrast, long-term monitoring of hydraulic head differentials did reveal increases with time, and suggested that clogging began to accelerate within a radius of one meter of the well after about one year of continuous pumping. It is concluded that continuous monitoring of hydraulic head in pumping wells and nearby piezometers, combined with breakpoint analyses of head differentials and specify capacity tests, will be more effective than standard pumping tests for detecting temporal and spatial trends in aquifer and well screen clogging.

**ASCE Subject Headings:** Groundwater supply, Aquifers, Wells, Pumping tests, Clogging

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## 1. Introduction

Aquifer pore clogging in the vicinity of a production well, or well screen clogging, may result in significant operational problems for municipal groundwater supplies (McLaughlan 2002, van Beek 1989). Well clogging produces a decrease in specific capacity, which is defined as the well discharge divided by the drawdown in the pumped well. If clogging is not detected and effectively treated, it may hinder the reliable delivery of drinking water and may eventually necessitate well abandonment. Two main types of clogging have been identified in the literature: mechanical and chemical. Mechanical clogging, also known as well bore clogging, is attributed to the accumulation of particles within the aquifer near the outside surface of the gravel pack, which is typically installed during well construction in the annulus between the borehole and well screen (Timmer et al. 2003, van Beek et al. 2009a). Well bore clogging would not necessarily be detected by examining the inside of the well screen, submersible pump, or water lines (van Beek et al. 2009b). Chemical clogging, also known as screen slot clogging, is caused by geochemical and/or biological reactions. Screen slot clogging is characterized by a temporal increase in entrance resistance due to the accumulation of chemical precipitates or biomass on or near the well screen (e.g. Sterrett 2007, van Halem et al. 2011). Screen slot clogging may also contribute to fouling of submersible pumps and water lines (van Beek et al. 2009b). Chemical clogging can be caused by inducing chemically and microbially reactive waters to mix near the pumping well; for example, oxygenated water from near the water table may be mixed with deeper anoxic groundwater containing dissolved iron (Stuetz and McLaughlan 2004).

Van Beek (1989) discussed the rehabilitation of clogged wells in the Netherlands, where it was estimated that 50 to 70% of municipal well fields have experienced clogging. Rehabilitation methods include physical and chemical treatments (e.g. concentrated hydrochloric acid, sodium hypochlorite) that must be repeated periodically during the life of the well. Van Beek et al. (2009b) have recommended well operation methods to help mitigate different types of well clogging, including operating wells continuously for as long as possible to mitigate screen slot clogging, and using separate wells (i.e. shallow and deep) to avoid mixing of chemically reactive waters. However, Stuetz and McLaughlan (2004) noted that the distribution of oxygenated and iron-rich groundwater may vary laterally, and not simply as a function of depth. Van Beek et al. (2009b, 2010) recommended alternating water abstraction and idle periods for limiting well bore clogging caused by particle accumulation. Globa et al. (2004) have piloted an experimental impressed current system to alleviate biofouling at wells utilized by the City of North Battleford, Saskatchewan, and suggested that the technology may hold promise as a nonchemical means of mitigating the clogging caused by well screen biofilm formation. The success of mitigation or remediation measures depends on the underlying clogging mechanisms (i.e., mechanical or chemical) and the timely identification and spatial extent of clogging (e.g. Howsam 1988).

The typical strategy used for detecting well clogging is periodic monitoring of specific capacity through the tracking of well discharge and well drawdown. Although declining specific capacity indicates the presence of a well clogging issue, specific capacity data alone do not reveal the underlying cause (e.g., mechanical or chemical) or the spatial extent of the clogging. Additional studies are required to evaluate methods to detect the onset of clogging, diagnose its underlying cause(s), and suggest appropriate action for groundwater supply operators. In particular, the literature does not appear to contain studies that have investigated the long-term hydraulic progression of clogging for new wells operated under known pumping regimes.

This paper presents a study that investigated practical hydraulic-based methods, in addition to specific capacity, to characterize the effects induced by clogging near municipal production wells. The main objectives were to determine if conventional pumping tests and the analysis of long-term hydraulic head data could be used to detect both the onset and spatial extent of clogging. The research presented here does not include a detailed study on the cause(s) of clogging, for example mechanical versus chemical clogging, but rather focuses on the hydraulic effects that result from clogging.

The research was part of a multidisciplinary study initiated in 2006 to provide a more detailed understanding of the causes and rates of clogging in the vicinity of the pumping wells utilized by the City of North Battleford (Saskatchewan, Canada). The larger study included geochemical and isotopic analysis of groundwater, microbiological analysis of groundwater and sediment, and the testing of an experimental impressed current system. Findings to date from these study components are reported elsewhere (e.g. Medihala et al. 2012a, 2012b, Rohde et al. 2009, Wassenaar et al. 2009). The investigations focused on two production wells that were installed specifically for the study and operated in a manner that would facilitate data collection.

## 2. Site Description

The study site is located near the City of North Battleford, Saskatchewan, Canada (52º46’N, 108º17’W). The city has a population of approximately 14,000 and relies on both surface water and groundwater for water supply. The municipal production wells are installed in an unconfined sand aquifer and are generally located within 100 m of the north bank of the North Saskatchewan River (Fig. 1). The aquifer, averaging about 20 m in thickness, consists of fluvial deposits of reworked sand and incorporated organic matter with abundant Fe and Mn in the sediments (Medihala et al. 2012a).

Three-dimensional numerical modeling of groundwater flow in the aquifer indicates that pumping wells are recharged predominately by flow induced from the North Saskatchewan River and that absolute hydraulic head and saturated aquifer thickness are dependent on the stage of the river. Inverse modeling of transient hydraulic head data has provided a large-scale estimate of horizontal hydraulic conductivity of approximately 23 m/d, which agrees well with the geometric mean value of 18 m/d determined from grain-size correlations (Morton 2010). Groundwater from the aquifer has been classified as a Ca-$HCO_3$ type water, similar to the North Saskatchewan River. However, groundwater conditions are consistently anoxic, high in dissolved Fe and Mn, and in some monitoring wells, sulfate reducing (Medihala et al. 2012a, 2012b).

Relatively rapid decline in specific capacity is common for production wells utilized by the City of North Battleford, and wells typically experience a 40 to 50% decrease in specific capacity within three years (Wassenaar et al. 2009). The City of North Battleford situation therefore represented a unique opportunity to investigate full-scale well deterioration in what was expected to be a relatively short observation period. Previous investigations have suggested that the specific capacity decrease is a result of clogging of the well screen and surrounding porous media with biofilm (Globa et al. 2004). More recently, Medihala et al. (2012a) demonstrated that the clogging of the aquifer arises due to enhanced microbial growth and chemical precipitation, rather than mechanical clogging, in the near-screen zone. Confocal laser scanning microscopy and biofilm thickness analyses were used to reveal extensive biofilm growth near a recently installed production well, whereas there was no change in biofilm thickness farther (i.e., greater

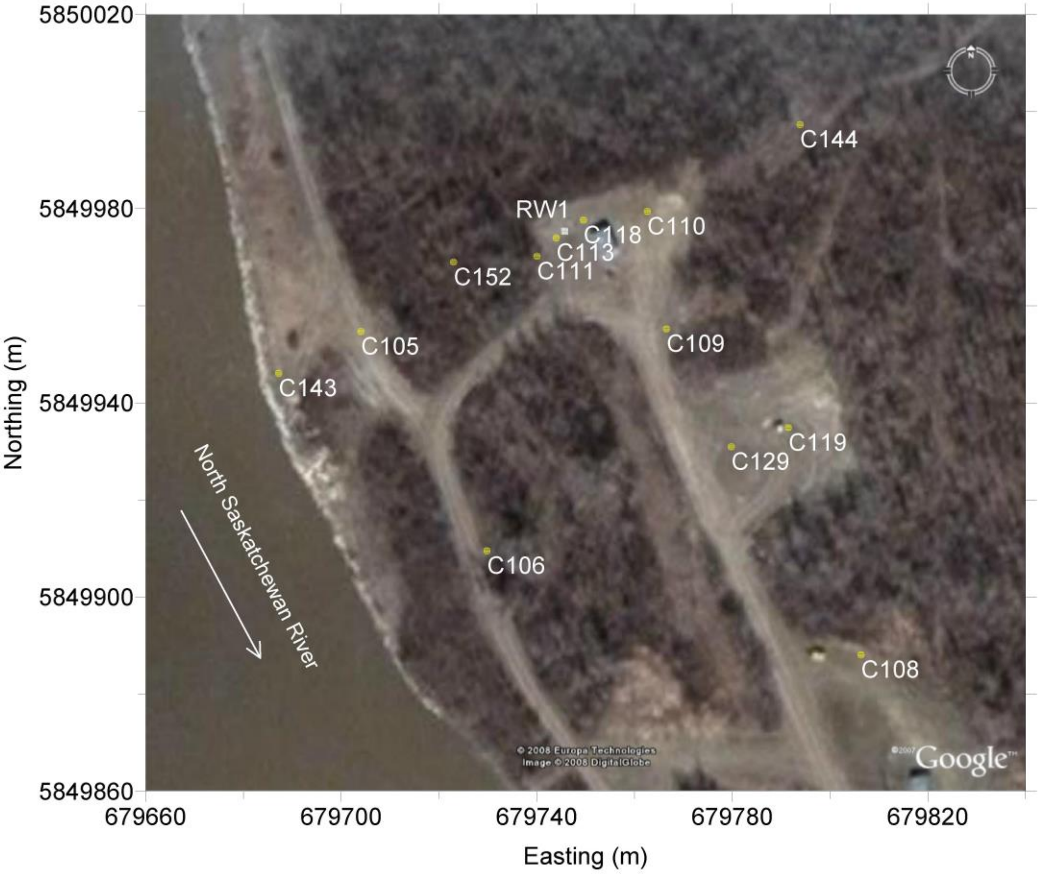

**Fig. 1: Plan view of the study site near the City of North Battleford, Saskatchewan, Canada. The monitoring locations C127, C115 and C114 (Table 1) are not shown due to their close proximity to the pumping well RW1 (white square). Base map image from Google Earth$^{TM}$.**

than about 2 m) from the production well. Biofilm growth and changes in the microbial community composition occurred in response to well pumping and were also coincident with reduced specific capacity (Medihala et al. 2012a).

## 3. Methods

In the fall of 2006 a pumping well (RW1) was installed approximately 70 m from the river using the cable tool drilling method; no drilling mud was used. The production well was completed in the poorly-graded fine sand aquifer using a 14.3 cm outside diameter, #10 slot stainless steel screen, which was installed between the depths of 12 m and 18 m in a 25.4 cm diameter borehole. Aquifer sand collapsed back around the well screen after the removal of the temporary casing to allow for a natural filter pack (Rohde and Stewart 2009).

**Table 1: Information for locations monitored during the study. The radial distances from the pumped well RW1 are indicated by "r". The asterisks (*) in the date columns indicate the piezometers for which drawdown or recovery data were collected during the pumping tests.**

| Location | r (m) | Piezometer | Screen length (m) | Screen mid-depth (m) | Apr 2007 | Oct 2007 | June 2008 | Oct 2008 |
|---|---|---|---|---|---|---|---|---|
| RW1 | 0.00 | Pumped well | 6.6 | 15.0 | * | * | * | * |
| C127 | 0.11 | PS2 | 0.3 | 16.0 | * | * | | |
| C115 | 0.48 | PS2 | 0.3 | 16.0 | * | * | * | * |
| C114 | 0.97 | PS2 | 0.3 | 15.3 | * | * | * | * |
| C113 | 2.32 | PS2 | 0.3 | 15.3 | * | * | * | * |
| C118 | 4.57 | PS1 | 0.3 | 18.0 | * | | * | * |
| C118 | 4.57 | PS2 | 0.3 | 9.0 | | * | | |
| C111 | 7.68 | PS1 | 0.3 | 18.0 | * | | * | |
| C111 | 7.68 | PS2 | 0.3 | 9.0 | | * | | |
| C152 | 23.61 | - | 0.3 | 17.4 | | | | |
| C109 | 28.96 | - | 1.4 | 18.8 | * | * | * | |
| C105 | 46.52 | - | 1.3 | 18.5 | * | * | * | |
| C143 | 65.43 | - | 15.1 | Full screen | * | * | * | |
| C106 | 67.71 | PS2 | 1.3 | 18.8 | * | * | * | |

A network of monitoring wells or piezometers at various locations, ranging from approximately 0.1 m to 68 m from the pumping well, were available for monitoring (Table 1). With the exception of C127 (Table 1), the piezometers were also installed using the cable tool method and, similar to the production well, the aquifer sand was allowed to collapse to form a natural filter pack. C127 was installed in the same borehole as the production well adjacent to the stainless steel well screen. Fig.1 shows the locations of RW1 and selected monitoring locations. This production well and the surrounding aquifer region are the same as those reported by Medihala et al. (2012a).

The production well and the piezometers were developed by air-lift pumping and surging until a clear discharge was obtained (Rohde and Stewart 2009). The upper three meters around the wells were backfilled with drill cuttings followed by bentonite to form a surface seal. The production well was equipped with a submersible pump, and essentially continuous pumping of RW1 began on June 13, 2007, with the pumped water being supplied to the municipal groundwater treatment plant.

### 3.1 Hydraulic head measurements

Both short-term and long-term hydraulic head data were collected during the study. The data set consisted of periodic pumping test drawdown and recovery data, continuous hydraulic head time-series for selected wells (pumping and monitoring), temporal river stage, and pumping well discharge.

Most of the hydraulic head data were collected using Solinst® Gold LT Leveloggers (models M10 and M20). The Leveloggers have a water level accuracy of ± 0.5 cm and ± 1.0 cm for the M10 and M20 models, respectively (Solinst® Canada Ltd 2010). The instruments were programmed to collect and store water level readings at various time intervals depending on whether they were being used to record pumping test drawdown or long-term hydraulic head trends. For pumping tests, the loggers were programmed to collect higher frequency data during the early-time drawdown and recovery intervals. Periodic manual water level readings were taken so that the instrument water levels could be converted to geodetic elevations (i.e. hydraulic head). All Levelogger readings were corrected for barometric pressure changes using data from a Solinst® Barologger that was installed in one of the on-site monitoring wells (C110).

### 3.2 Pumping tests

Four 24-hr pumping tests were conducted between April 2007 and October 2008. The primary purpose for performing these tests was to collect drawdown and recovery data, which were then used to assess temporal and spatial variations in the aquifer hydraulic conductivity in the vicinity of RW1. Information for each pumping test, including the radial distances and screened depths of the monitoring wells and the discharge rates for the pumping well, is provided in Tables 1 and 2. It should be noted that the first pumping test was completed before RW1 was brought into continuous operation. Pumping well RW1 was shut off for at least 24 hours before the pumping tests began. Pumping rates were measured regularly with a cumulative flow meter installed on the discharge line and with periodic readings from electronic flow meters that were located in the nearby pump house.

**Table 2: Pumping test dates and discharge information for well RW1**

| Date | $Q_{avg}$ ($m^3$ $hr^{-1}$) | Standard Dev. ($m^3$ $hr^{-1}$) |
|---|---|---|
| 25/04/2007 | 24.0 | 0.10 |
| 2/10/2007 | 24.3 | 0.34 |
| 23/06/2008 | 23.0 | 0.07 |
| 27/10/2008 | 9.6 | 0.21 |

Between 9 and 10 monitoring wells or piezometers were monitored for drawdown and recovery during each of the first three pumping tests. Due to logistical problems, only four monitoring locations with radial distances between 0.48 m and 4.6 m were used for the final test conducted in October 2008 (Table 1). Recovery data were typically collected for 24 hours following cessation of pumping, and all drawdown and recovery data were corrected for any regional trends in hydraulic head that were identified during the pre-pumping time interval. The stage of the North Saskatchewan River was also recorded.

It should be noted that the absolute drawdowns should be less pronounced in wells located close to the river (due to the presence of the constant head boundary); however, the observed drawdown at any piezometer should be of similar magnitude for each individual pumping test if the pumping rates were similar and there was no temporal change in hydraulic conductivity.

### 3.3 Cooper-Jacob analysis for aquifer transmissivity/hydraulic conductivity

The temporal and spatial variations of horizontal hydraulic conductivity (or radial hydraulic conductivity, $K_r$) within approximately 10 m of the pumping well were of primary interest in this study. As discussed above, the horizontal hydraulic conductivity near the pumping well was expected to be significantly affected by clogging (Medihala et al. 2012a), and this parameter is one that is believed to be reliably determined from pumping tests (e.g. Chen et al.1999).

The analysis for aquifer transmissivity was initially conducted by preparing semi-log plots of drawdown versus time for each observation well and determining the slope of the linear early-time portion of the drawdown (or recovery) data (i.e. the traditional Cooper-Jacob (1946) method). The method assumes a homogeneous aquifer of infinite extent, and in the case of unconfined aquifers, that drawdowns are small compared to the saturated aquifer thickness.

The Cooper-Jacob (1946) relationship for computing transmissivity is:

$$T = \frac{2.3Q}{4\pi(\Delta s)} \tag{1}$$

where $T$ is the transmissivity ($L^2\ t^{-1}$), $Q$ is the well pumping rate ($L^3\ t^{-1}$), and $\Delta s$ is the change in drawdown over a $\log_{10}$ cycle in time (L).

For the recovery data, the solution can be rewritten as:

$$T = \frac{Q}{4\pi(\Delta s_e)} \ln\left\{ \frac{t_2}{t_1} \times \frac{t_1 - t_{off}}{t_2 - t_{off}} \right\} \tag{2}$$

where $t$ is the time since pumping began, $t_{off}$ is the time when the pump was turned off, and $\Delta s_e$ is the change in drawdown over a natural log cycle in time (L).

The computed transmissivity values were subsequently converted to horizontal hydraulic conductivity ($K$) by dividing by the saturated aquifer thickness, which was determined from hydraulic head data collected prior to each pumping test. The saturated thickness of the sand aquifer varied seasonally, but was typically in the range of 12.2 to 16.1 m in the vicinity of RW1.

### 3.4 Butler method for aquifer and near-well transmissivity/hydraulic conductivity

As an alternative to the traditional Cooper-Jacob analysis, the method of Butler (1988) was also employed to compute transmissivity. The Butler (1988) method allows for consideration of radial heterogeneity in which the aquifer region surrounding the well consists of two different materials as depicted in Fig. 2. Such a situation might be anticipated because of localized increases in microbial growth and clogging as described by Medihala et al. (2012a). Butler's (1988) solution, and the earlier comparable solution of Barker and Herbert (1982), considers drawdown during a pumping test to consist of two components: the first being dependent on the aquifer properties near the well, while the second component is independent of the near-well properties.

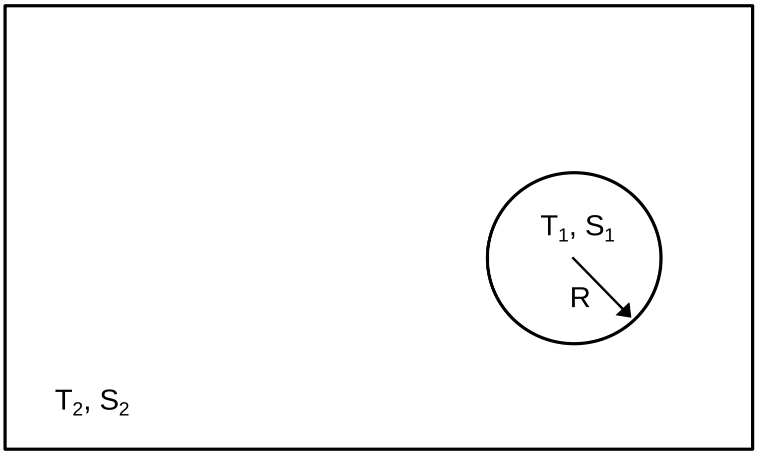

**Fig. 2: Conceptual plan view of an aquifer consisting of a disk of material 1 (transmissivity= $T_1$, storage coefficient= $S_1$, radius = R) surrounded by a more extensive region of aquifer material 2. The pumping well is located at R= 0. Modified after Butler (1988).**

Butler (1988) has shown that the near-well transmissivity, $T_1$, which is the primary parameter of interest in this study, can be determined by applying the Cooper-Jacob approach over a single $\log_{10}$ cycle in distance:

$$T_1 = \frac{2.3Q}{2\pi(\Delta s_d)} \tag{3}$$

where $\Delta s_d$ the change in drawdown over a $\log_{10}$ cycle in distance for observation wells located near the pumping well (L). Transmissivity values computed from equation (3) were subsequently converted to horizontal hydraulic conductivity by dividing by the saturated aquifer thickness at the time of the pumping test.

The uncertainties in the hydraulic conductivities obtained from the Cooper-Jacob (1946) and Butler (1988) methods were estimated using the propagation methods for independent random uncertainties as presented by Taylor (1997). For the well discharge rate, the largest absolute uncertainty determined from the four pumping tests (i.e. ± 0.14 $m^3 hr^{-1}$, standard deviation of the mean) was chosen to compute the fractional uncertainty, while uncertainty values of ± 0.01 m and ± 0.5 m were chosen for the hydraulic head and saturated aquifer thickness, respectively.

Monotonic temporal trends in hydraulic conductivity were assessed using the non-parametric Mann-Kendall test (Gibbons 1994). The null hypothesis of no temporal trend in hydraulic conductivity was tested at a significance level of $\alpha = 0.05$. The test was only performed for locations that had at least four values of hydraulic conductivity as this is the minimum number of data points required for the Mann-Kendall test. The coefficient of variation was also assessed to support conclusions of no trend or a declining trend in hydraulic conductivity.

### 3.5 Long term specific capacity, hydraulic head, and pumping data

Long term monitoring of the specific capacity of RW1 was initiated on October 30, 2006. Specific capacity was determined by taking the well out of normal operation and carefully controlling the discharge rate and monitoring drawdown in RW1 (Rohde et al. 2009).

Beginning in the spring of 2007, long-term hydraulic head data were monitored at 10 locations at a 2-hr frequency; seven of these locations are shown in Fig. 1. These data were used to track the influence of variations in the river stage and well pumping rates and to identify trends which may have been indicative of the onset of clogging in the vicinity of RW1. The absolute hydraulic heads in the monitoring wells were expected to vary with time due to the variability in the river stage and short-term fluctuations in the pump discharge; however, the head differences between well pairs would be expected to be constant under conditions of constant pumping and non-varying hydraulic conductivity. When a well is being pumped, the hydraulic gradient that causes flow to converge toward the well screen will create a head difference (*Δh*) between the pumped well and a near-by piezometer, or between two piezometers located at different radial distances from the pumped well. If the well is pumped at a constant rate, then temporal changes in the magnitude of the head difference will result only if there is a change in the hydraulic conductivity in the portion of the aquifer located between the two piezometers. This inverse relationship between the hydraulic conductivity and the head difference is expressed by rearranging Darcy's (1856) law:

$$K = \frac{\Delta L}{\Delta h}\left(\frac{Q}{A}\right) \tag{4}$$

where $K$ is the hydraulic conductivity ($\mathrm{L\,t^{-1}}$), $Q$ is the discharge rate (constant pumping rate for the well, $\mathrm{L^3\,t^{-1}}$), $A$ is the cross-sectional area for flow ($\mathrm{L^2}$), $\Delta h$ is the magnitude of the head difference between two fixed locations (L), and $\Delta L$ is the horizontal distance between the points (L).

An iterative linear regression technique (e.g. Ryan and Porth 2007) was used to determine the temporal rate of change of the head difference between pairs of wells or piezometers. This analysis gave the rate of change (slope) of *Δh* versus cumulative pumping days (i.e. time) and indicated when a significant change in the slope occurred. The time corresponding to a significant slope change, which is referred to as the breakpoint, was interpreted to coincide with a significant acceleration of clogging. After a breakpoint was determined for a particular *Δh* time series, the Excel® linest function was used to obtain best-fit slopes and associated 95% confidence intervals for the data prior to and after the breakpoint.

Long-term discharge data for RW1 were recorded digitally at the municipal groundwater treatment plant.

## 4. Results

### 4.1 Hydraulic conductivity results from the Cooper-Jacob method

Fig. 3 provides an example of the drawdown results for piezometer C114-PS2, illustrating that the slopes of the early-time drawdown data (from approximately 0.1 to 1.0 minute) were of similar magnitude for each of the four pumping tests. The drawdown data generally followed several quasi-straight line segments on semi-log time-drawdown plots, as has been observed previously for observation wells located close to pumping wells (Schad and Teutsch 1994) and as depicted by Barker and Herbert (1982) for idealized cylindrical regions with $T_1 < T_2$ (Fig. 2). Table 3 presents the results for when the time-drawdown data were used with the Cooper-Jacob method to determine the aquifer hydraulic conductivity for locations near pumping well RW1. A notable characteristic of the single-piezometer results was the increase in computed hydraulic conductivity with increasing distance from RW1. This spatial trend was consistent for all tests and was present for both the drawdown and recovery data sets. Reanalysis of the drawdown data using the Moench (1997) method, which considers non-ideal factors such as well bore storage, delayed piezometer response, and partial penetration of the pumped well and piezometers, produced somewhat higher values for hydraulic conductivity within 10 m of the pumping well; however, the trend of increasing hydraulic conductivity with increasing radial distance was also noted (B. Kurylyk, unpublished internal report, August 2009).

The hydraulic conductivity results for radial distances between 0.48 m and 2.3 m exhibited an increase between April 2007 and October 2007 for the drawdown data, but no consistent increase for the recovery data (Table 3). Although there appeared to be a decrease in $K$ at distances of 0.48 m to 2.3 m from October 2007 to October 2008, when the Mann-Kendall test was applied to the four sets of K results for piezometers C113-PS2, C114-PS2, and C115-PS2 (Drawdown; Table 3), the null hypothesis of no temporal trend could not be rejected. This finding, taken in isolation, would suggest that clogging did not significantly affect the hydraulic conductivity in the vicinity of RW1.

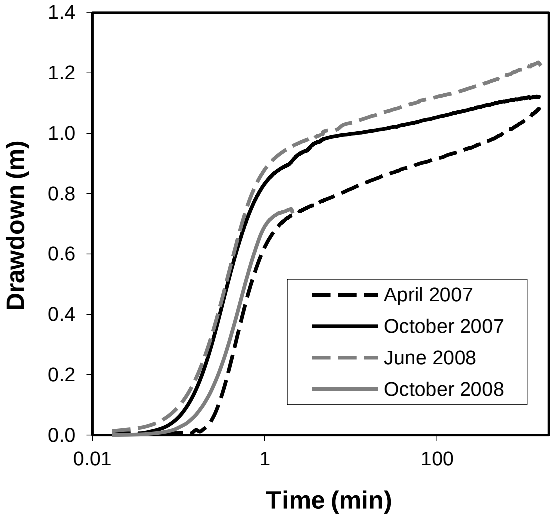

**Fig. 3: Drawdown data recorded at piezometer C114-PS2. The piezometer was located at a radial distance of 0.97 m from RW1.**

**Table 3: Hydraulic conductivities and associated uncertainties from Cooper-Jacob analyses of drawdown and recovery data for piezometers near RW1. Locations/dates with no results were not monitored.**

| | **Piezometer** | | **April 2007** | **October 2007** | **June 2008** | **October 2008** |
|---|---|---|---|---|---|---|
| | | **r (m)** | **K (m d$^{-1}$)** | **K (m d$^{-1}$)** | **K (m d$^{-1}$)** | **K (m d$^{-1}$)** |
| Drawdown | **C111 PS1** | 7.68 | 48.8 ± 3.5 | | 36.8 ± 2.2 | |
| | **C118 PS1** | 4.57 | 18.1 ± 0.8 | | 22.6 ± 1.1 | 14.0 ± 0.8 |
| | **C113 PS2** | 2.32 | 11.6 ± 0.4 | 15.1 ± 0.6 | 10.4 ± 0.4 | 5.0 ± 0.2 |
| | **C114 PS2** | 0.97 | 7.5 ± 0.3 | 8.9 ± 0.3 | 6.9 ± 0.2 | 3.6 ± 0.2 |
| | **C115 PS2** | 0.48 | 2.5 ± 0.1 | 3.0 ± 0.1 | 2.8 ± 0.1 | 1.6 ± 0.1 |
| Recovery | **C111 PS1** | 7.68 | 48.5 ± 3.4 | | | |
| | **C118 PS1** | 4.57 | 19.7 ± 0.8 | | | |
| | **C113 PS2** | 2.32 | 11.5 ± 0.4 | 10.8 ± 0.4 | | |
| | **C114 PS2** | 0.97 | 6.5 ± 0.2 | 7.9 ± 0.3 | | |
| | **C115 PS2** | 0.48 | 4.1 ± 0.1 | 3.1 ± 0.1 | | |

The percent difference between single-piezometer hydraulic conductivities determined from drawdown versus recovery data (for individual piezometers) ranged from -28% (C113-PS2; October 2007) to 64% (C115-PS2; April 2007).

### 4.2 Hydraulic conductivity results from the Butler method

Fig. 4 shows an example of the spatial drawdown response at two times during the April 2007 pumping test. These results were typical in that the slope of the drawdown versus log-distance plot within about one meter of the well was larger than for distances beyond one meter. Hydraulic conductivities obtained using $\Delta s_d$ values (Eq. 3) for radial distances of less than one meter are therefore referred to as near-well results, whereas far-field results are those obtained by determining $\Delta s_d$ for distances greater than one meter.

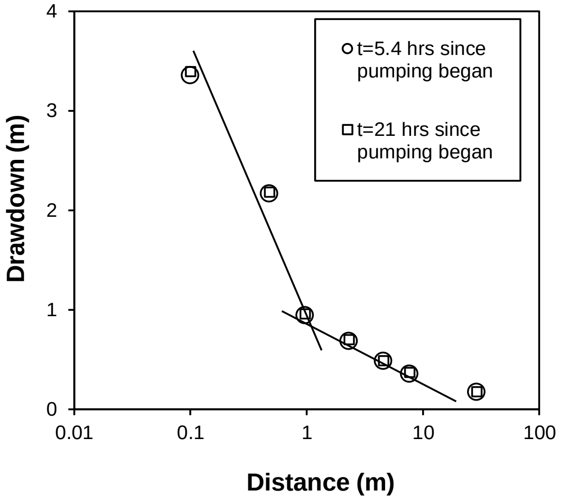

**Fig. 4: Example of the drawdown response at monitoring wells near pumping well RW1 during the April 2007 pumping test. The slopes of the two straight line fits were used to compute the near-well and far-field values of hydraulic conductivity (Table 4). Results for two times are shown to illustrate the relative stability of the drawdown values after 5.4 hours of pumping.**

The hydraulic conductivity results obtained using the Butler (1988) method are presented in Table 4. Consistent with the Cooper-Jacob results, lower hydraulic conductivity values were obtained near the pumping well (i.e. within 1 meter) in comparison to the surrounding aquifer. At distances greater than one meter from RW1, the hydraulic conductivity exhibited an overall decrease of about 48% during the study period, whereas it tended to fluctuate close to the pumping well. However, for both the near-well and the far-field data, the Mann-Kendall test results indicated that the null hypothesis of no trend could not be rejected.

**Table 4: Hydraulic conductivities and associated uncertainties from applying the Butler (1988) method of analysis to drawdown data collected near RW1.**

| Date<br>- | K (m $d^{-1}$)<br>near-well | K (m $d^{-1}$)<br>far-field |
|---|---|---|
| Apr-07 | 5.9 ± 0.2 | 25.8 ± 1.0 |
| Oct-07 | 8.1 ± 0.3 | 22.7 ± 0.9 |
| Jun-08 | 2.7 ± 0.1 | 18.0 ± 0.7 |
| Oct-08 | 3.7 ± 0.1 | 13.3 ± 0.6 |

### 4.3 Specific capacity, long-term water levels and hydraulic gradients

The specific capacity data for RW1, which are shown in Fig. 5, show relatively constant values (~ 95 L $min^{-1}$ $m^{-1}$) until approximately January 2008. After March 2008, the specific capacity exhibited a consistent period of decline, and by February 2009 the specific capacity had declined by 77% compared to the initial value obtained in October 2006.

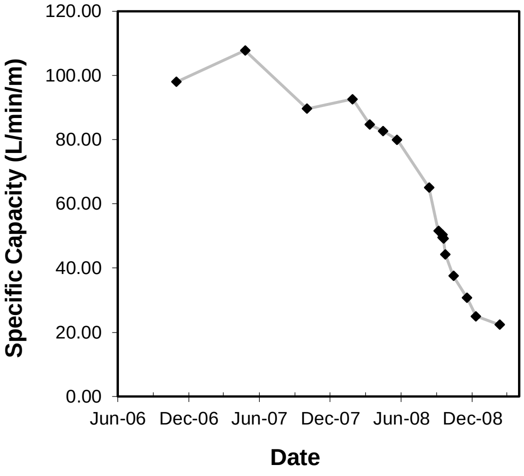

**Fig. 5: Specific capacity data for pumping well RW1. The well was placed into essentially continuous operation on June 13, 2007.**

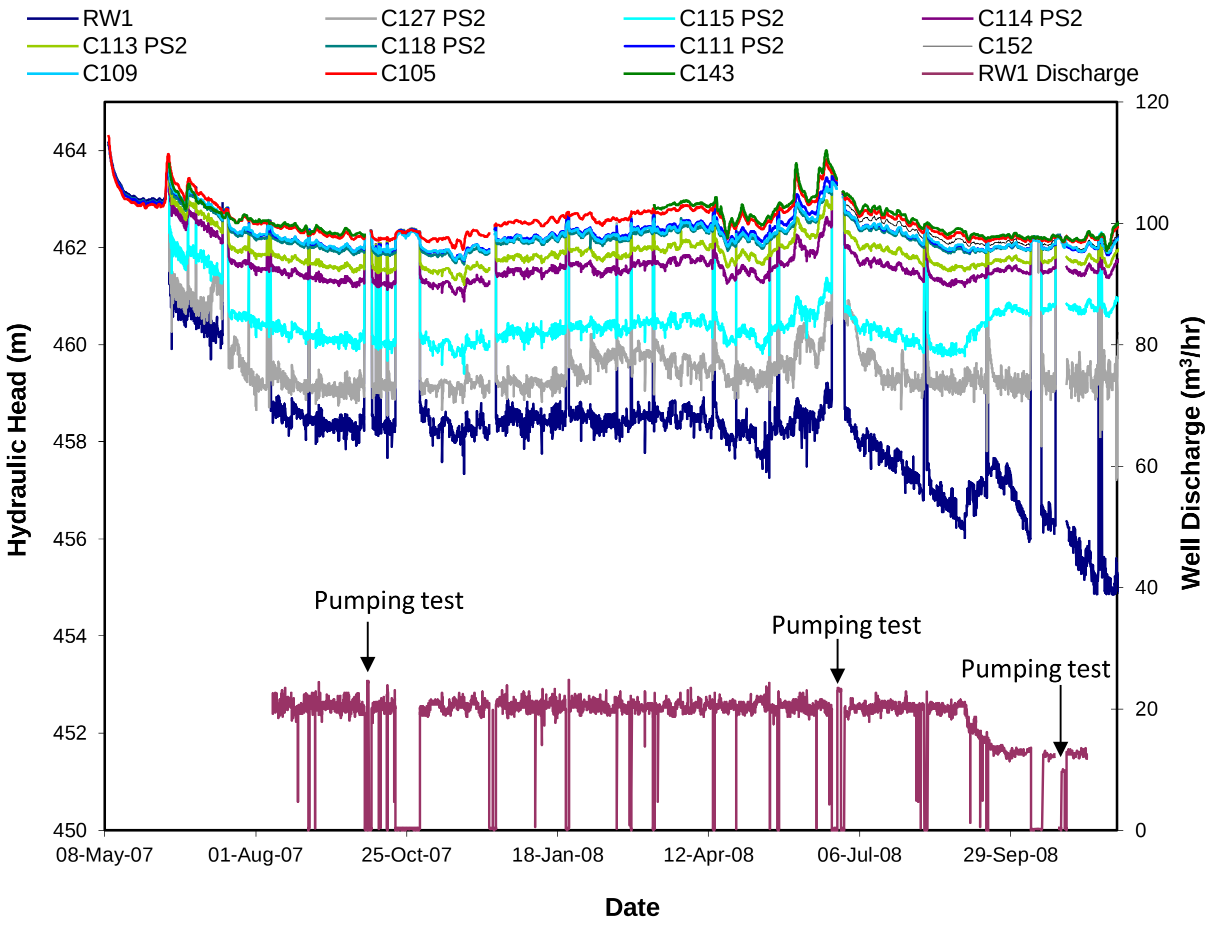

**Fig. 6: Long-term hydraulic head data for selected locations and discharge record for RW1.**

Fig. 6 shows the long-term hydraulic head data collected for RW1 and nearby observation wells and piezometers. When no pumping was taking place (e.g. May-June, and late October 2007), the hydraulic head values at these locations were all comparable and similar to the stage of the North Saskatchewan River. However during times of pumping, the hydraulic head values exhibited differences of up to four meters (e.g. difference between C127-PS2 and C105). Fig. 7 shows the hydraulic-head difference ($\Delta h$) time series for selected locations near the pumping well. Well RW1 was pumped at an essentially constant rate during this period, thus removing the influence of pumping rate on hydraulic gradient; Fig. 7 illustrates that the magnitude of the head differences for several well pairs were increasing with time.

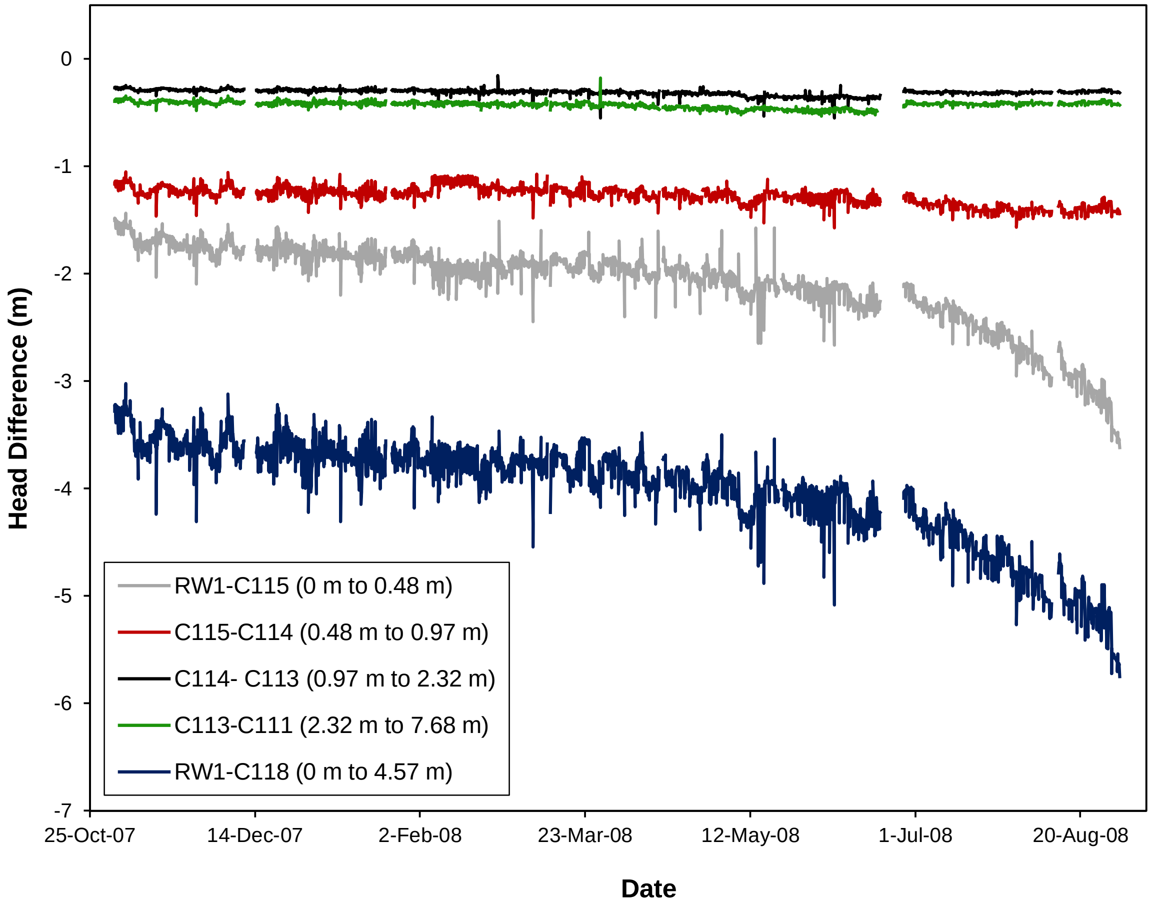

**Fig. 7: Hydraulic head difference (Δ*h*) between selected monitoring locations near pumping well RW1. The values given in parentheses are the radial distances of the two monitoring locations measured from RW1.**

The iterative linear regression and breakpoint analyses were performed on daily average Δ*h* values versus cumulative pumping days as shown, for example, in Fig. 8. This representative example demonstrates that the Δ*h* time series was well described by two linear trends, which in this case converge at a breakpoint of 364 days. Fig. 8 also shows that there was an obvious increase in the slope of the Δ*h* time series after 364 pumping days even though the well pumping rate did not vary. Fig. 9 presents a summary of the results for similar linear regression analyses for selected locations near RW1. The pre-breakpoint rate of change for all well pairs was close to zero, indicating limited temporal change in the aquifer properties between the two locations. Large differences between the pre- and post-breakpoint rates of change occurred primarily at distances of less than one meter from the pumped well. Although the RW1-C118 (0 to 4.6 m) well pair exhibited a significant change in slope pre- and post-breakpoint, the computed head differences were likely affected by clogging much closer to the well than C118 (4.6 m). This is supported by the results for well pair C114-C113 (0.97 to 2.32 m from RW1), which exhibited only minor changes in slope, and the biofilm growth studies of Medihala et al. (2012a). For the well pairs with the largest differences in slopes (e.g. RW1-C115, Fig. 9), the breakpoints occurred between 300 and 365 pumping days.

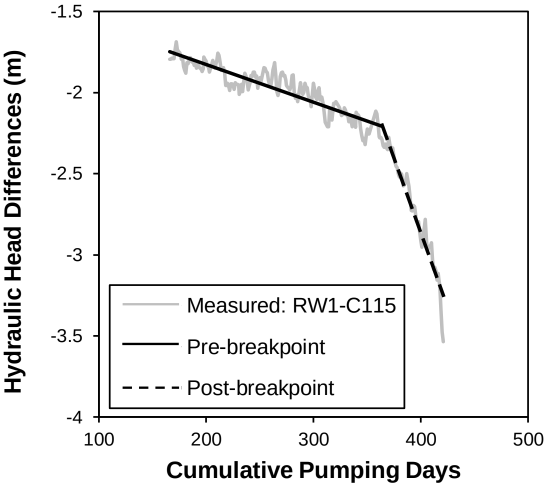

**Fig. 8: An example of the piecewise linear regression performed to determine breakpoints and slopes for the *$\Delta h$* time series for monitoring locations RW1 and C115 (located 0.48 m from RW1).**

## 5. Discussion

The pumping test results indicated that the hydraulic conductivity of the sand aquifer increased with increasing distance from the pumping well. While this spatial trend would be expected if aquifer clogging occurred near the pumping well, the lower near-well hydraulic conductivities were also obtained for pumping tests conducted prior to the initiation of long-term pumping or aquifer clogging. Thus, the spatial variability in $K$ cannot be attributed solely to transient mechanical or chemical clogging. The lower near-well conductivities may be an artefact related to the method used to develop the well, or to the assumptions inherent in the pumping test analyses. For example, Barrash et al. (2006) describe how well drilling and construction can create an imperfect hydraulic connection between the well bore and formation. Depending on the underlying mechanisms, this ‘wellbore skin’ can result in additional hydraulic resistance (a ‘positive skin’ would produce low near-well conductivity) or conductance (a ‘negative skin’).

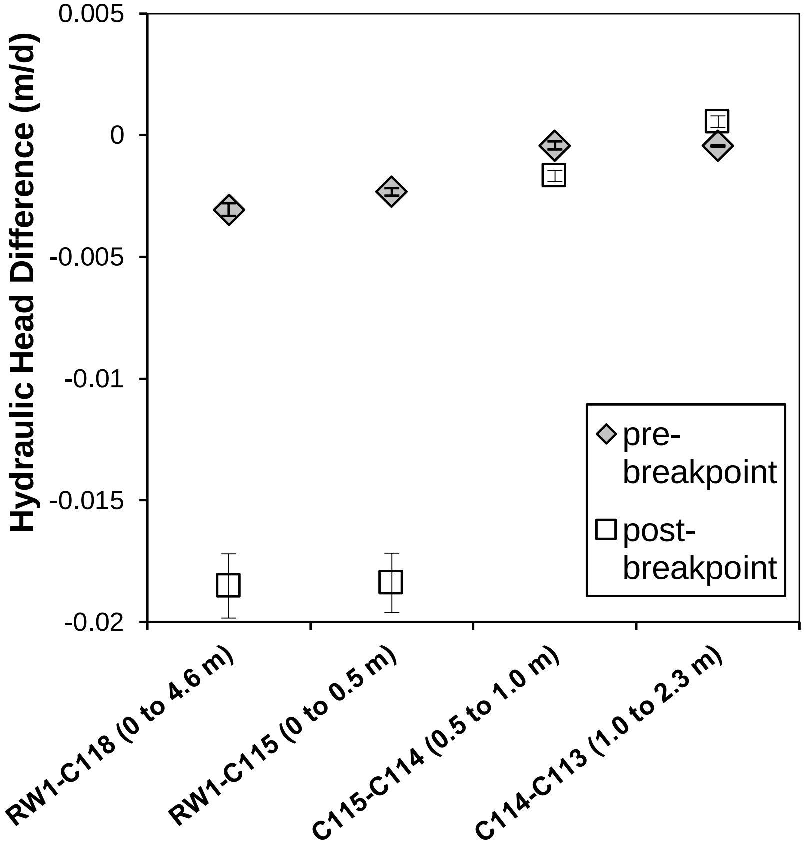

**Fig. 9: Rate of change of the hydraulic head difference (*Δh*) between selected locations adjacent to RW1. Error bars indicate the 95% confidence intervals on the slope of the *Δh* time-series as determined by linear regression. The values given in parentheses are the radial distances of the two monitoring locations measured from RW1.**

Barrash et al. (2006) also noted that surging and purging well development techniques did little to attenuate the positive skin they observed for a pumping well installed using methods similar to those used for RW1. On a larger scale, Chen et al. (2003) found that observation wells located at radial distances of 21 to 23 m from a pumping well in an alluvial sand and gravel aquifer at the McCook test site in southern Nebraska tended to yield smaller $K_r$ values than more distant (46 to 47 m) observation wells. Schad and Teutsch (1994) conducted a series of pumping tests in a heterogeneous poorly sorted sand and gravel aquifer and their results for transmissivity also exhibited a general increase over small to intermediate spatial scales (i.e. radial distances of 2 to

36 m). They noted that different observation time intervals and observation well distances will inherently lead to different "effective" hydraulic conductivity results for heterogeneous (i.e. natural) porous media aquifers.

Although spatially variable hydraulic conductivity results may be an inherent consequence of pumping tests, repeated testing with the same monitoring time intervals and observation well locations should only yield different results if there has been a temporal change in the $K$ distribution. No statistically significant (Mann-Kendall test; $\alpha = 0.05$) temporal decline in hydraulic conductivity was found within 2.3 m of pumping well RW1 for either the time-drawdown or distance-drawdown results, which suggests that traditional pumping tests and common methods of transmissivity/hydraulic conductivity analysis were not effective in detecting the onset or spatial extent of the clogging that was noted using other methods. Although relatively small uncertainties were computed for individual hydraulic conductivity values, it appears that pumping tests may not be repeatable enough or have sufficient accuracy to detect temporal changes in near-well (e.g. less than 2 m) hydraulic conductivity. Conducting such testing on a frequent basis for a large number of pumping wells and associated observation locations also requires significant resources (human and equipment) and may mean removing the wells from production for several days.

In contrast to the pumping test results, the long-term hydraulic head differences ($\Delta h$) obtained near RW1 clearly showed responses beginning in early July 2008. Analysis of the hydraulic head difference trends for those well/piezometer pairs within about one meter of the pumping well exhibited significant increases in $\Delta h$ (and by inference decreased $K$) after approximately one year of continuous pumping, which is in agreement with the onset of the rapid decline in specific capacity for RW1.

In addition to the hydraulic data presented in this paper, independent in situ microbiological investigations have been conducted near RW1. During the same time interval reported on here, the number of culturable microorganisms, metabolic activity and community composition increased with the progression of well pumping, with the largest changes confined to a zone within 1 to 2 meters of the well (Medihala et al. 2012a). These findings are consistent with the results of our breakpoint analyses, which also indicated that the clogging occurred within a limited extent of RW1. The microscopic and molecular studies of Medihala et al. (2012a) have provided significant insight into the mechanisms and extent of clogging near this production well, and in the future such techniques may become more widely adopted by water well managers.

## 6. Conclusions

Pumping tests were conducted in a sand aquifer in an attempt to identify temporal and spatial changes in hydraulic conductivity that may have been caused by aquifer and/or near-well clogging. Although other means of investigation revealed that clogging occurred near the production well, results from four pumping tests, conducted over a period of one and a half years, indicated no significant temporal changes in hydraulic conductivity within approximately two meters of the pumping well. It is concluded that the pumping tests and subsequent analyses were not sensitive enough to be used as a monitoring strategy for near-well clogging in this aquifer.

Conversely, breakpoint analyses of long-term hydraulic head differences ($\Delta h$) showed that $\Delta h$ increased significantly at locations close to the pumping well after about one year of continuous pumping. This increase in $\Delta h$ was not apparent for well pairs beyond one meter of the pumping well. Because the analyses were conducted during a time when the pumping rate was constant, it is concluded that the increases in $\Delta h$ were a direct hydraulic indication of clogging within this near-well region. Continuous monitoring of hydraulic heads in wells, combined with breakpoint analyses, appears to be more effective than standard pumping tests for detecting temporal and spatial trends in clogging. An effective hydraulic monitoring strategy for near-well clogging could combine periodic specific capacity testing and continuous monitoring of hydraulic head differences. The clogging found in this study was of limited spatial extent, which may also have implications for the selection of appropriate rehabilitation techniques.

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