Measuring the Hydraulic Response due to Aquifer Clogging in the Vicinity of Municipal Pumping Wells

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ABSTRACT
Decline in well yield because of clogging is a recurring problem. To gain a better understanding of the basic mechanisms responsible for clogging during well pumping and the associated hydraulic response in aquifers, two research pumping wells were installed by the City of North Battleford. Pumping has been continuous since 2007 and significant declines in specific capacity have occurred. Pumping tests were conducted to assess changes in aquifer hydraulic conductivity; however, the results did not reveal a systematic decline. Long-term hydraulic head differences measured during continuous pumping do exhibit increases near the pumping wells and reveal patterns of clogging.

RÉSUMÉ
Causé par des obstructions dans la couche aquifère, le déclin en performance est chose commune. Pour mieux comprendre les mécanismes responsables des obstructions qui développent pendant le pompage et la réponse hydraulique, deux puits ont été installé dans la couche aquifère près de la ville de North Battleford. Avec un pompage continu depuis 2007, un déclin en capacité a été observé. Avec des essais de pompage, l'analyse des données ne démontre pas de déclin en conduction hydraulique systématique. Par contre, avec un pompage constant, les données en surveillance à long terme démontrent que les valeurs augmentent temporellement près des puits.

1 INTRODUCTION

In some groundwater extraction situations, it is common for well performance to decline with time. The decline in well performance may be addressed with various physical or chemical treatments; however, the success of many treatments is limited and in severe cases wells may have to be abandoned. To more effectively deal with these problems we need to better understand the mechanisms of well and/or aquifer clogging, which is usually the cause of declines in well performance.

Relatively rapid decline in specific capacity is common for wells utilized by the City of North Battleford, Saskatchewan, and wells installed in the alluvial aquifer typically experience a 40 to 50% decline in performance within 3 years (Agriculture and Agri-Food Canada 2008). The City of North Battleford situation thus presents an opportunity to investigate well deterioration in a relatively short observation period. In 2006 a multidisciplinary study was initiated to provide more detailed understanding of the causes and rate of clogging in the vicinity of pumping wells in the North Battleford aquifer. Groundwater chemistry, groundwater and aquifer microbiological characterization, and isotope analysis of groundwater were conducted in parallel with hydraulic studies, and the use of an experimental impressed current system (Rohde and Stewart 2008; Globa et al. 2004) to prevent clogging was investigated. The research focused on the behavior of two research pumping wells that were installed specifically for the study and which were operated in a manner that would facilitate data collection.

The main objective of the component of the study reported on here was to determine if periodic pumping tests and the analysis of long-term hydraulic head data could be used to detect the spatial extent and temporal pattern of clogging.

2 SITE DESCRIPTION

The study site is located in North Battleford, Saskatchewan (52°46'N, 108°17'W) adjacent to the North Saskatchewan River. Municipal wells are generally located within 100 m of the river bank in an alluvial sand aquifer. Two pumping wells (RW1 and RW2) were located approximately 70 m and 95 m from the river, and over 90 monitoring wells or piezometers were installed at various locations ranging from approximately 0.5 m to 68 m from the pumping wells. Both research pumping wells were completed in poorly-graded fine sand using a 12.5 cm inside diameter, #10 slot, stainless steel screen which was installed between the depths of 12 and 18 m. Essentially continuous pumping of the wells began on June 13, 2007.

3 METHODS

Both short-term and long-term hydraulic data were collected during the study. The data consisted of pumping test drawdown and recovery data; continuous hydraulic head time-series for selected wells (pumping and monitoring); temporal river stage; and, well discharge. Solinst® Gold Leveloggers were used to collect the required water level data. Manual water level readings were also taken so that the instrument water levels could be converted to geodetic elevations. All instrument readings were corrected for barometric pressure changes using data from a Solinst® Barologger installed in one of the monitoring wells. Long-term discharge data for both research pumping wells were collected by the City of North Battleford.

3.1 Pumping Tests

During the course of the project, eight 24-hr pumping tests were conducted. The drawdown and recovery data were used to determine the hydraulic properties of the aquifer in the vicinity of the research wells. Determination of temporal variations in hydraulic conductivity since the research wells were brought into operation was thus possible.

Table 1. Pumping test information for RW1.

Date	25-Apr-07	2-Oct-07	23-Jun-08	27-Oct-08
Start time	10:00 AM	4:00:30 PM	3:00:30 PM	3:00:30 PM
Q_{avg} (igpm)	88.1	89	84.2	35.2
Standard deviation (igpm)	0.36	1.26	0.26	0.77
Q_{avg} (m^3/hr)	24.0	24.3	23.0	9.6

Table 2. Pumping test information for RW2.

Date	1-May-07	11-Dec-07	24-Jun-08	28-Oct-08
Start time	4:30:30 PM	3:00 PM	3:00:30 PM	3:00:30 PM
Q_{avg} (igpm)	87.8	68.3	81.8	35.2
Standard deviation (igpm)	0.35	0.30	0.88	0.04
Q_{avg} (m^3/hr)	24.0	18.6	22.3	9.6

Information for each pumping test can be found in Tables 1 and 2. Both RW1 and RW2 were shut off for at least 24 hours before the pumping tests began. For the first four tests (those in 2007), the two research wells were pumped independently. For the other four tests (those from 2008), RW1 was pumped for 24 hours then both RW1 and RW2 were pumped for an additional 24 hours. Recovery data was also collected for 24 hours after the pumps were shut off. All pumped water was discharged into the river, and pumping rates were measured regularly with a cumulative flow meter installed on the discharge line, and by taking readings from electronic flow metres in the pump house.

For each test, a minimum of 6 locations were monitored during the pumping tests (October 2008 tests), but typically, 12 near-by locations were monitored. The stage of the North Saskatchewan River was also recorded.

The pumping test data analysis was carried out by preparing semi-log plots (drawdown versus time) and determining the slope of the linear early-time portion of the drawdown (or recovery) data. The computed T was converted to hydraulic conductivity (K) by dividing by the saturated aquifer thickness. The uncertainties for K were also estimated using the uncertainty propagation methods for independent random uncertainties as presented by Taylor (1982). For the discharge rate, the largest absolute uncertainty determined from the eight pumping tests (i.e. ± 0.14 m^3/hr, standard deviation of the mean) was chosen to compute the fractional uncertainty, while values of ± 0.01 m and ± 0.5 m were chosen for the hydraulic head and saturated aquifer thickness, respectively.

3.2 Long-term Hydraulic Head Data

Beginning in the spring of 2007, long-term hydraulic head data were monitored at 21 locations at a frequency of 2-hrs since the spring of 2007. These data were used to track the influence of variations in the river stage and well pumping rates, and to identify trends that may indicate the onset of clogging in the vicinity of the production wells.

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 changes in the magnitude of the head differences will result if there is a change in the hydraulic conductivity in the portion of the aquifer located between the two piezometers.

To determine the rate of change of the head difference between pairs of piezometers, an iterative linear regression technique was used. This analysis yielded the rate of change of Δh versus cumulative pumping days and allowed us to estimate when a significant increase in the slope occurred. Refereed to as the breakpoint, this time is interpreted to correspond to when a significant acceleration of clogging occurred because clogging is expected to reduce K, which in turn requires an increase in Δh (for constant Q). After a breakpoint was determined for a particular time series of Δh, linear regression was performed to obtain the best-fit slopes and associated 95% confidence intervals for the data prior to, and after, the breakpoint.

4 RESULTS AND DISCUSSION

4.1 General Hydraulic Head Distributions

When neither RW1 nor RW2 are pumping, the natural groundwater flow direction at the study site is generally southeast, with a gradient of 0.002, and parallels the flow direction of the North Saskatchewan River. Observations of the hydraulic head distributions obtained before, or after, pumping tests show a comparable natural flow pattern. With a typical pumping rate of 23 m^3/hr, the radius of influence of the pumping wells extends to approximately 70 m and the hydraulic head data indicates that the flow is induced from the North Saskatchewan River (data not shown).

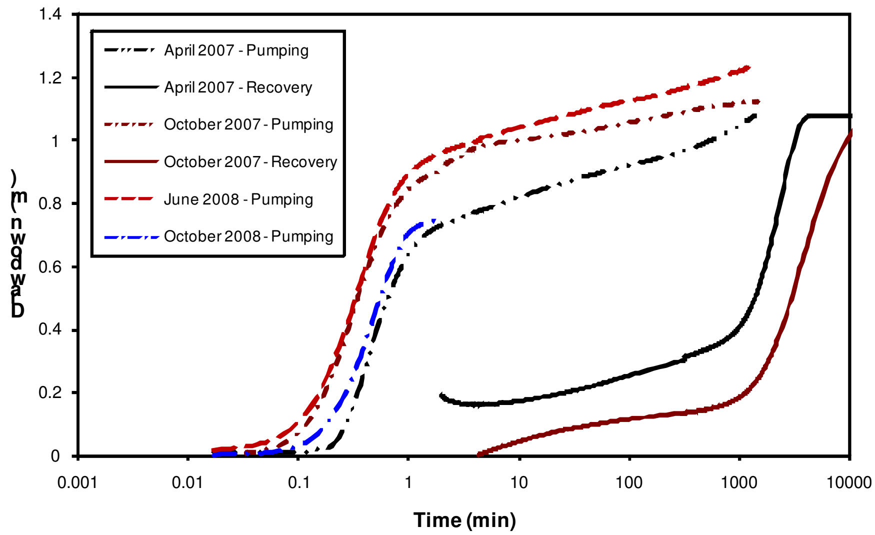

Figure 1. Drawdown and recovery data for piezometer C114 PS2 (r = 0.97 m).

4.2 Pumping Tests at RW1

Figure 1 shows an example of the response to pumping for four pumping tests at RW1 Recovery data is only shown for the two 2007 tests since in 2008, both RW1 and RW2 were pumping prior to the collection of the recovery data.

When data such as that shown in Figure 1 are used to estimate the aquifer K near RW1, where clogging might be expected to be most severe, the results presented in Table 3 are obtained. It is observed that there is a steady increase in K with an increasing radial distance (r) from RW1. This trend is consistent for both the drawdown and recovery (not shown) data for all tests, and may be related to non-ideal factors that have not yet been incorporated into the analyses, such as well bore storage, delayed piezometer response, or partial penetration of the pumped well and piezometers (Moench 1997).

The hydraulic conductivity values for distances between 0.48 m and 2.32 m increase between April 2007 and October 2007 for both the drawdown and recovery data (Table 3 and Figure 2). Such an increase may be related to additional well-aquifer development that resulted from the initiation of long-term pumping, or the apparent increase in K may arise because of uncertainties in conducting the pumping tests and subsequent analyses. From October 2007 to October 2008 there appears to be a progressive decrease in K at distances of 0.97 m and 2.32 m (tests 2 to 4, Figure 2); however, it appears that only the results from the final test are significantly less than the initial K values. Hydraulic conductivity values at 0.48 m are relatively consistent for all tests, which is somewhat surprising given the expectation that clogging will initiate in the vicinity of the pumping well screen (e.g. van Beek 1989).

4.3 Pumping Tests at RW2

To estimate the aquifer hydraulic conductivity near RW2, data from locations near the well were treated in the same manner as for RW1. The results are shown in Table 4. Similar trends are observed for RW2, for example, the increase in K with increasing distance from the well.

Figure 3 presents the temporal variations in K for four locations near RW2. Unlike the results for RW1, K did not increase between pumping test 1 and 2. This finding is believed to be related to the severe clogging that was detected near RW2 (as evidenced by rapidly accelerating drawdown in the pumping well) and subsequent acid treatment that was carried between the times when these two tests were conducted. The clogging was independently confirmed to be caused by carbonate mineral precipitation generated by an impressed current field that was established around RW2 (Agriculture and Agri-Food Canada 2008). After acid treatment of the well in late October 2007 and with cessation of the impressed current, RW2 was brought back into continuous production.

Table 3. Hydraulic conductivities and associated uncertainties, from drawdown data, for piezometers near RW1.

		Apr-07		Oct-07		Jun-08		Oct-08	
	r (m)	K (m/d)	±	K (m/d)	±	K (m/d)	±	K (m/d)	±
C111 PS1	7.68	43.29	3.07	N/A	N/A	31.90	1.86	N/A	N/A
C118 PS1	4.57	16.80	0.68	N/A	N/A	23.75	1.17	12.70	0.72
C113 PS2	2.32	9.88	0.36	13.16	0.53	11.66	0.45	6.05	0.26
C114 PS2	0.97	6.48	0.23	7.45	0.28	6.57	0.23	3.37	0.14
C115 PS2	0.48	2.43	0.08	2.98	0.11	2.78	0.10	1.87	0.07

Table 4. Hydraulic conductivities and associated uncertainties, from drawdown data, for piezometers near RW2.

		May-07		Dec-07		Jun-08		Oct-08	
	r (m)	K (m/d)	±	K (m/d)	±	K (m/d)	±	K (m/d)	±
C129 PS1	7.66	33.36	1.98	N/A	N/A	28.43	1.59	N/A	N/A
C119 PS1	4.47	26.17	1.33	N/A	N/A	19.01	0.85	11.07	0.67
C126 PS2	2.30	17.47	0.72	13.35	0.57	12.72	0.49	6.10	0.28
C130 PS1	2.05	17.80	0.74	13.28	0.56	15.98	0.67	8.02	0.41
C123 PS2	1.03	10.98	0.39	6.00	0.22	6.83	0.23	6.10	0.28
C120 PS2	0.61	5.68	0.19	4.59	0.16	3.78	0.12	3.67	0.15

As was noted for RW1, it is difficult to determine a consistent trend in the K results in the vicinity of RW2, although the test 4 results for distances of 2.05 m and 2.30 m appear to be significantly less than the results obtained from preceding tests (Figure 3). This finding is unexpected because as discussed above it was anticipated that clogging would develop close to the well screen, which should have also produced decreased K values at distances closer to the well (e.g. 0.61 or 1.03 m).

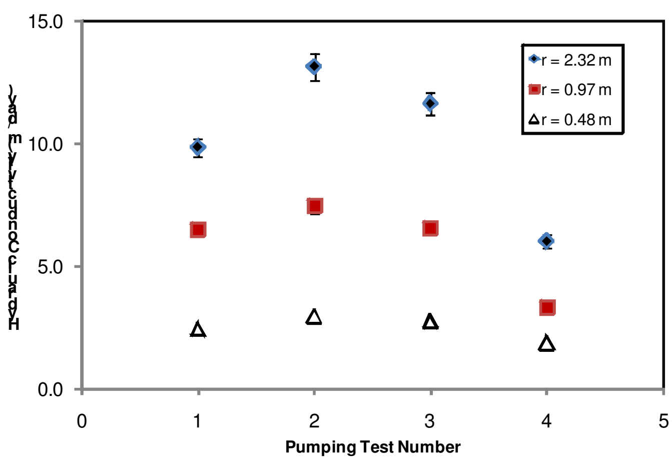

Figure 2. Hydraulic conductivity near RW1 determined using drawdown data collected during four pumping tests. For the distances of 0.48 m and 0.97 m the computed error bars are approximately the same size as the data symbols.

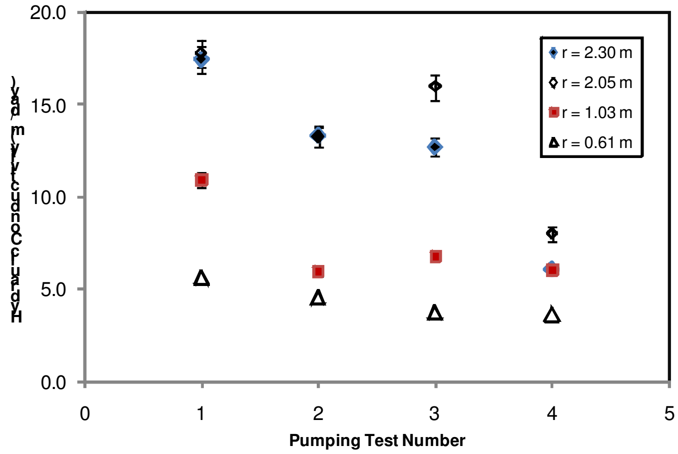

Figure 3. Hydraulic conductivity near RW2 determined using drawdown data collected during four pumping tests. For the distances of 0.61 m and 1.03 m, the computed error bars are approximately the same size as the data symbols.

4.4 Long-term Water Levels and Hydraulic Gradients

Figure 4 shows the long-term hydraulic head data for RW2 and nearby observation wells and piezometers. When no wells were being pumped (e.g. May-June, and late October 2007), the hydraulic head values were all quite similar. The hydraulic head for RW2 begins to deviate from that of the other locations in early July 2007, and by early October the head had fallen about five metres below what might have been expected given the behavior of RW1 (data not shown). The cause of this head decline was the clogging of the aquifer and/or well screen with carbonate precipitate generated by the impressed current field. In the last few weeks of operation before well rehabilitation, the discharge from the well is seen to decline (starting at Oct. 5 in Figure 4) which results in a decrease in the hydraulic gradients in the aquifer during this same time period.

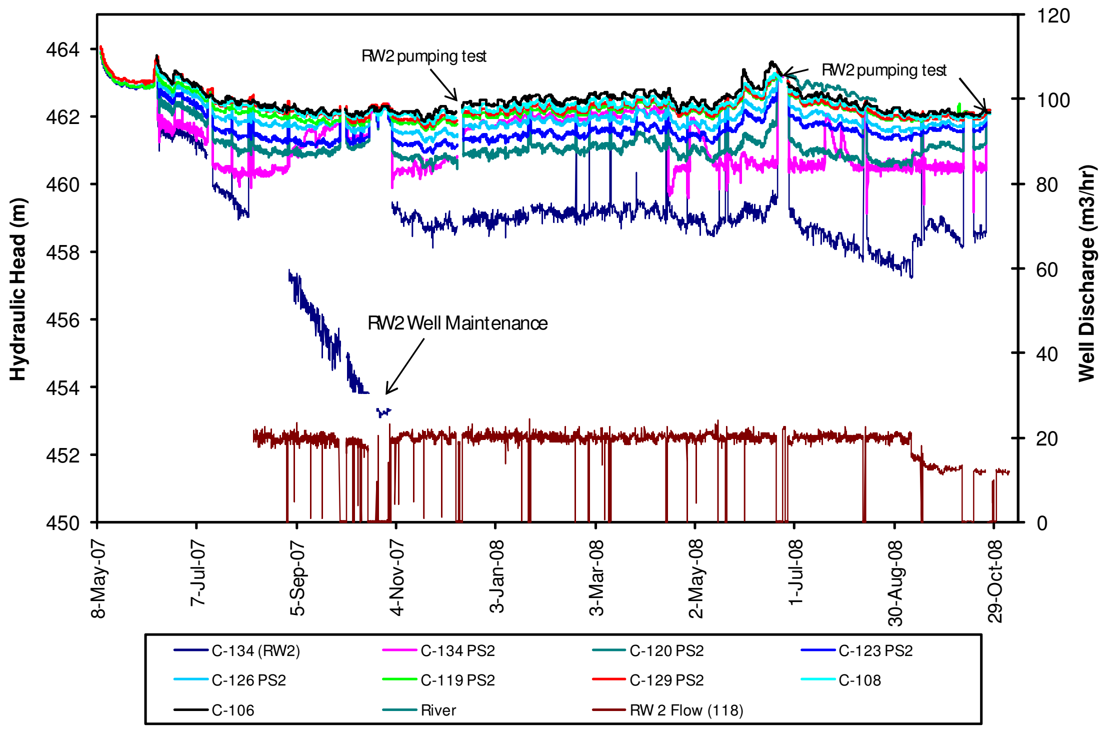

Figure 4. Long-term hydraulic head data and pumping record for RW2.

After acid treatment of the well in late October 2007, and with cessation of the impressed current, the well was pumped at about 20 m^3/hr and the hydraulic head in the well remained stable until early July 2008 (Figure 4). The pumping rate was reduced in early September 2008 to compensate for the acceleration in drawdown that appears to have started in early July 2008 (similar to RW1).

The response of the water level in C134 PS2 (Figure 4), which is located just outside the well screen of RW2, is unusual, and prior to shut down of RW2 and acid treatment in October, the trend was opposite to that of the pumping well and inconsistent with other nearby piezometers (e.g. C120 or C123). For approximately 10 days following the acid treatment and resumption of pumping, the level in the C134 PS2 piezometer appeared reasonable; however, subsequently, deviated from that of other nearby instruments. Manual water level readings taken in this piezometer in March 2008 during pumping of RW2 indicate that the Levelogger in C134 PS2 is operating correctly, but that the piezometer screen was likely plugged.

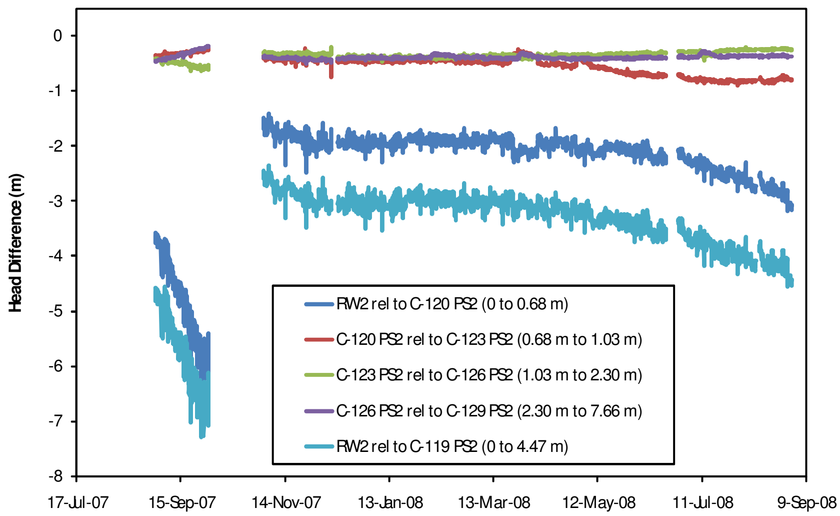

Figure 5. Hydraulic head differences **(**Δh) between selected locations near pumping well RW2. The break in the time series in October 2007 corresponds with the acid treatment of the well.

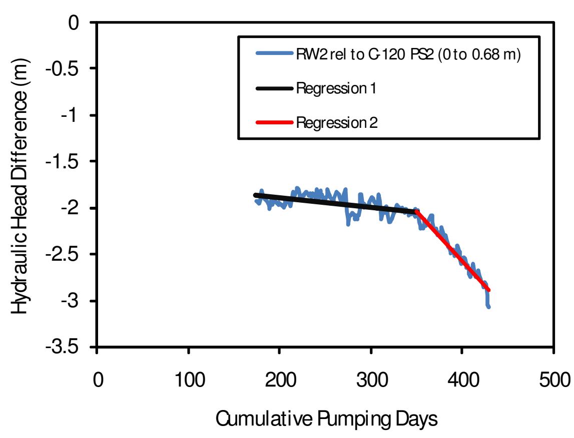

Figure 6. An example of the piecewise linear regression analysis performed to determine breakpoints and slopes for the Δh time-series.

Figure 5 shows the Δh time series for selected locations near pumping well RW2. The Δh time series have been analysed to determine if and when a significant change in the slope occurred; the time corresponding to significant slope changes is interpreted to indicate when clogging began to accelerate. For these analyses we have only considered data collected between December 2007 and early September 2008 because for this period the pumping rates for RW1 and RW2 were essentially constant (e.g. Figure 4). In order to relate slope changes to the operating life of the wells, daily average Δh values were plotted versus cumulative pumping days.

From the example shown in Figure 6 it can be seen that the Δh time series is well described by two linear trends, which are forced to match (in this case) at a breakpoint of 350 days. Figure 6 also shows that there is an apparent increase in the slope of the data after 350 pumping days.

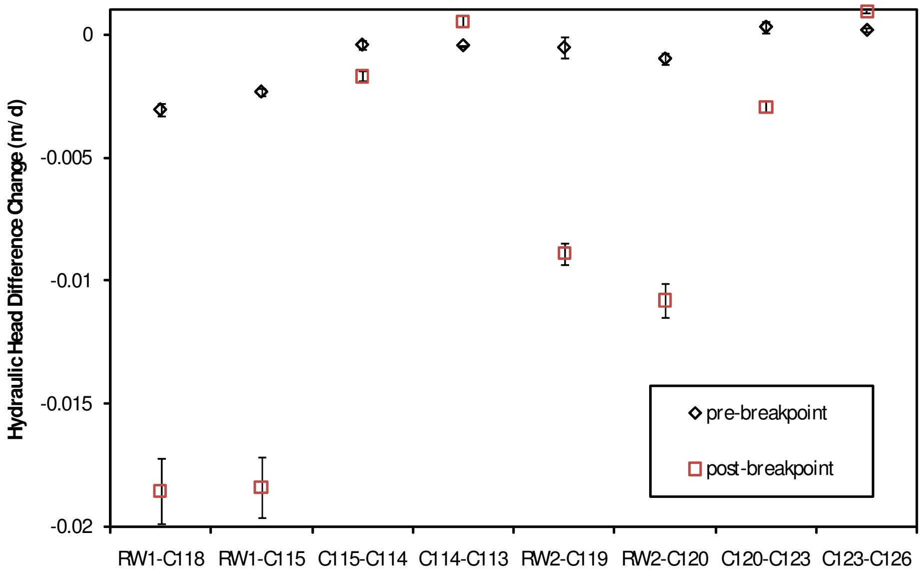

Figure 7. Rate of change of the hydraulic head differences (Δh) for selected locations adjacent to RW1 and RW2. Error bars indicate the 95% confidence intervals on the slope of the Δh time-series as determined by linear regression.

Shown in Figure 7 are the results of similar analyses for selected locations near RW1 and RW2. For both wells, the major changes in slope occur at distances less than one metre from the pumped well. Although the RW1-C118 and RW2-C119 well pairs exhibit a significant change in slope pre- and post-breakpoint, the computed head differences are most likely affected by clogging much closer to the well than either C118 (4.57 m) or C119 (4.47 m). This is supported by the results for well pairs C114-C113 (0.97 m to 2.32 m) and C123-C126 (1.03 m to 2.30), which exhibit minor changes in slope. It is noteworthy that independent microbiological investigations have revealed that in general there was an increase in the numbers of culturable microorganisms in the water and biofilm material obtained from both well systems, and that the greatest effect was primarily confined to a zone within 1-2 m of the wells (Lawrence et al. 2009).

For the well pairs with the largest differences in slopes, the breakpoints occur between 300 and 365 pumping days. The hydraulic head data therefore suggests that clogging near these wells began to accelerate significantly after approximately one year of continuous operation.

5 CONCLUSIONS

In an attempt to indentify changes in the hydraulic conductivity, K, caused by aquifer or near-well clogging, pumping tests were conducted at RW1 and RW2. Even though severe clogging occurred during the fall of 2007 at RW2, the pumping tests were conducted too infrequently to detect the onset of this clogging. After rehabilitation of RW2 with acid treatment, the pumping test results did not indicate a significant change in K until the final test (October 2008). Results from that test suggest that, for distances of 2.05 m and 2.30 m from the well, K was significantly less than the results obtained from preceding tests. However, this finding is unexpected and contradictory because it was anticipated that clogging would develop close to the well screen, and no significant decline in K was observed at distances closer to the well. The similar findings at RW1, that is, a significant decline in K only for distances away from the well screen, suggests that traditional pumping tests will not be an effect means for monitoring the onset or magnitude of clogging, even if monitoring wells are available within close proximity of the production wells.

The onset of clogging at/near the well in the fall of 2007 can clearly be seen in the long-term hydraulic head data set for RW2. Clogging appears to have started about one month after pumping, and operation of the impressed current began. After cessation of the impressed current, and the acid treatment of the well, the drawdown in RW2 remained stable until early July 2008. No significant declines in hydraulic head were observed at RW1 until early July 2008.

Analysis of the hydraulic head difference (Δh) trends showed that Δh increased significantly at locations close to RW1 and RW2 after about 300 to 365 pumping days. The increases were consistently noted at locations within one metre of the wells. Since the analysis was conducted during a time when the pumping rates were relatively constant, the increases in Δh are an indication of clogging. Therefore, it appears that after about one year of continuous operation, clogging of pumping wells in the North Battleford aquifer will rapidly accelerate; however, the Δh results also indicated that this clogging may be limited to within a zone of approximately one meter from the well. The spatial extent of clogging inferred from the hydraulic data is consistent with the findings of microbiological studies at this site. From an operational point of view, long-term monitoring of hydraulic heads in, and adjacent to, pumping wells may be an effective method to detect the trends and spatial extent of clogging.

ACKNOWLEDGEMENTS

Acknowledgments are made to the field support by Harry Rohde, Bob Stewart, and Doug Andrew of Prairie Farm Rehabilitation Administration – Agriculture and Agri-Food Canada, Regina, and by the City of North Battleford for their logistical support and long-term discharge data.

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