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EXECUTIVE SUMMARY

The City of North Battleford Well Rehabilitation Project was undertaken as a research initiative to investigate the extent and nature of biofouling in the City of North Battleford well field, and to develop appropriate well maintenance and well rehabilitation techniques. In order to initiate this project, a contribution agreement was signed between PFRA, Droycon Bioconcepts Inc. (DBI) and the City of North Battleford, with partial funding provided by the *Canada-Saskatchewan Agri-Food Innovation Fund*. This project is divided into three phases: a diagnostics phase, a well rehabilitation phase and a post treatment phase. The detailed results of the Phase 1 diagnostics program are provided in this report.

The Phase 1 diagnostics program consisted of a compilation of background data on Wells 15, 16 and 17, pump testing of these wells, drilling and aquifer sampling, water chemistry and microbiological testing of the wells and aquifer material, and laboratory testing and analysis to evaluate the suitability of potential treatment chemicals. The findings from these diagnostic procedures provide a more comprehensive understanding of the extent and degree of aquifer biofouling and also assist in refining the well rehabilitation process for Phase 2 of this project. These diagnostic procedures are also expected to be invaluable in evaluating the effectiveness of any well treatments, since they will be repeated after the well rehabilitation phase and the results can then be compared to the pre-treatment findings.

The pump test and microbiological test results provide an indication of well site conditions. The Well 15 pump test conducted in April, 1998, revealed that there has been ***no decrease in specific capacity over the past six months***, since the Ultra-Acid Base ™ (UAB™) well treatment in October 1997. The Well 16 pump test indicates that there has been ***a 43% reduction in specific capacity*** since its installation in 1995, while Well 17 has had ***no reduction in specific capacity*** since its installation in 1995. The microbiological testing of the water and aquifer sand samples was conducted by using Biological Activity Reaction Tests (BART™), which provide an evaluation of the level of bacterial activity at each well site. The BART™ results reveal that the severity of biofouling is high at Wells 15 and 16, and moderate at Well 17.

Drilling and aquifer sampling was conducted in order to provide water and aquifer sand samples for laboratory testing and analysis. Aquifer sand samples and water samples were collected from six test holes drilled in vicinity of Wells 15, 16 and 17. At five of the six test hole sites, 50 mm diameter PVC piezometers were left in place to monitor the well treatments in Phase 2 of this project and to collect water samples in the post treatment phase (Phase 3) of this project.

Water analysis samples were collected from the North Saskatchewan River, and Wells 15, 16 and 17, in order to determine the water chemistry at each well site, as well as to determine the influence that the river water has in providing nutrients to the wells. The results of these analyses reveal that the nutrients levels in the well field are sufficiently high to encourage biological

growth, and thereby, enhance the plugging potential of the aquifer. Also, iron levels in the wells are up to three times higher than the manganese levels. This suggests that iron related bacteria predominate in the biofouled zones around the wells.

The aquifer sand samples, collected from the City of North Battleford well field, were used during the laboratory testing and analysis work to evaluate the effects of various chemicals and treatment processes on aquifer permeability and porosity. The initial chemicals evaluated were those associated with the UAB™ treatment process, which ultimately led to improvements to this treatment process. The laboratory experimentation was conducted jointly by PFRA and DBI.

Swell-consolidation tests conducted by PFRA indicate that hydroxide compounds should not be used as well treatment chemicals, due to their ability to swell clays. Further experimentation also shows that sodium hypochlorite is preferred as a replacement for sodium hydroxide in the alkali (base) phase of the UAB™ treatment process. Permeameter tests conducted by PFRA indicate that increasing the temperature of treatment fluids results in increased efficiencies of fines removal, dissolution of organics and better overall increase in the permeability of aquifer materials. Permeameter test results also show that the key compound in the UAB™ treatment process, the surfactant CB-4, effectively disperses clay particles and increases aquifer permeability. However, these test results suggest that CB-4 solutions should not exceed 1% by volume in water, and that residence times in the aquifer should be less than a day, otherwise clay swelling may be a problem. Permeameter tests of sulfamic and hydrochloric acid solutions indicate that these acids increase the permeability of aquifer materials more effectively than any other chemicals tested in this laboratory study. Additional tests using small-scale model wells, referred to as mesocosms, were conducted by DBI to evaluate various chemical treatment trains. These test results indicate that a treatment train which includes CB-4, hydrochloric acid and sodium hypochlorite, appears to be the most effective in recovering the biofouled void spaces in an aquifer.

A laser particle counting (LPC) analysis was conducted by DBI in order to determine if this procedure could provide some insight into the potential of treatment processes to breakdown biological matter into particle sizes that could be removed from the aquifer matrix. Laser particle counting data was collected from the well sites, and this data will hopefully be a valuable indicator of biofilm removal, when compared to the post treatment findings.

Preventative maintenance (PM) procedures are presently being developed and tested by DBI. The goal is for the City of North Battleford to be able to use as much of their present set-up and equipment as possible. It is *absolutely* critical that accurate records be kept on the operation and condition of each well after treatment. Any loss in specific capacity or increase in microbiological activity must be noted and appropriate PM procedures should be implemented at the earliest opportunity.

RECOMMENDATIONS

1. Based on the results of the laboratory studies, modifications to the UAB™ will be implemented that should improve the effectiveness of the treatment process. It is recommended that Well 15 be treated with the modified UAB™ treatment process to evaluate its effectiveness.

2. Based on the results of the diagnostics program, Well 16 is severely biofouled. It is recommended that Well 16 be treated before there is a further reduction in specific capacity.

3. Based on the results of the diagnostics program, Well 17 has not yet experienced a decline in specific capacity. However, the BART™ results indicate that biofouling is occurring at Well 17, and therefore, to prevent a decline in specific capacity in the future, it is recommended that preventative maintenance procedures (PM) be developed and implemented at the earliest opportunity.

4. The laboratory experimentation has provided guidance in improving the UAB ™well treatment process. It is recommended that an evaluation of other acids and combinations of acid types be conducted to further evaluate and refine the treatment process.

5. It is recommended that preventative maintenance protocols be developed and implemented to prevent a decline in the specific capacity of the wells in the future.

ACKNOWLEDGEMENTS

Project Partners:

Droycon Bioconcepts Incorporated: Dr. Roy Cullimore, Brent Keevill, Lori Johnston
City of North Battleford: Bob Berry, City Engineer; Ivan Katzell, Plants Foreman

Special thanks to Dr. Cullimore for his technical input and guidance in directing the microbiological testing and analysis component of this project. Acknowledgement is also given to Brent Keevill and Lori Johnston for their expertise in the microbiological assessment of the wells and aquifer and for their joint collaboration with PFRA staff during the field work and in the laboratory studies.

The support and contributions to this project by Bob Berry and Ivan Katzell are gratefully acknowledged. Also, special thanks to Ivan Katzell and his staff for their cooperation and assistance during the field diagnostics work.

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The in-kind contributions provided by all the project partners is also gratefully acknowledged.

1.0 BACKGROUND

The Sustainable Water Well Initiative (SWWI) was created by the Prairie Farm Rehabilitation Administration (PFRA) in response to a need to address concerns of declining well yield, water quality deterioration and a reduction in well lifespan. Many of the physical and chemical problems that are often experienced in water wells can be solved by well-established diagnostic and rehabilitation techniques. Therefore, the SWWI has initially focussed on the microbiological aspects of water well deterioration and rehabilitation, since this aspect is still the least understood. As a result of SWWI studies, a new treatment process for biofouled wells was developed and is currently being evaluated. This treatment process, known as Ultra Acid-Base™ (UAB™), was developed by Droycon Bioconcepts Inc. (DBI) in conjunction with PFRA, and a joint venture arrangement was established in 1996 to field test this treatment technology.

In October 1997, PFRA and DBI field tested this water well treatment technology on the City of North Battleford Well 15. Representatives from the City of North Battleford had previously approached Dr. Roy Cullimore of Droycon Bioconcepts Inc. with concerns about the steady decline in water production from their well field. Well 15 was chosen for the field test since preliminary diagnostics work conducted by PFRA and DBI had indicated that the reduction in well yield over the past seven years was largely due to plugging caused by biofouling of the well intake area and aquifer. The City of North Battleford was extremely interested in determining an effective well rehabilitation method, since previous attempts to restore the well yield, using conventional acid treatments, have proven to be ineffective. It also provided a unique opportunity to field test this treatment technique in a well field which has well-documented historical data and piezometers in place for monitoring. As a result of this field test, the UAB™ treatment process proved more effective than previous well treatments, doubling the current yield of Well 15. Although the original 1990 well yield was not restored, the treatment process showed definite promise for treating biofouled wells. The results of this field test are summarized in the report, *City of North Battleford Well 15, 1997 Field Test of UAB™ Water Well Treatment Technology (PFRA, 1998).*

1.1 Introduction

The UAB™ treatment process appears to be a viable treatment method for the City of North Battleford well field, based on the positive results of the 1997 field test on Well 15. Since the 1997 treatment result for Well 15 was much better than any of the previous treatments applied to this well, the City of North Battleford was extremely interested in further investigating the effectiveness of this treatment process. Pursuant to this, the City of North Battleford Well Rehabilitation Project was initiated and a contribution agreement was signed between PFRA, DBI and the City of North Battleford. Partial funding for this project was also provided through the *Canada-Saskatchewan Agri-Food Innovation Fund.*

The purpose of the City of North Battleford Well Rehabilitation Project is to further investigate the aquifer and wells from which the city obtains its water supply, in order to better understand the extent and nature of biofouling in this well field. The project is designed to evaluate the diagnostic tools and testing procedures which are currently used to determine the extent and nature of biofouling in wells and aquifers, and will provide recommendations on their applicability at the City of North Battleford. Where well rehabilitation is required, an appropriate treatment process will be recommended, tested and evaluated on the appropriate production well.

In initial consultations between PFRA, DBI and the City of North Battleford, two wells were being considered for this project, Well 15 and one other well. Well 15 was the prime candidate, since there was a need to better understand the extent of biofouling that may still be present in the aquifer surrounding this well and to determine if additional treatment could further improve the well yield. After some consideration, Well 17 was also chosen since it was only installed in 1995 and it would be of interest to determine if biofouling was occurring around more recent well installations. However, once the diagnostics work commenced, it became evident that Well 16 would also become part of this project, due to its significant decline in specific capacity. As a result, the wells evaluated as part of this project are Well 15, Well 16 and Well 17, as shown in Figure 1.

The City of North Battleford Well Rehabilitation Project is divided into three phases: a diagnostics phase, a well rehabilitation phase and a post treatment monitoring phase. The Phase 1 diagnostics program consists of a compilation of background data on the wells to be evaluated, pump testing of these wells, drilling and sampling of the aquifer, water chemistry testing and microbiological testing of the wells and aquifer material, and laboratory testing and analysis to evaluate the suitability of potential treatment chemicals. The results of the Phase 1 diagnostics work are provided in this report, with recommendations provided for Phase 2 of this project.

2.0 DIAGNOSTIC PROCEDURES AND RESULTS

As a result of the promising results of the 1997 field test of the UAB™ treatment process on Well 15, there is a need to continue to better understand the effect of the key elements of this treatment process on the biofouled aquifer material and also to better understand the extent of biofouling in the aquifer. In order to continue this evaluation process, a number of field diagnostics procedures were implemented to collect the required data. First, pump tests were performed on the Wells 15, 16 and 17 to evaluate their performance characteristics. Secondly, drilling and sampling of the aquifer material in vicinity of these wells was conducted to determine the extent and degree of biofouling in the aquifer. Thirdly, water samples were collected from each well and test hole site for water chemistry and microbiological analysis. The results of these diagnostic procedures provide a more comprehensive understanding of the extent and degree of biofouling in the aquifer and also assist in refining the well rehabilitation process for Phase 2 of this project. These diagnostic procedures appear to be useful in evaluating the effectiveness of the well treatments. Consequently, they will be repeated once the well rehabilitation phase has been completed. The results of the diagnostics program are provided in the following sections.

2.1 Pump Testing

A two-hour pump test was conducted on Wells 15, 16 and 17 to determine their specific capacity and to collect water samples for chemical and microbiological analysis. This data would then also be used to evaluate the effectiveness of any subsequent well rehabilitation procedures utilized during Phase 2 of this project. During each test, water was pumped from the well at a constant rate and the water level was recorded at regular time intervals. The pump test results for each well are presented below and the construction details of each well are illustrated in Appendix A.

2.1.1 Well 15

Well 15 is a 305 mm (12 inch) diameter well completed to a depth of 25 metres and is located about 82 metres from the North Saskatchewan River (Figure 1). The well was placed into service in 1990, with a specific capacity of 18.0 igpm/ft. By 1993, Well 15 began to show a decrease in specific capacity and despite regular attempts to restore the well's original capacity, a steady decline in specific capacity has been observed. Prior to the UAB™ treatment in October, 1997, Well 15 had a specific capacity of 0.49 L/s/m (1.96 igpm/ft). After the UAB™ treatment, the specific capacity increased to 0.72 L/s/m (2.87 igpm/ft) and reached a high of 0.86 L/s/m (3.45 igpm/ft) by December, 1997 (PFRA, 1998). As part of the diagnostics program, pump tests were performed on Well 15, with the results shown in Figure 2. On April 6, 1998, the well was pumped for two hours at 5.3 L/s (70 igpm) and a specific capacity of 0.77 L/s/m (3.09 igpm/ft) was calculated. On April 7, 1998, the well was pumped for 40 minutes at 9.1 L/s (120 igpm) and a specific capacity of 0.80 L/s/m (3.22 igpm/ft) was calculated. The results of these pump tests indicate that since the treatment in the fall of 1997, Well 15 has experienced no appreciable decrease in specific capacity over this six month period.

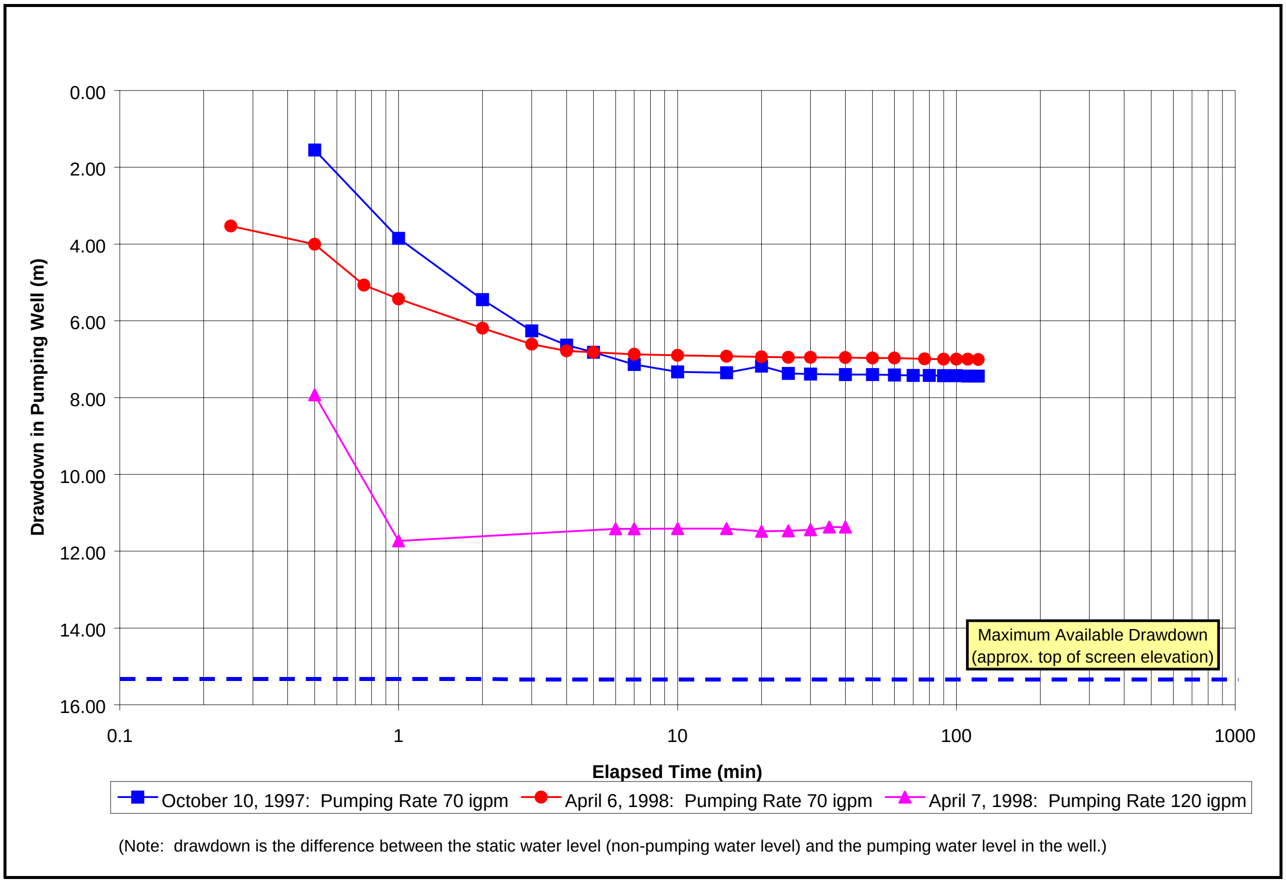

FIGURE 2 Well 15: Post-Treatment Pump Test Results

2.1.2 Well 16

Well 16 is a 305 mm diameter well completed in May, 1995, to a depth of about 21 metres, and is located about 20 metres from the North Saskatchewan River (Figure 1). As part of a regular well maintenance and evaluation program, the City's wells are pump tested to determine their specific capacity. The specific capacity for each well is then compared to the results from previous tests to determine if any change has occurred. To this point, Well 16 had not been evaluated with respect to specific capacity, and therefore, a pump test was performed by the City of North Battleford on April 8, 1998. A step drawdown test was performed, consisting of 3 consecutive, 10-minute pumping intervals at 150, 200 and 250 igpm, respectively. The pump rates and step durations were the same as those used in the original pump test (see Appendix B), in order to allow a direct comparison of drawdown measurements. A comparison of these results indicates that there has been *an approximate 40 per cent reduction in specific capacity*. A two-hour pump test was then performed on April 15, 1998, at a constant rate of 15.2 L/s (200 igpm), and a specific capacity of 2.84 L/s/m (11.44 igpm/ft) was calculated (Figure 3). This compares to an estimated specific capacity of 4.97 L/s/m (20 igpm/ft) obtained from the original pump test data. Based on this pump test result, there has been a *43 percent reduction in the specific capacity over the past three years*. Although this well was not originally included in the diagnostics phase, in conversation with representatives from the City of North Battleford, it became evident that Well 16 would be a potential candidate for the well rehabilitation phase.

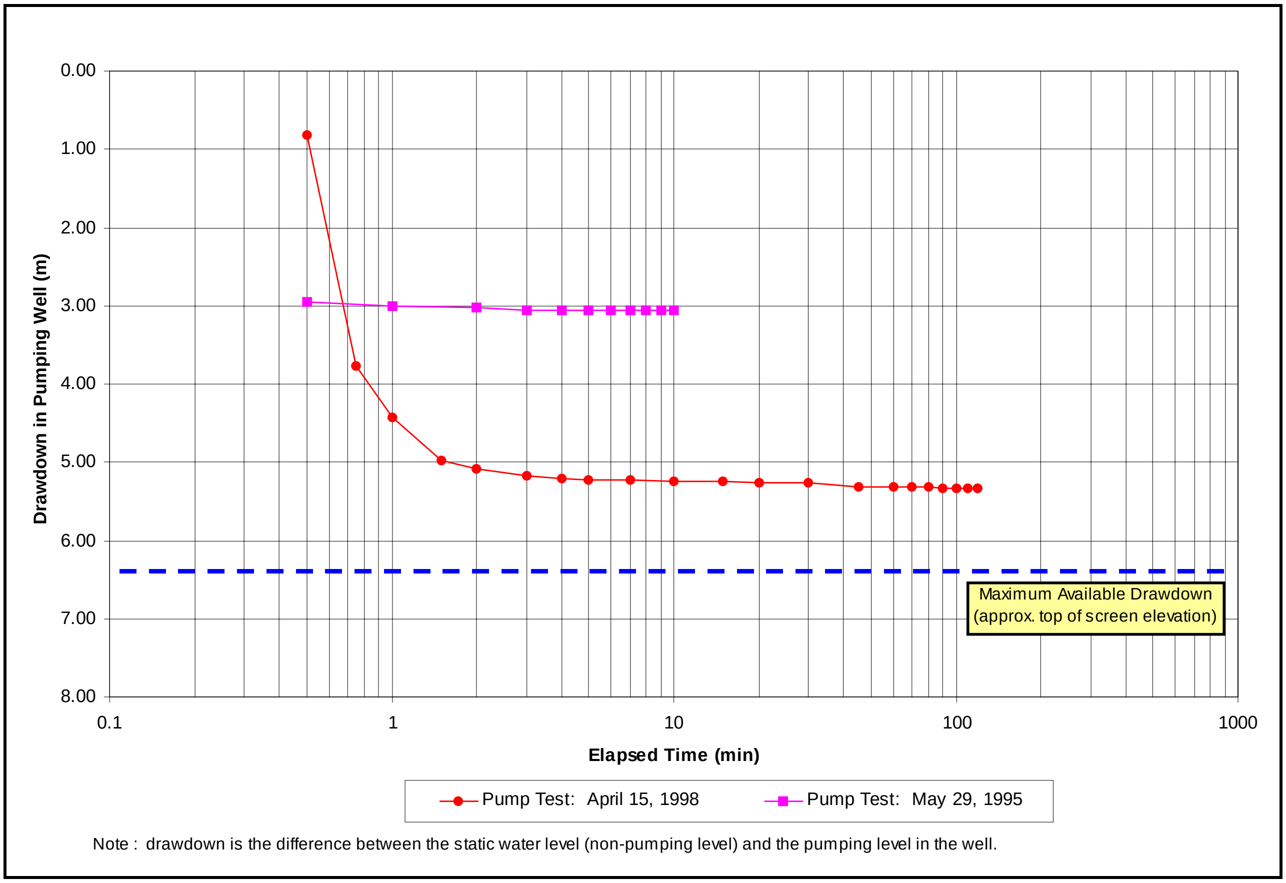

FIGURE 3 **Well 16: Pump Test Results @ 15.2 L/s (200 igpm)**

2.1.3 Well 17

Well 17 is a 305 mm diameter well completed in May, 1995, to a depth of about 20 metres. This well is located about 100 metres from the North Saskatchewan River (Figure 1). Prior to April 1998, this well had not been evaluated with respect to specific capacity. Well 17 is an extremely important well, since it serves as the emergency back-up water supply in case of a power failure, and therefore, is served by an emergency power source. Therefore, it is imperative that this well be able to sustain design pumping rates. For this reason, Well 17 was included in this project, since it would be a candidate for rehabilitation if a considerable drop in specific capacity was measured. With the cooperation of personnel from the City of North Battleford, a step drawdown test was performed, consisting of 3 consecutive, 10-minute pumping intervals at 150, 200 and 250 igpm, respectively. These pumping rates and step durations were equivalent to the original pump test data (shown in Appendix B), in order to allow a direct comparison of drawdown measurements. The results of this test indicated that there had been *little or no reduction in specific capacity from the original data*. A two-hour pump test was then performed on April 8, 1998, at a constant rate of 15.2 L/s (200 igpm), and a specific capacity of 4.97 L/s/m (20 igpm/ft) was calculated (see Figure 4).

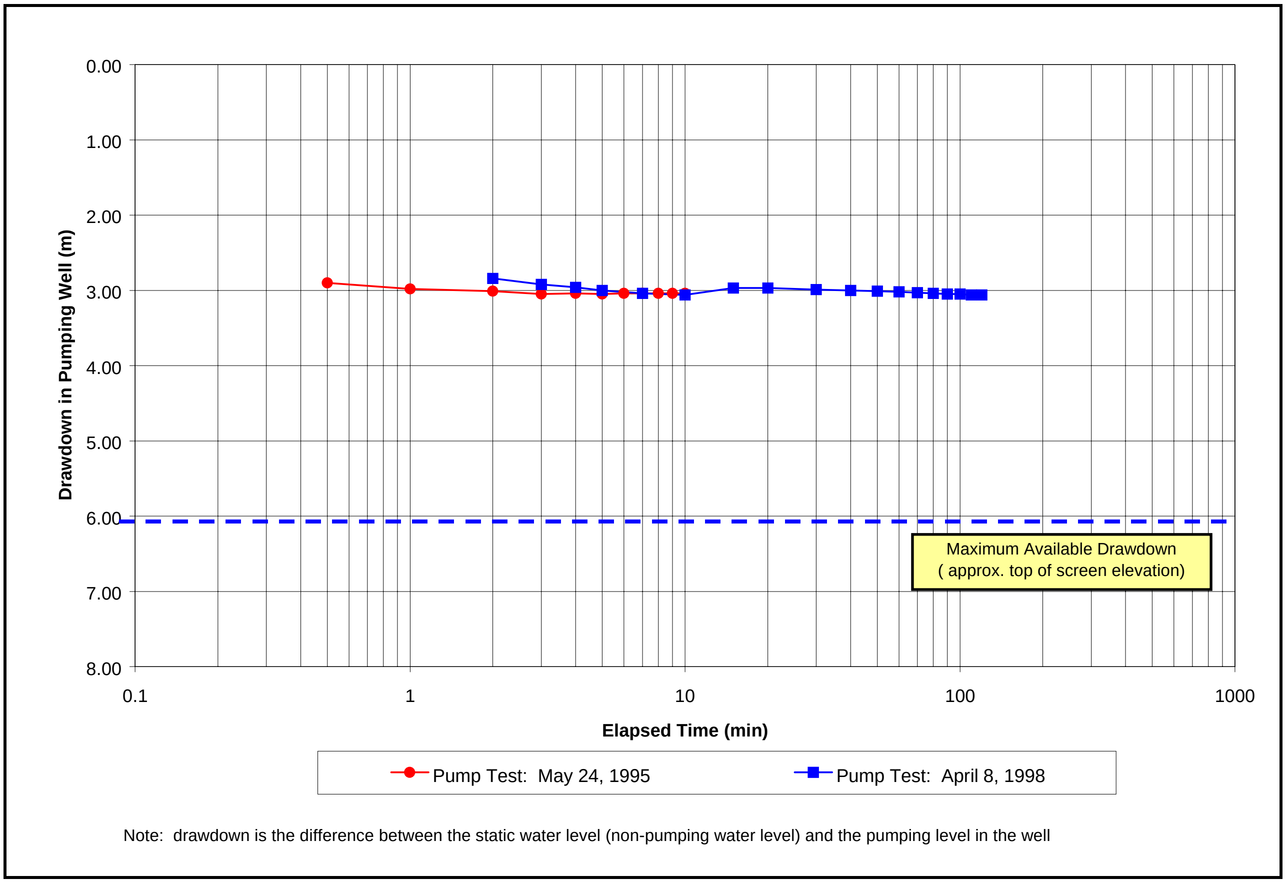

FIGURE 4 **Well 17: Pump Test Results @ 15.2 L/s (200 igpm)**

This specific capacity is equivalent to the estimated specific capacity of 4.97 L/s/m (20 igpm/ft) obtained from the original pump test data. Based on this pump test, there has been *no reduction in the specific capacity over the past three years*. A review of the historical record of specific capacity measurements from Well 15 indicates that there was also no specific capacity reduction in the first 3 years of production. However, in subsequent years the specific capacity of Well 15 experienced a steady decline. Although intensive treatment may not yet be required, a preventative maintenance program is essential if the capacity of this well is to be maintained.

Based on the pump test results for these wells, it appears that short duration pump tests can be used to determine the specific capacity of each well, which is an extremely useful diagnostic tool in determining if there has been is a reduction in well performance. The specific capacity comparisons for each well are shown in Figure 5.

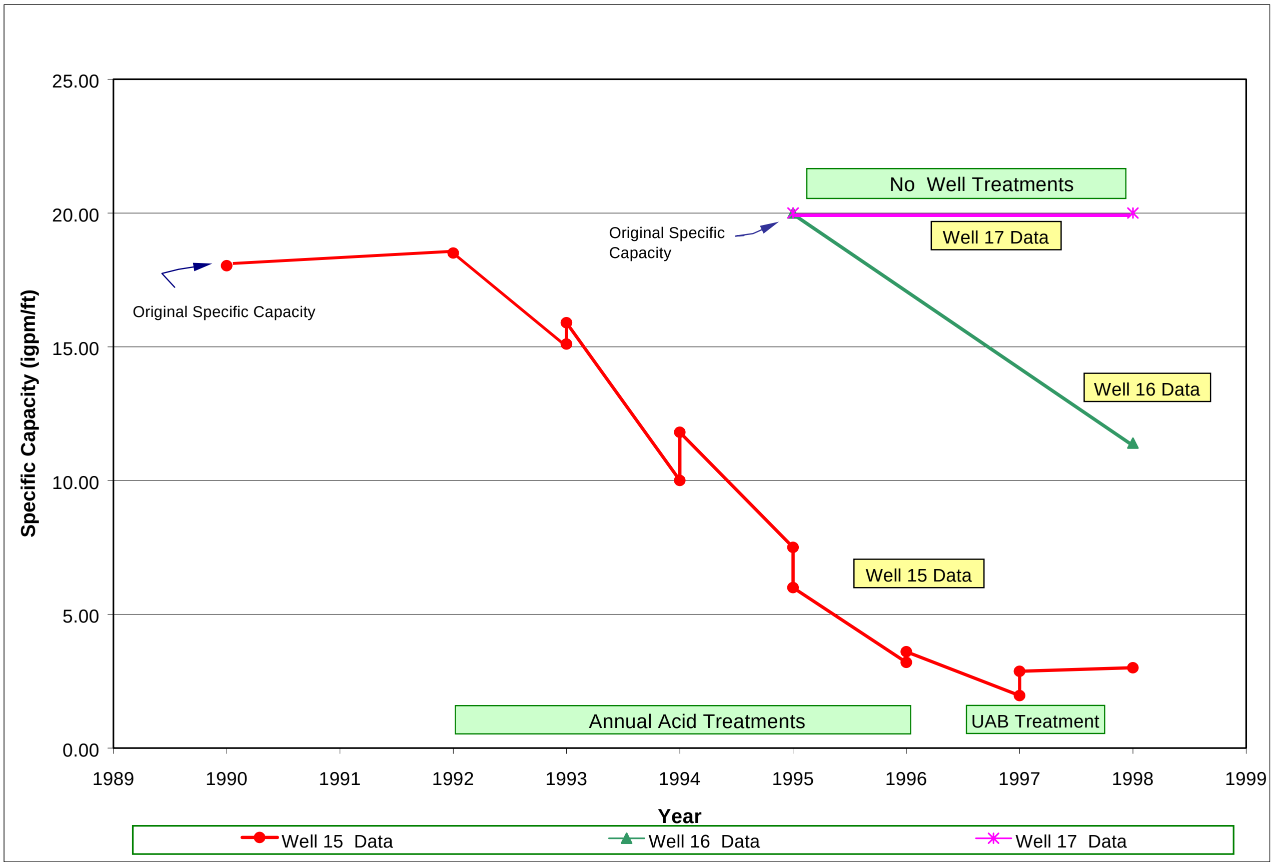

FIGURE 5 **Specific Capacity Comparisons for Wells 15, 16 and 17**

2.2 Drilling and Aquifer Sampling

The purpose of the drilling and aquifer sampling was to determine the extent of biofouling in the aquifer surrounding a well site, and to collect water and formation samples for detailed laboratory analysis. Aquifer sand samples and water samples were collected from each test hole site, according to a sampling protocol jointly established by PFRA and Droycon Bioconcepts Inc. The test hole drilling was conducted with a cable tool rig, with continuous aquifer samples collected in core barrels (Shelby tubes). Continuous aquifer sampling commenced once the saturated level of the aquifer was encountered and continued until the mid-point of the screened interval of the adjacent well was reached. A 50 mm (2-inch) diameter drive-point screen, with steel piezometer pipe was then driven into the underlying aquifer and pumped for a 2-hour interval to obtain water samples. This piezometer was then removed and continuous core sampling continued to the bottom of the screen level. Finally, a 50 mm diameter, PVC piezometer, with a screened interval similar to the adjacent well, was installed and water samples were collected. These piezometers will be used to monitor the well treatments in Phase 2 of this project and to collect water samples in the post treatment phase (Phase 3) of this project. The water samples were retained by DBI for chemical and biological analysis. The aquifer sand samples were collected and delivered to Regina for laboratory analysis, to be conducted by both PFRA and DBI. The test hole logs and general piezometer construction details are included in Appendix C.

2.2.1 Characterization of Aquifer Material

The City of North Battleford well field is situated in a terrace deposit along the north side of the North Saskatchewan River, and the wells obtain their water primarily through induced infiltration from the river. The terrace deposit is comprised mainly of fine sand and fine, silty sand that is up to 25 metres thick. The terrace deposits appear to become thinner in an easterly direction and the underlying till rises slightly in elevation in the same direction.

During the current diagnostics program conducted from April 7-27, 1998, a total of six test holes (C-85 to C-90) were drilled. Three test holes were drilled in vicinity of Well 15, two in vicinity of Well 16 and one test hole in vicinity of Well 17 (Figure 1). The lithology at each site was similar, consisting of 18 to 25 metres of fine sand and fine, silty sand. Intervals of organic material and coal were observed during the test drilling. Aquifer samples obtained during test drilling were further assessed at the PFRA Technology Adaptation Facility in Regina. Grain size analyses conducted, using the Unified Soil Classification System, indicate that the aquifer material consists primarily of well-sorted, fine sand (77-84%) and medium sand (10-20%), with only 1% to 4% fines (silt and clay). The bulk dry density of this material, as measured from C-90, is 2.59 g/cc and the aquifer material has an average porosity of 30%. The permeability of the aquifer material, based upon fourteen initial permeameter tests in the laboratory, ranges from 3.2×10^{-2} cm/sec to 2.2×10^{-3} cm/sec, which is in the range for a fine clean sand. The grain size curves are included in Appendix C.

This detailed drilling and aquifer sampling revealed that the terrace deposit has a relatively low amount of fine material and a considerable amount of organics, approximately 0.9%, in the form of coal fragments and fine black organic material. The organic layers occur as thin seams within the water-bearing formation and as entrained matter within the sand. This organic matter originates from within the river terrace environment. Regularly occurring events of material deposition, not only of sand and silt, but organic matter as debris, flooding of terrace vegetation, and vegetation regrowth have contributed to the supply of organic matter within the terrace deposits. The effects of organic matter on the treatment process is unclear at this time, however, there are several speculative theories. It is possible that the organic material, in the 1997 treatment process on Well 15, was dissolved or reduced in particle size by the chemicals used in the early treatment stages. To a certain extent, the organic material may have been removed, or dissolved, while other particles may have been reduced in size and left within the aquifer material. A further discussion of this possible effects of treatment chemicals on the aquifer material is contained in Section 3.0.

2.3 Water Chemistry

The purpose of this diagnostic component is to obtain an understanding of the water chemistry in the aquifer and nearby river. This allows the effect of biofouling on the water chemistry at each well site and surrounding aquifer, and the influence of the river water in providing nutrients to the wells to be determined. Water samples were collected for chemical analysis from the North

Saskatchewan River, Wells 15, 16 and 17, and from each test hole site. A chemical analysis of the aquifer sand samples collected from the test hole sites was also performed, using the US EPA Method 3051, to determine the iron and manganese concentrations in the aquifer sand samples. All water chemistry analyses were conducted by DBI in the field, using a HACH DR-2010 Spectrophotometer.

2.3.1 North Saskatchewan River

Water samples were collected at three different locations along the North Saskatchewan River. Representative samples were obtained by using a bailer, with three bailed samples collected at each location. In vicinity of Wells 15 and 16, the samples were collected one metre from the shore, at a depth of about one half the distance to the river bottom. A river water sample was also collected downstream from the well field. A bailer was lowered into the river from the mid-point of the Highway 16 bridge and water samples were collected from three different depths, which were then blended together to obtain a representative sample from that site. As expected, the results of the analyses indicate that the water chemistry of the North Saskatchewan River is fairly uniform in vicinity of the City's well field, as shown in Table 1.

Water Chemistry Parameter	River (Well 15) (1 metre from shore) April 7, 1998	River (Well 16) (1 metre from shore) April 21, 1998	River (Hwy. 16 Bridge) April 9, 1998
pH	8.06	8.36	8.02
Iron (mg/L)	0.34	0.17	0.41
Manganese (mg/L)	0.156	0.162	0.121
Total Hardness (mg/L $CaCO_3$)	170	163	134
Conductivity (mS/cm)	0.321	0.341	0.307
Total Dissolved Solids (mg/L)	161	171	154
Turbidity (FTU's)	19	19	41
Colour (ptco units)	162	105	212
Nitrate (mg/L)	0.1	0.11	0.08
Sulfates (mg/L)	54	54	52
Nitrogen (mg/L)	0.04	0.04	0.06
Phosphorus (mg/L)	0.21	0.2	0.18

TABLE 1 North Saskatchewan River Water Chemistry

2.3.2 Production Well Sites

Water samples were collected from Wells 15, 16 and 17 during a two-hour pump test performed on each well. Samples were collected at 1, 3, 5, 10, 15, 30, 60, 90 and 120 minutes. The water chemistry data from Wells 15, 16 and 17 is shown in Table 2, and the detailed water chemistry data is included in Appendix C. The water quality analyses were conducted in order to compare the results before and after a well treatment, and to determine if there are any water quality changes. Water samples were also collected from the six test holes and piezometer installations completed as part of the diagnostics work.

Water Chemistry Parameter	Well 15 Sept. 15, 1997	Well 15 April 7, 1998	Well 16 April 15, 1998	Well 17 April 8, 1998
pH	7.56	7.63	7.81	7.47
Iron (mg/L)	2.3	2.22	1.38	1.82
Manganese (mg/L)	0.76	0.68	0.566	0.63
Total Hardness (mg/L $CaCO_3$)	274	249	185	235
Conductivity (mS/cm)	0.619	0.545	0.376	0.497
Total Dissolved Solids (mg/L)	310	272	195	249
Turbidity (FTU's)	35	28	20	24
Colour (ptco units)	182	154	105	132
Nitrate (mg/L)	<0.04	0.01	0.02	< 0.01
Sulfates (mg/L)	126	105	64	74
Nitrogen (mg/L)	Not tested	0.36	0.13	0.54
Phosphorus (mg/L)	Not tested	0.13	0.12	0.03

TABLE 2 Water Chemistry Results from Wells (after 120 minutes of pumping)

Water samples from the test hole sites, shown in Figure 1, were collected from the top, middle and bottom third of the aquifer. The water chemistry data for the middle interval of each test hole are shown in Table 3.

Water Chemistry Parameter	C-85	C-86	C-87	C-88	C-89	C-90
pH	7.78	7.75	7.79	7.68	7.65	7.66
Iron (mg/L)	1.69	1.34	1.17	1.18	1.36	0.98
Manganese (mg/L)	0.63	0.616	0.392	0.553	0.556	0.418
Total Hardness (mg/L $CaCO_3$)	200	183	195	177	195	185
Conductivity (mS/cm)	0.451	0.411	0.38	0.393	0.398	0.394
Total Dissolved Solids (mg/L)	227	204	192	196	199	197
Turbidity (FTU's)	54	70	31	30	31	17
Colour (ptco units)	305	370	152	167	168	88
Nitrate (mg/L)	<0.01	<0.01	<0.01	0.01	<0.01	0.03
Sulfates (mg/L)	63	64	60	68	68	64
Nitrogen (mg/L)	0.13	0.17	0.15	0.14	0.12	0.34
Phosphorus (mg/L)	0.05	0.02	0.06	0.04	0.11	0.05

TABLE 3 Water Chemistry Results from Test Hole Water Samples: April 1998

Several observations can be made from the water analysis results for the production wells and adjacent test hole sites. First, when comparing the water analysis results, the total dissolved solids levels are higher at the production well sites. This may be due to the higher concentration of minerals that have collected in the biofilm around the well intake area. The exception is Well 16, where the water analysis results from the well and adjacent test holes are similar. This may be due to more direct recharge occurring to this site from the nearby river. Test hole C-87 had the best overall quality. This is probably due to the fact that C-87 is situated near the river and is also located some distance from any production wells, and therefore, is not directly influenced by the environment created in vicinity of these pumping wells. Secondly, as shown in the detailed water analysis results in Appendix C, the phosphorus and nitrogen levels measured at several of the production well sites suggest that the nutrient levels are sufficiently high to have a significant biological impact around these wells. These nutrients, which are available from the nearby river, encourage biological growth, and thereby, enhance the plugging potential of the aquifer. Thirdly, the iron, manganese and sulphate levels are the highest at Well 15, which is also the site that has experienced the most severe biofouling. As suggested earlier, this is probably due to the fact that the biofilm collects and concentrates these minerals in the area surrounding the well intake. Well 15 was treated with the UAB ™ process in October 1997 and water testing conducted in April, 1998, indicated that there has been a slight decrease in the iron, manganese and sulphate levels. This may be due to the treatment process which may have removed some of the minerals that had collected in the biofilm around the well.

2.3.3 Chemical Analysis of Aquifer Sand Samples

The aquifer sand samples were analyzed by DBI for iron and manganese concentrations using US EPA method 3051. This laboratory method uses acid digestion of a representative sample from each core sample and inductively coupled plasma (ICP) to determine the iron and manganese concentrations, with the results shown in Table 4.

Aquifer Sand Sample	Iron Concentration (mg/kg)	Manganese Concentration (mg/kg)
Black Coal Seams	28,500	625
C-85: (3 m from Well 15)	7440	277
C-86: (6 m from Well 15)	6290	195
C-87: (60 m from Well 15)	6020	209
C-88: (6 m from Well 15)	3800	80.4
C-89: (3 m from Well 15)	5900	170
C-90: (4 m from Well 15)	4680	106

TABLE 4 ICP Chemistry Results from Core Samples

The iron and manganese concentrations from the aquifer core samples were measured to determine if the levels change as the distance from the well increases. The results of these analyses indicate that the iron and manganese levels appear to decrease away from the well. The water chemistry results from the core sample holes, shown in Table 3, also indicate that the iron and manganese levels decrease slightly away from the well. As part of this project, it is hoped that these findings can be compared to the microbiological testing results to determine if a relationship exists between the degree of biofouling and the water chemistry results from aquifer core samples. The thin black coal seams in the core samples were also analyzed for their iron and manganese concentrations. These coal seams appear to be a source of iron and carbon, which may also encourage the growth of iron-related bacteria.

2.4 Microbiological Testing

The purpose of the microbiological testing was to determine the degree of biological activity in the wells and surrounding aquifer. The results of these tests will also be use to evaluate the effectiveness of well rehabilitation, since they will be repeated once the well rehabilitation phase has been completed. Water samples for microbiological analysis were collected during a two-hour pump test on each well, as well as from the six test holes completed as part of the diagnostics work. Aquifer core samples were also collected at each of the six test hole sites, for microbiological analysis to determine the biological activity in the aquifer material in vicinity of each well. A brief discussion of the BART™ results for both the water and aquifer sand samples is provided in the following sections.

2.4.1 BART™ Analysis of Water Samples

Water samples for microbiological analysis were collected at 1, 3, 5, 10, 15, 30, 60, 90 and 120 minutes, during a two-hour pump test on each well. Water samples were also collected from the six test holes completed as part of the diagnostics work. During the drilling of each test hole, a water sample was collected from the top, middle and bottom of the aquifer. These water samples were collected in order to provide a vertical profile of the microbiological activity in the aquifer surrounding each well. All the analyses for bacterial activity were conducted by using Biological Activity Reaction Tests (BART™), which determine the presence and aggressivity of the bacteria causing the biofouling problems. The BARTs™ used for the microbiological testing of the water were the IRB-BART™ (for iron related bacteria), the SRB-BART™ (for sulphate reducing bacteria), the HAB-BART™ (for heterotrophic bacteria), the DN-BART™ (for denitrifying bacteria), the SLYM-BART™ (for slime forming bacteria) and the TCOLI-BART™ (for coliform bacteria). A generalized summary of the results are shown in Tables 5 and 6, and the more detailed data and a graphical representation of the results are provided in Appendix D.

BART™ Test	Well 15					Well 16	Well 17
	Pre-Treatment		Post Treatment			Pre-Treatment	
	July 30, 1997	October 6, 1997	October 10, 1997	February 2, 1998	April 6, 1998	April 15, 1998	April 8, 1998
HAB	medium	high	low	medium	medium	high	medium-high
IRB	medium	high	high	medium	high	high	high
SRB	high	high	high	high	high	high	medium
DN	-	high	medium	low	medium	high	medium
TCOLI	-	negative	negative	negative	negative	negative	negative

TABLE 5 BART™ Interpretation Results from Wells

BART™ Test	Well 15			Well 16		Well 17
	C-85 (3 m from well)	C-86 (6 m from well)	C-87 (60 m from well)	C-88 (6 m from well)	C-89 (3 m from well)	C-90 (4 m from well)
HAB	medium	medium	high	high	medium	medium
IRB	high	high	high	high	high	high
SRB	high	negative	high	high	medium	medium
SLYM	high	high	high	high	high	high
DN	high	high	medium	high	medium	high

TABLE 6 BART™ Interpretation Results from Test Hole Sites: April 1998

Well 15: A general reduction in biological activity was observed after the 1997 UAB ™ treatment of Well 15, as shown in Appendix D. However, BART™ testing, conducted in April, 1998, indicates that the IRB and SRB bacteria are again approaching the highly aggressive levels measured prior to treatment. The results of the HAB and DN tests indicate that the aggressivity of these bacteria is still lower than measured prior to treatment. The biological analyses from the water samples collected from C-85 and C-86 physically confirm that IRB are within 3 metres of the well and that the SRB's are between 3 and 6 metres from the well. The HAB tests indicate that these bacteria are at a medium aggressivity level, to a distance of at least 6 metres from the well.

Well 16: Based on BART™ analysis of water samples obtained during a two-hour pump test of this well, the IRB, HAB, SRB and DN bacteria are highly aggressive. BART™ analysis of water samples obtained from both C-88 and C-89, indicate that the IRB, SRB, HAB, DN and SLYM bacteria are also generally highly aggressive at these sites. These results indicate that Well 16 is severely biofouled, which appears to relate directly to the 43% decrease in specific capacity measured during the pump test.

Well 17: Although Well 17 was installed at the same time as Well 16, this well has shown no loss in specific capacity. The BART™ analysis results from the water samples collected at Well 17 indicate a medium aggressivity for HAB, SRB and DN bacteria, and a high aggressivity for IRB. Also, samples taken from C-90, 3.9 metres from the well, indicate IRB, DN and SLYM bacteria to be highly aggressive and HAB and SRB to have a medium aggressivity. These results indicate that aquifer biofouling is occurring at this site, although the bacterial problem appears not to be quite as advanced, as compared to Wells 15 and 16. However, a preventative maintenance program must be implemented to prevent an increase of biological activity in vicinity of this well, and thereby, prevent a reduction in well yield.

2.4.2 BART™ Analysis of Aquifer Sand Samples

The core sampling of the aquifer material was used to determine the biological activity in vicinity of each well. At each of the six test hole sites, core samples of the aquifer material were collected and the samples were then dissected in the laboratory for analysis. The biological analysis for each of these samples was conducted by placing 0.1 grams of aquifer sand into a BART™ sample container and adding 15 ml of sterile water. The BARTs™ used for the microbiological testing of the aquifer sand samples were the IRB-BART™, the SRB-BART™, the HAB-BART™, the DN-BART™ and the SLYM-BART™. A summary of the results are provided in Table 7, with detailed results in Appendix D.

The analysis of the BART™ data for the aquifer core samples conducted by DBI indicates that the degree of biofouling is generally high in vicinity of each of the wells. The bacterial aggressivity of the IRB appears to increase as the wells are approached, as indicated in Table 7. This also appears to correlate with the iron concentrations reported from the water analysis data for the test hole sites (Table 3) and with the iron concentrations measured from the aquifer core samples (Table 4), which show that iron levels are increasing closer to the well. This suggests that these higher iron concentrations are a result of the iron related bacteria which removes iron from the water and surrounding aquifer material, concentrating the iron within the biofilm formed by the bacteria.

BART™ Analysis	Well 15			Well 16		Well 17
	C-85 (3 m from well)	C-86 (6 m from well)	C-87 (60 m from well)	C-88 (6 m from well)	C-89 (3 m from well)	C-90 (4 m from well)
HAB	medium	medium	medium-high	high	low	medium
IRB	high-medium	low-medium	low-medium	low	high	high-medium
SRB	high	high	high	high	high-medium	medium
SLYM	high	high	high	high	high	high
DN	low	low	low	low	low	medium

TABLE 7: Bacterial Aggressivity Levels in Aquifer Core Samples: April 1998

The biological data from the core samples, along with the biological data from water samples collected during the pump tests, provide insight into the severity of biofouling in vicinity of each well. The BART™ evaluation of the aquifer core data, as shown in Appendix D, reveals that the degree of biofouling may vary at different depths. Based on the test results, the aquifer is severely biofouled in vicinity of Well 15, and the degree of biofouling appears fairly uniform. However, at the Well 16 site, results from C-88 and C-89 indicate that there are areas where no bacteria may be present. In C-88, at depths of 8 to 10 metres and 13 to 14 metres, and in C-89, at a depth of 11 to 14 metres, no aggressive iron-related bacteria or sulphate-reducing bacteria were detected. This suggests that the microorganisms have not caused plugging of the void spaces in these areas, and therefore, groundwater can flow more freely through this interval. However, as other areas around the well become more plugged and a greater volume of groundwater flows through this interval, the higher flow velocities combined with more microorganisms and a higher nutrient load could initiate the formation of biofilms in this area as well. Therefore, this well would benefit from a well treatment designed to remove biofilms that are currently plugging the void spaces of the aquifer. This would reduce the entrance velocities at the well screen and hopefully distribute the flow more equally across the screen interval. The BART™ results from C-90, located about 4 m from Well 17, indicate that the bacteria are generally of medium aggressivity. However, some of the sample core intervals were not tested since the samples were used by PFRA for conducting other laboratory tests.

3.0 LABORATORY TESTING AND ANALYSIS

The purpose of the laboratory testing and analysis component was to evaluate the suitability of potential treatment chemicals on aquifer material collected from the City of North Battleford well field. The laboratory experimentation consists of using aquifer sand samples, small-scale well models (mesocosms), permeameters and swell-consolidation tests to evaluate the effects of various chemicals and treatment processes on the aquifer material. As well, live biological material was cultured in a mesocosm containing aquifer sand, which allowed a closer simulation of actual sub-surface conditions. By simulating well treatment processes, their effect on the biological mass and the ability of the treatment chemicals to reduce the size of the biological matter sufficiently for removal from the aquifer matrix are all studied in laboratory conditions.

The laboratory testing was conducted jointly by PFRA and DBI. Personnel from the Geotechnical and Earth Sciences Units of PFRA studied the effect that various treatment chemicals will have on the aquifer permeability. The initial chemicals tested were those associated with the UAB™ treatment process. Permeameters and swell-consolidation tests were the methods used to evaluate the various treatment chemicals. DBI personnel studied the ability of the treatment chemicals, as well as the entire well treatment process to effectively remove biological matter from the aquifer, by using small-scale well models also referred to as mesocosms. DBI also conducted a biological analysis of the aquifer sample cores. The results of the laboratory testing conducted by both PFRA and DBI are provided in the following sections.

3.1 Permeability Effects of Treatment Compounds on Aquifer Material

Tests to evaluate the effect of proposed well maintenance chemicals on aquifer materials were conducted at the PFRA Technology Adaptation Facility in Regina. Swell-consolidation tests were designed to evaluate the effect of various concentrations of well treatment chemicals on the swelling of clays which exist in small proportions in most aquifer materials. Permeameter tests compared the initial (pre-process) permeability of aquifer materials with that measured following a chemical treatment (post process), at varying temperatures and concentrations.

3.1.1 Swell-Consolidation Tests

The one-dimensional swell potential of cohesive soils (ASTM D:4546) is a test method used to determine the magnitude of swell of compacted, cohesive earth materials under a known axial pressure. A calcareous, oxidized, clay from the Morden-Portage area in Manitoba was utilized as the test specimen in all cases (see hydrometer curve site: ECC1C, Appendix E). The clay was trimmed and placed within a consolidometer under a specified pressure (4.6 kPa) and inundated with a chemical at a specified concentration. A continuous readout of the test results allowed a comparison of the amount of swell to that of a control consisting of clay in distilled water. The results of these tests are shown in Table 8 and Appendix E.

Test Number	Agent	Concentration	Swell (%)	Time (days)	Comments
1	WATER		4.78	7	control
2	NaOH	1%	8.82	1	sodium hydroxide
3	NaOH	1%	29.55	4.5	
4	NaOH	1%	38.5	14	
5	NaOCl	12.50%	21	4	sodium hypochlorite
6	CB-4	1%	9.47	16	surfactant
7	CB-4	1%	13.1	34	
8	CB-4	100%	1.2	12.5	no water used in test
9	CB-4	50%	2	7	
10	CB-4	est<1%	29.9	7	test completed with water
11	HCl	10%	3.8	5	muriatic acid
12	KOH	2g/L	4.2	7	potassium hydroxide
13	HTH	2g/L	3.7	7	calcium hypochlorite

TABLE 8 Swell-Consolidation Test Results

Distilled water generated about a 5% swell in the clay over a period of 7 days. Sodium hydroxide at a 1% concentration indicated a swell approaching 40% and, on the basis of this test, this chemical was not considered for further testing. Sodium hypochlorite caused a swell of 21% during the 4-day test period. Calcium hypochlorite (HTH) was then considered as a possible replacement for sodium hypochlorite and was subsequently tested, showing a swell of 3.7% over 7 days. The surfactant Arccsperse CB-4, an anionic polyelectrolyte, the chemical formula of which is proprietary, was tested at an initial concentration of 1%. A swell of 13.1% over 3.5 days was measured. As a follow-up test, a pure 100% solution of CB-4 was tested with the result being a 1.2% swell over 12.5 days. On the basis of this test it was concluded that water was necessary to induce swelling and the solution was diluted to 50% with water. Swelling increased to 2% over 7 days and ultimately to 29.9% at a very dilute concentration. Tests on hydrochloric acid (HCL) at 10% and potassium hydroxide (KOH) at 2g/L indicated swelling at rates less than water over 7 days.

3.1.2 Permeameter Tests

Eight permeameters were designed and constructed for the purpose of investigating the effect of well treatment chemicals on the permeability (K) of the North Battleford aquifer sand. Each permeameter cell was designed with a 160 mm length of 63.53 mm I.D. clear acrylic tubing, sufficient to contain approximately 425 to 445 cc of soil materials. A 60 micron nylon screen was selected for the base, following test results on aquifer sands that used both metal and plastic, and finer and coarser screens. Each cell was saturated under a 25 cm head for a minimum of 24 hours prior to any tests of pre-process permeabilities. In all cases, falling head tests were conducted through use of 19.45 mm diameter riser pipes with an initial one-metre head, a final 25 cm head, and a total fall of 75 cm. A total of 44 tests were conducted; twenty-one to determine initial (pre-process) K values and twenty-three to determine K values following the application of chemical solutions to the cells (post process). To reduce the number of variables involved in assessing the results, all processes involved the injection of 500 ml of solution to the cell, under gravity and through the riser pipe, and a residence time of 5 hours prior to flushing and initiation of falling head tests. Variables included differences in solution concentrations, solution temperatures, and K-values of aquifer materials.

A total of eight different compounds at different concentrations and temperatures were evaluated with respect to their influence on the North Battleford aquifer materials. The results of this experimentation are shown in Appendix E. One compound initially considered for investigation was sodium hydroxide (NaOH). However, this chemical was eliminated due to a demonstrated swelling potential of clay (see section 3.1.1). Calcium hydroxide ($Ca(OH)_2$) was then considered. However, this chemical compound could not be dissolved in water without forming a heavy floc which would severely reduce K-values. This problem could be resolved if the compound were to be dissolved in distilled, degassed water, but its use in field conditions would be impractical. Therefore, no further consideration was given to testing this compound.

The surfactant CB-4 was investigated, since it is a fundamental compound in the UAB™ treatment process. This surfactant compound was tested at three different concentrations and at temperatures of 20°C and 65°C. In all instances, the post process K-values were increased following a 5-hour flush with CB-4 solution. In all instances, considerable volumes of fines were released from the cells and higher temperatures and solution concentrations increased the amounts released. Due to the significant percentage of organics in the aquifer material (approximately 0.9%), the effluent from the cells contained dissolved organics and the colour was a very dark brown. The average increase in K-value for all concentrations at a flush temperature of 20°C was 12% and for 65°C the increase was 27.3%. However, testing indicates that the smaller the concentration of CB-4 to be used under field conditions, the better the result may be in terms of maintaining or increasing aquifer K-values, as indicated in Table 9.

Concentration of CB-4 (%)	Average percent increase in K-value
0.75	30.5
1	20
2	8.5

TABLE 9: CB-4 Concentration vs Permeability (K) Increase

The results in Table 9 indicate that CB-4 improves the permeability of the North Battleford aquifer sands. Test results also indicate that the efficiency of CB-4 is improved by heat, and that concentrations in excess of 1% volume in water may provide reduced benefits. Although CB-4 acts as a dispersant of clays, CB-4 will also swell clays as shown by the results of the swell tests. The North Battleford aquifer sands contain only 1% to 5% fine material. However, aquifers which may contain larger proportions of fine material could be adversely affected if the concentrations of CB-4 are too high, if the compound remains in the aquifer for long time periods, or if the compound is not sufficiently removed from the aquifer.

A locally available surfactant was also tested to determine its effect on aquifer permeability relative to CB-4. This compound was flushed through two cells at a concentration of 1% and at temperatures of 20°C and 65°C. The permeability of the sands was neither increased nor decreased, nor was there any significant removal of fine material or organics. Therefore, the compound was found to be of no value for water well treatment purposes.

Calcium hypochlorite (CaOCl), also referred to as HTH, solutions were flushed through the permeameter cells at concentrations of 2g/L and 5g/L with mixed results. The higher concentration solution resulted in a 5.5% increase in K-value while the 2g/L solution resulted in a 3.8% reduction in K-value. A 1% solution of sodium hypochlorite (NaOCl) was also tested resulting in a 7.1% increase in permeability. However, in combination with a 1% concentration of CB-4 neither of the hypochlorite solutions provided improvements in the permeability of aquifer materials. A 12.5% solution of sodium hypochlorite in a 1% solution of CB-4 reduced the permeability by 18% and a 5g/L concentration of calcium hypochlorite in a 1% solution of CB-4 resulted in a 25% reduction in permeability over a 5-hour time period. The sodium hypochlorite-CB-4 combination did result in significant removal of fine material. No such effect was observed for the calcium hypochlorite-CB-4 combination and, furthermore, a precipitate was produced when these two chemicals were mixed. On the basis of these preliminary results, and in consideration of practical field applications, sodium hypochlorite appears to promise greater benefits over calcium hypochlorite in well-aquifer rehabilitation programs.

Hydrochloric acid (HCL) was tested at concentrations of 1% and 5%. The permeability of the aquifer material increased 200% with the 1% solution and 137% with the 5% solution. A concern for the stability of the nylon screening and the possibility of spurious results due to breakdown under acidic conditions required an examination of the screens after the cells were dismantled. Microscopic examination of the screens showed they were intact, and therefore, the HCL results are deemed valid. Although the 1% solution resulted in a greater increase in K-value than the 5% solution, both trials resulted in dramatic increases in permeability. The reason for the disparity in results is due to the fact that the stronger solution of HCL was significantly neutralized by KOH which remained in the cell following an earlier test. Inhibited hydrochloric acid (iHCl) was also tested at a 1% concentration and at a 1% concentration with CB-4. Permeability increases in excess of 200% were observed, with the acid-CB-4 combination providing the best results.

Sulfamic acid (NH_2SO_3H) was also evaluated as a possible alternative to the use of hydrochloric acid. A solution of 1g/L increased material permeability 28% and a solution of 3g/L improved permeability 64%. In combination with CB-4, sulfamic acid at a 21g/L concentration increased permeability about 124%. The screens were also examined to ensure the results were valid.

Two trials of potassium hydroxide (KOH) solutions, both 2g/L were also conducted to determine the effect of this compound on aquifer material. The use of this compound has been considered as possibly serving to provide a pH adjustment during well servicing instead of compounds such as sodium or calcium hydroxides which do not have favourable characteristics. Swelling tests on KOH have shown it to have favourable attributes in this regard. Unfortunately, in both instances, the solution formed a floc while in the riser tube and the results of K-testing were unfavourable. Significant decreases in K-values were observed, likely because of plugging at the top of the column in each cell. These decreases were 17.5% and 22.7%, as shown in Appendix E. The formation of a floc with KOH solutions may be similar to problems experienced with $Ca(OH)_2$ solutions. Unless this problem can be adequately handled under field conditions, it is likely that potassium hydroxide compounds will not be used in well-aquifer treatments.

3.1.3 Discussion of Swell Consolidation and Permeameter Test Results

The results of swell-consolidation tests and/or permeameter tests indicate that hydroxide compounds should be avoided for water well servicing. Sodium hypochlorite has greater promise than calcium hypochlorite, but it may swell clay if not sufficiently removed from aquifers following treatment.

Increasing the temperature of treatment fluids results in increased efficiencies of fines removal, dissolution of organics and better overall increase in the permeability of aquifer materials. The optimum temperature for treatment has not been determined. Further testing to determine optimal temperature for water well treatment may be warranted.

The CB-4 effectively dispersed clay particles and its use increased the permeability of aquifer materials. Tests suggest that solutions should not exceed 1% by volume in water and that residence times in the aquifer should be minimized, otherwise clay swelling may be a problem.

Permeameter tests of sulfamic and hydrochloric acid solutions indicate that these acids increase the permeability of aquifer materials more effectively than any other agent that has been evaluated in this study. The evaluation of other acids and combinations of acid types for water well treatment should also be considered.

3.2 Selection of Suitable Treatment Chemicals and Procedures

Droycon Bioconcepts Inc. (DBI) has developed and constructed small-scale model wells, also referred to as mesocosms, to evaluate water well treatment chemicals and treatment processes. Some of their initial mesocosm tests were conducted on a patented treatment process known as Blended Chemical Heat Treatment (BCHT™). As a result of their mesocosm tests on the BCHT™ process, DBI modified this treatment process and developed the Ultra-Acid Base (UAB™) treatment process (PFRA and DBI, 1997). Initial mesocosm testing on the UAB ™ treatment process indicated that wells, where the void spaces in the surrounding sand pack and aquifer are less than 70%

plugged/biofouled with iron-related bacteria, may expect up to 75% void space recovery with a single treatment. However, as the severity of biofouling increases to 100% plugging of the void spaces, the void space recovery with a single treatment material was reduced to about 36%, and required up to three treatments to achieve 75% void space recovery (Keevill, 1997).
For this project, the mesocosms were redesigned by DBI to evaluate chemical treatment trains that will be effective on the biological problems encountered at Wells 15 and 16. These mesocosms were designed to simulate the environment around these two wells, by using actual aquifer sand samples collected from the test hole sites in April 1998 (Keevill, 1999). Preliminary laboratory tests were conducted by both PFRA and DBI to evaluate and design the optimum Ultra-Acid Base (UAB™) chemical treatment train for the North Battleford well sites. Initial laboratory results conducted by PFRA, as outlined in Section 3.0, have shown that sodium hydroxide, which was used as a pH buffer in the October 1997 treatment of Well 15, is undesirable as a well treatment chemical. This is due to the swelling potential of sodium hydroxide, which can cause clay particles to swell, and thereby, can cause restrictions in the water pathways to the well screen. Additional laboratory experimentation, as outlined in Section 3.0, has shown that either sodium hypochlorite or calcium hypochlorite could replace sodium hydroxide in the alkali (base) phase of the UAB™ treatment process, described in Section 4.1.1. However, based on laboratory results and observations, sodium hypochlorite is preferred over calcium hypochlorite in well rehabilitation applications.

Based on further laboratory tests conducted by DBI, sodium hypochlorite (NaOCl @ 12.5%), in combination with CB-4, proved very effective at raising the pH to 10.0. Mesocosms tests have been conducted using sulfamic acid, acetic acid and hydrochloric acid, as outlined in Table 10.

Mesocosm	Chemical Treatment Train	Before Treatment Void Space biofouled (%)	After Treatment Void Space biofouled (%)	Percent Change
1	Heat; Agitation	53	46	13
2	1% CB-4, NaOCl; Heat, Agitation	57	45	12
3	1% CB-4, 1% HCl, NaOCl; Heat, Agitation	47	20	27
4	1% CB-4, 5% HCl, NaOCl; Heat, Agitation	49	13	36
5	1% CB-4, 1 g/L Sulfamic, NaOCl; Heat, Agitation	44	26	18
6	1% CB-4, 3 g/L Sulfamic, NaOCl; Heat, Agitation	45	24	21
7	1% CB-4, 10% Acetic, NaOCl; Heat, Agitation	44	21	23

8	1% CB-4, 15% Acetic, NaOCl; Heat, Agitation	43	15	28

TABLE 10: Mesocosm Testing Results

The sulfamic and acetic acid tests showed some early promise, however, muriatic acid was more effective at dissolving the iron and manganese oxides that had collected in the biofilms and encrustations. Hydrochloric acid is also very effective at lowering the pH in the mesocosm, thereby traumatizing the bacteria. The acetic acid was found to be less effective in maintaining a low pH in the biofouled mesocosm. However, the combination of muriatic acid in the acid phase of the UAB™ treatment and sodium hypochlorite during the alkali (base) phase was able to cause the required pH shift of 7 pH units (2.5-10.0). The sodium hypochlorite has the added benefit of disinfecting the pumping equipment when it is placed back into the well. Inhibited hydrochloric acid was also tested on the biofouled mesocosms and was found to be just as effective as the non-inhibited acid. Inhibitors are designed to reduce the corrosiveness of the acid on metal screens. However, since they are extremely toxic, inhibitors should not be used in potable water supplies

Based on the permeameter test results outlined in Section 3.1.2, calcium hypochlorite is not a preferred well treatment chemical since a precipitate is produced when mixed with water or when used in combination with other treatment chemicals. This precipitate could cause further plugging of the well intake area. However, the City of North Battleford still prefers to use granular calcium hypochlorite as a preventative maintenance chemical, since it has good disinfection potential, with a 65% active chlorine content, and can be more easily handled and stored than sodium hypochlorite.
Additional laboratory studies by DBI have indicated that if granular calcium hypochlorite is used, the crystals must first be fully dissolved in a mixing container filled with clean water. This mixture must be allowed to settle for at least one hour and then the solution must be decanted slowly so as not to allow the particulate matter to enter the well. This decanted solution can then be applied in combination with CB-4, and used as a preventative maintenance treatment.

3.3 Laser Particle Counting Results

The laser particle counting (LPC) analysis was conducted by DBI to provide some insight into the potential of the treatment processes to breakdown biological matter into particle sizes that could be removed from the aquifer matrix. The laser particle counting results on water samples obtained from Wells 15, 16 and 17 and North Saskatchewan River samples are provided in Appendix F.

This is the first time that laser particle counting data has been collected for most of these wells, and this data will be more valuable as an indicator of biofilm removal as a result of subsequent treatments. A comprehensive interpretation of the LPC data is underway by DBI, and hopefully, by the time the post monitoring phase (Phase 3) of this project has been completed, a correlation between the LPC data and water well biofouling will be derived. A brief initial summary of the results for each well are provided in Table 11.

Laser Particle Counter Analysis	Well 15			Well 16	Well 17
	Pre-Treatment	Post Treatment		Pre-Treatment	
	October 6, 1997	October 10, 1997	April 6, 1998	April 9, 1998	April 9, 1998
Mean Particle Size: (120 min. sample)	2.8 microns	5.2 microns	2.8 microns	3.4 microns	3.6 microns
Per cent greater than 8 microns (by volume): (120 min. sample)	19.4%	38.3%	60.0%	62.5%	73.3%

TABLE 11: Laser Particle Counter Analysis

Well 15: Prior to treatment in October 1997, the mean particle size obtained from Well 15 was 2.82 microns. After treatment the particle size increased to 5.21 microns, since the void spaces were opened up during treatment, allowing larger particles to migrate into the well. On April 6, 1998, six months after treatment, the mean particle size was 2.77 microns. However, 59.83% of the present day particles are in the 8-16 micron range compared to 19.44% before treatment in October 1997. This indicates that the larger void spaces opened during treatment are still allowing larger physical and biological particulate matter to migrate into the well under pumping conditions. By allowing these larger particles to enter the well, the biofouling material has been reduced or removed, thereby increasing the void space openings in the surrounding sand pack and aquifer.

Wells 16 & 17: This is the first extensive particle counting performed on these two wells, and therefore, there is no baseline data available. It is probably more useful to compare the laser particle counts (LPC) of these two wells, recognizing that Well 17 has a higher specific capacity and less biofouling than Well 16, based on microbiological testing results provided in Section 2.4. Both Wells 16 and 17 were pumped at 15.2 L/s (200 igpm) for a period of two hours to obtain a representative comparison. Well 16 had a mean particle size of 3.39 microns, compared to Well 17 with a mean size of 3.55 microns. The significance of this observation is the fact that Well 17 had 73.32% of its particulates larger than 8 microns, whereas Well 16 only had 62.49% of its particulates larger than 8 microns. This indicates that Well 17 is allowing larger particles to pass through the aquifer material and sand pack, thereby signifying larger void spaces and less restriction (biofouling) around the well.

4.0 WELL TREATMENT AND MAINTENANCE

4.1 Ultra-Acid Base (UAB™) Well Treatment Process

The Ultra-Acid Base (UAB™) treatment process was developed by DBI to treat biofouled wells. This process uses a combination of chemicals and hot water to remove the plugging biofilms from both the sand pack and aquifer material around the well. Heat (hot water) is used to facilitate the destruction of the biofilms, which then allows the treatment chemicals to more effectively penetrate the regions of severe plugging around the well intake area. During this treatment process, the water in and around the well is maintained at a temperature of at least 65°C. This elevated temperature allows the reaction rate of the chemicals to increase, which reduces the amount of chemicals required for treatment. Heat also extends the distance of the treated zone, since heat moves toward the colder zones surrounding the well. CB-4 has also proven to be an effective surfactant to facilitate the penetration of the heat and chemicals into the biofilms. When this combination of heat and chemistry was applied to the model wells (mesocosms), the biofilms were disrupted and the plugging materials were kept in suspension so that they could be more effectively dispersed. Therefore, this process is still recommended for use in the North Battleford well field. A detailed description of the UAB™ treatment process is included in an earlier report prepared for the City of North Battleford entitled, *City of North Battleford Well 15, 1997 Field Test of UAB™ Water Well Treatment Technology (PFRA, 1998).*

4.1.1 Modified UAB™ Treatment Process

Water samples The UAB™ treatment process has been slightly modified based on the results of the laboratory analysis conducted jointly by PFRA and DBI. The modified treatment process is described below and consists of three distinct phases.

The *first phase* involves a screen clean-up stage and an initial **SHOCK** phase using muriatic acid (3 – 5% by volume), CB-4 wetting agent (1% by volume) and a water solution heated to about 80°C. The amount of solution required is 1.5 times the static water column volume of the well. The purpose of this phase is to remove screen incrustations and to open up the void spaces in the adjacent sand pack that are plugged or restricted with biological slimes. This first step opens up more pathways and preheats the area around the screen. A wire brush is also lowered up and down the screen surface to help clean out the screen slots.

The *second phase* is designed to **DISRUPT** the plugging/biofouled zone. This is accomplished by inducing a pH “flip-flop”, by altering the pH from 2.5 to 10, in and around the well screen. Applying a pH shift of seven units over a very short time period can cause severe disruption of the biofilms and is lethal to most bacteria. This pH shift is obtained by first using muriatic acid (4 % by volume) to obtain a pH of 2.5, and then using sodium hypochlorite to obtain a pH of 10.0. Both steps involve using CB-4 (1% by volume), a hot water solution, surging and pumping clean. An overnight contact time will be required to dissolve iron and manganese oxides that have collected in the biofilms and encrustations.

The *third phase* is the **DISPERSE** phase. This phase is designed to facilitate the dispersion and removal of the biofilms along with the other associated plugging material from the aquifer. Removal is achieved by surging (air or mechanical), bailing (bailer or air lifting) and pumping. The main purpose of surging (re-developing) the well is to suspend the disrupted plugging material so it can be removed by air-lifting pumping. The final step is to pump the treated water from the well until the water is clear and the pH has returned to its original (ambient) levels. Regularly changing the pumping rate can also assist in causing additional detachment of plugging material and improved rehabilitation.

4.2 Potential Preventative Maintenance Procedures

Preventative maintenance (PM) procedures are presently being developed and tested by DBI. The focus is for the City of North Battleford to be able to use as much in-situ equipment as possible. This includes the use of submersible pumps with down hole check valves relocated to allow the pump to be used to lift and drop a volume of water continuously, thereby surging the well. Some of the PM procedures being considered for upcoming testing with aforementioned surging are standard bleach (6%), sodium hypochlorite (12.5%), calcium hypochlorite (65%), CB-4 (0.75%). More extensive PM procedures on problem wells may require air-lift pumping and a combination of acid, CB-4 (wetting agent), or larger concentrations of chlorine solutions. It is *absolutely* critical that accurate records be kept on the condition and operation of the well after it has been treated, and any loss in specific capacity or decreased time lag difference (TLD) using the BART™ system must be noted and the appropriate PM procedures implemented at the earliest opportunity.

5.0 CONCLUSIONS

1. Diagnostic testing in April 1998 revealed that Well 15 had experienced no decrease in specific capacity, since the UAB™ treatment was completed in October 1997. However, biofouling is still evident, since BART™ results indicate that aggressive populations of IRB and SRB are present within 6 metres of the well.

2. In April 1998, Well 16 had experienced a 43% reduction in specific capacity, since its installation in 1995. Based on the BART™ results the biological activity in the immediate vicinity of the well is highly aggressive and the well appears severely biofouled.

3. In April 1998, Well 17 had experienced no reduction in specific capacity, since its installation in 1995. However, aquifer biofouling is occurring at the Well 17 site, since BART™ results from C-90 indicate that there are highly aggressive populations of IRB and SLYM bacteria present.

4. Nitrogen and phosphorus are nutrients that are present in the City of North Battleford well field, as shown in the water analysis results in Appendix C. These nutrients are a food source for bacteria, and may be responsible for the severe biofouling experienced in Wells 15 and 16.

5. The water chemistry results from the wells indicate that, on average, iron levels in these wells are up to three times higher than the manganese levels. This indicates that iron related bacteria may predominate in the biofouled zones around the well.

6. Laboratory experimentation has resulted in improvements to the UAB™ treatment process. The laboratory results indicate that sodium hydroxide and other compounds of hydroxide should not be used as well treatment chemicals, due to their ability to swell clays.

7. Laboratory testing indicates that increasing the temperature of treatment fluids results in increased fines removal, dissolution of organics, and an overall increase in aquifer permeability.

8. Laboratory results indicate that CB-4 effectively disperses clay particles and increases the permeability of aquifer material. Tests suggest that solutions should not exceed 1% by volume in water, and that residence times in the aquifer should be less than one day, otherwise clay swelling may be a problem.

9. Permeameter and mesocosm tests with sulfamic, hydrochloric and acetic acid solutions indicate that these acids increase the permeability of aquifer material more effectively than any other chemicals tested during the laboratory studies.

10. Mesocosm tests to evaluate various chemical treatment trains on the North Battleford sands indicates that a treatment train which includes CB-4, hydrochloric acid and sodium

hypochlorite appears to be the most effective in recovering the biofouled void spaces in this aquifer material.

6.0 RECOMMENDATIONS

1. Based on the results of the laboratory studies, modifications to the UAB™ will be implemented that should improve the effectiveness of the treatment process. It is recommended that Well 15 be treated with the modified UAB™ treatment process to evaluate its effectiveness.

2. Based on the results of the diagnostics program, Well 16 is severely biofouled. It is recommended that Well 16 be treated before there is a further reduction in specific capacity.

3. Based on the results of the diagnostics program, Well 17 has not yet experienced a decline in specific capacity. However, the BART™ results indicate that biofouling is occurring at Well 17, and therefore, to prevent a decline in specific capacity in the future, it is recommended that preventative maintenance procedures (PM) be developed and implemented at the earliest opportunity.

4. The laboratory experimentation has provided guidance in improving the UAB ™ well treatment process. It is recommended that an evaluation of other acids and combinations of acid types be conducted to further evaluate and refine the treatment process.

5. It is recommended that preventative maintenance protocols be developed and implemented to prevent a decline in the specific capacity of the wells in the future.

7.0 REFERENCES

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