CHALLENGES IN SUSTAINING WATER WELL INFRASTRUCTURE ON THE CANADIAN PRAIRIES

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ABSTRACT

Through the Sustainable Water Well Initiative (SWWI), PFRA is addressing concerns of declining yield and water quality deterioration in water wells in many areas across the Canadian Prairies. Several SWWI studies have investigated the impact of microbiological activity in wells, which is a poorly understood aspect of the water well environment. These studies clearly illustrate the significance of microbiological activity on the sustainability of water well infrastructure.

Field and laboratory testing were undertaken to develop and evaluate an innovative treatment process for biofouled wells. As a result of this testing, new challenges in dealing with biofouled wells were identified. These include developing treatment methods to improve biofilm particle-size reduction, which will facilitate easier biofilm removal, and developing new methods to control biofilm growth.

RÉSUMÉ

Grâce au Projet de puits d'eau durables (PPED), l'ARAP se penche sur les problèmes liés au déclin de débit et à la déterioration de la qualité de l'eau des puits de plusieurs regions des Prairies canadiennes. Plusieurs études ont évalué l'effet de l'activité microbiologique, un aspect peu compris de l'environnement des puits d'eau. Ces études démontrent clairement l'incidence de l'activité microbiologique sur la durabilité de l'infrastructure des puits d'eau.

Des essais en laboratoire et sur le terrain en vue d'élaborer et évaluer un processus novateur pour traiter l'encrassement biologique des puits d'eau ont été entrepris. Ces essais ont découvert de nouveaux problèmes à résoudre dans le domaine du traitement de l'encrassement biologique. Ceux-ci comprennent la mise au point de traitements qui augmentent la comminution des particules des films biologiques afin d'en faciliter l'extraction, ainsi que l'élaboration de nouvelles méthodes pour réduire la croissance des films biologiques.

1. INTRODUCTION

Water wells are the primary water supply source for most rural residents on the Canadian Prairies (Coote and Gregorich, 2000). Groundwater is preferred in rural areas since it is readily available and accessible over large portions of the Prairies, and is also regarded as a water supply alternative with a marked degree of drought tolerance (Maathuis and Thorleifson, 2000). A joint study conducted by the Prairie Farm Rehabilitation Administration (PFRA) and the provincial groundwater agencies on the Prairies revealed that about 400,000 water wells have been installed across the three Prairie Provinces, since 1960 (Lebedin et al, 2000). The distribution of these wells is shown in Figure 1.

The proper operation and maintenance of rural wells is important in ensuring sustainable groundwater supplies for the agricultural sector across the Prairies. Although many rural residents are highly dependent on groundwater supplies, wells are often managed with an "install and forget" attitude. This attitude generally leads to a poor understanding of the conditions that cause many of the problems encountered in the water well environment, and when problems do arise, inappropriate remedial actions are often applied.

There are many challenges related to sustaining water well infrastructure on the Prairies. This paper does not attempt to provide an exhaustive list of all potential challenges that exist, but focuses primarily on issues that have been identified and addressed as part of SWWI activities in the Prairie region. In the following sections a brief description of SWWI will be provided, along with several challenges encountered in providing safe and reliable groundwater supplies to the rural sector on the Canadian Prairies.

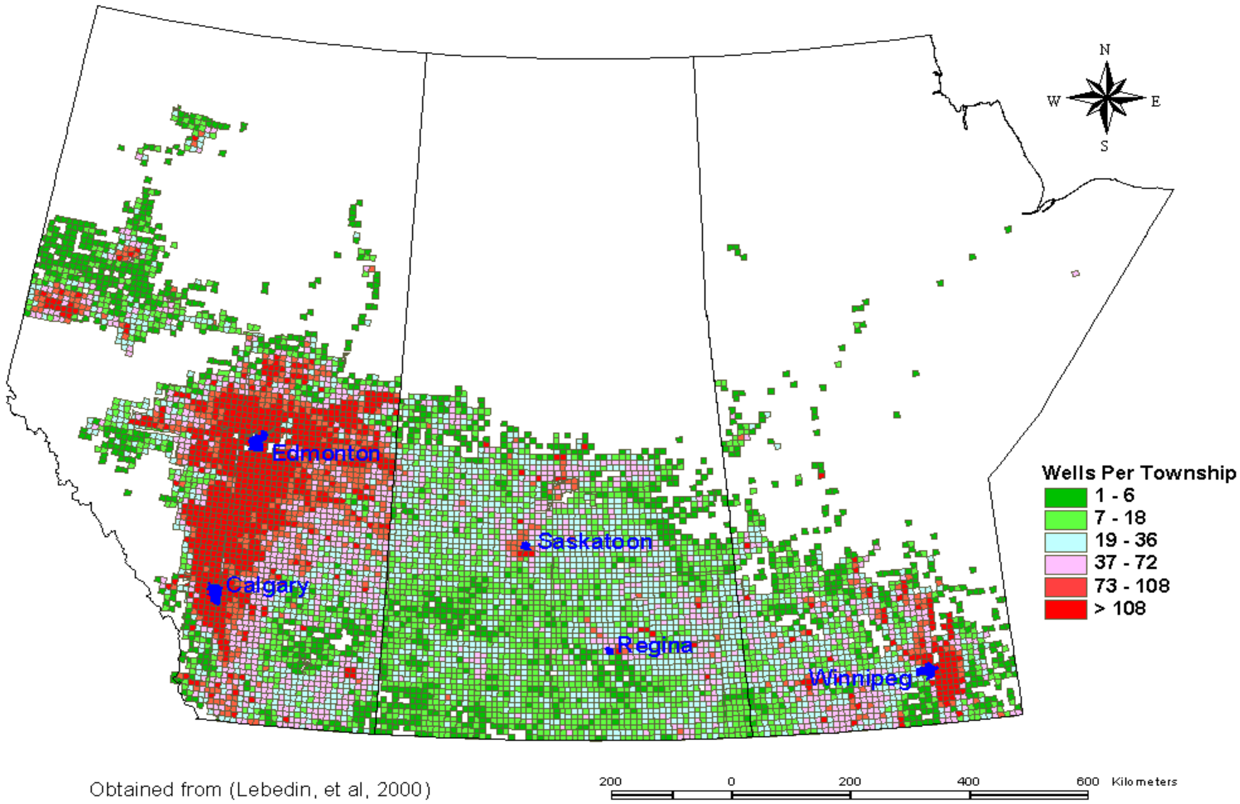

Figure 1. Total Number of Wells Per Township: 1961-1999

2. SUSTAINABLE WATER WELL INITIATIVE

The Sustainable Water Well Initiative (SWWI) was established by PFRA-Technical Service in 1996, to address concerns from rural residents who were experiencing problems with declining well yield and water quality deterioration. The goal of SWWI is to provide improved knowledge on the diagnosis, prevention and remediation of groundwater-related problems.

Initially, SWWI activities focused on the effects of microbiological activity on groundwater supplies, since the diagnosis and remediation of this aspect of water well deterioration is poorly understood. As part of SWWI, PFRA initiated several field studies to investigate the role microbiological activity plays in the deterioration of groundwater supplies. (Cullimore and Legault, 1997; Jaques and Rohde, 2001).

Field and laboratory studies were also undertaken by PFRA to develop and field test new and innovative well treatment processes (PFRA, 1999a; PFRA, 1999b; PFRA 2000; Stewart, 2000). The results of these studies can be obtained from the SWWI web site at www.agr.ca/pfra/water/swwie.htm.

3. CLIMATE CHANGE ON THE PRAIRIES

An ongoing challenge for many water supplies on the Prairies is the variation in climatic conditions. The semi-arid regions in the Prairies are particularly sensitive to climate variability and most scenarios suggest an increase in the frequency and length of droughts (Environment Canada, 1997; Byrne, 2000). This shift in climate to warmer and drier conditions will stress many surface water supply sources, and will thereby create an even greater dependence on groundwater and water-well related infrastructure.

During times of drought, “sudden” well failures are often a consequence of over-extended groundwater pumping. These failures are usually a combined effect of natural water level decline and a progressive loss in well efficiency, generally beginning from the time the well was first installed. A study conducted in the M.D. of Kneehill, Alberta, revealed that losses in well efficiency could be attributed to increased drawdown compounded by the effects of microbiological activity (PFRA, 1997). These microbiologically-induced failures arise quickly in improperly designed and poorly maintained well systems.

With this anticipated climate change to more frequent and extended periods of drier conditions, adaptive measures must be place to prevent future well failures, thereby sustaining and extending the life of water well infrastructure across the Prairies.

4. MICROBIOLOGICAL ACTIVITY IN GROUNDWATER SUPPLIES

Another challenge to sustaining water well infrastructure in the Prairies is recognizing the role microbiological activity plays in water well deterioration. Various physical and chemical aspects of water well deterioration have been extensively documented, and the necessary steps required for remedial action are generally well understood and accepted. Less understood is the effect of microbiological activity on the water well environment (Mansuy, 1999).

In the past, groundwater was viewed as being “essentially sterile” and the potential for biological events was believed to be small and, even if they occurred, were usually regarded as insignificant (Cullimore, 2000). Today, it is recognized that microorganisms are present even in the deeper aquifer units and that microbiological activity is the main contributor to many water well problems (Smith, 1995).

4.1 Water Well Biofouling

The causes, diagnosis and treatment of the effects of microbiological activity in the water well environment can be better addressed when it is understood that microorganisms attach themselves directly to surfaces in and around the well, and then proceed to modify their immediate environment. This process is termed water well biofouling, and has, only recently, been recognized as an important consideration in the design, operation and maintenance of groundwater supplies (Borch et al, 1993).

Studies conducted under SWWI, revealed that biofouling is a significant factor in the overall deterioration of the yield and water quality of rural water wells. The biofouling process alters the water well environment, as various types of microorganisms colonize the surfaces around the well intake and process groundwater constituents that flow to the well.

4.1.1 Effects of Water Well Biofouling

One of the major effects of biological activity in the water well environment is the plugging of both the well screen and the pore spaces of the surrounding aquifer material, as shown in Figure 2. This plugging generally occurs at the reduction-oxidation (redox) front, where the greatest microbial activity usually occurs (Cullimore, 1993). The redox front physically corresponds to the area where oxygen diffusing from the well into the aquifer encounters nutrients that are moving towards the well.

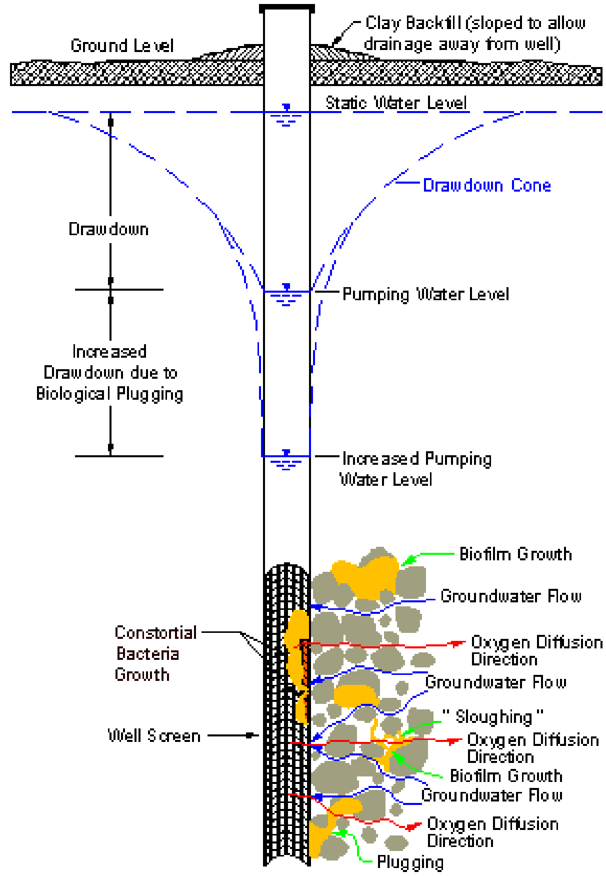

Figure 2. Effects of Biological Plugging

As bacterial colonies become established, they form a slime coating or biofilm, which provides a protective environment for the microorganisms. As water flows to the well during pumping, the biofilms begin to accumulate a considerable amount of material, which eventually causes plugging of the well intake area. These accumulates include silts, organics, nutrients and mineral deposits. Over time, these accumulations evolve from a simple bacterial slime coating to a mature biomass that contains a variety of microorganisms and “hard” incrusting mineral deposits, which then become increasingly difficult to remove.

Understanding the nature of this biomass is essential when applying appropriate treatments to a biofouled well. Most well treatments are applied at the latter stages of biomass development, since there is often no noticeable effect on the overall quality or well yield in the early stages, or some decline in yield or quality is tolerated due to the increasing age of a well.

4.1.2 Water Quality Issues in Biofouled Wells

As biofouling progresses, water quality changes may also be experienced. Elevated iron and hydrogen sulphide concentrations, water discolouration, increased turbidity, and taste and odour problems are all symptoms of active biofilm development (Smith, 1995). Also, during the natural growth of biofilms and the ongoing operation of a well, biofilms may periodically detach, temporarily affecting the water quality. This may result in sporadic changes in the taste and odour of the water, and can also cause plugging of in-house treatment equipment.

The formation and establishment of biofilms can also influence water quality testing results. Biofilms are natural filters and have the ability to collect various types of material, including a variety of microorganisms. Biofilms can filter certain constituents present in the groundwater, sometimes resulting in "false" negative readings for parameters such as coliform bacteria. Also, the consortium of microorganisms present within the biofilm could include some non-desirable microbes, which may present a health risk as portions of the biofilm periodically detach and are released into the water supply. These potentially pathogenic organisms can cause health problems in people with suppressed immune systems (Cullimore, 2000).

Since the influence of biofilm development on water quality issues is generally not considered, well owners may develop a false sense of security in the safety of their water supply. Therefore, the need for diagnostic monitoring procedures and preventative maintenance techniques is essential in dealing with problems associated with microbiological activity.

5. PREVENTATIVE MAINTENANCE TECHNIQUES AND MONITORING PROCEDURES

Ongoing monitoring and preventative maintenance are key to providing reliable groundwater supplies for the rural sector. There are many monitoring procedures and preventative maintenance techniques that can be readily implemented (Borch et al, 1993; Smith, 1995). Studies conducted by Droycon Bioconcepts Incorporated (DBI) indicate that preventative maintenance should be conducted before a well has experienced a 20% loss in specific capacity or the biological aggressivity has increased by one order of magnitude (Keevill, 2000).

5.1 Preventative Maintenance Techniques

Preventative measures must be in place to prevent or, at least, control the biofouling process, since the restoration of a severely biofouled well is extremely difficult. For water well environments that are extremely susceptible to biofouling, "shock" chlorination, or physical disruption by air-lift pumping may be used to disrupt and remove biofilms in their early stages of development.

Another possible preventative maintenance technique, being explored by PFRA, is the application of electric currents to prevent biofilm growth. Cathodic protection techniques have long been used to prevent corrosion of metal surfaces, and a similar approach may also prevent the adherence of biofouling bacteria to the surface of the well screen, and thereby, eliminate the accumulation of biofilms. To investigate this further, PFRA is constructing a large-scale well/aquifer model for experimental purposes. This physical model will simulate the biofouling process in a water well environment and experimentation will be conducted to determine if impressing an electric current on the well screen will be able to arrest biofilm development.

Laboratory experimentation by others has shown that the application of an electric current, with a sterilant used to combat biofilms, greatly increases the efficacy of the sterilization process used in hospital and industrial processes (Wellman et al, 1996). Laboratory studies conducted by DBI have also shown that the induction of an electric current, along with appropriate treatment chemicals, can successfully remove biological plugging material (Johnston, 2001).

Although only in the initial stages of experimentation, the potential for utilizing electrical currents in future preventative maintenance strategies for water wells appears promising.

5.2 Monitoring Procedures

A further challenge in sustaining and prolonging the life of rural farm wells is having the ability to easily monitor changes in the water well environment. Regular monitoring is essential if problems are to be identified early and rectified before significant deterioration occurs. Non-pumping and pumping water level measurements must be collected on a regular basis. Periodic pump testing should also be conducted to measure specific capacity, and to collect samples for water quality and microbiological activity analysis.

Monitoring for changes in biological activity is an important consideration in any preventative maintenance program. Laboratory experimentation conducted by PFRA indicates that biological activity can increase with no appreciable decrease in well performance. There are many methods that can be used to measure the level of biological activity in water wells (Smith, 1995). The method used in several SWWI studies is the Biological Activity Reaction Test (BART™). The BART™ method was used to evaluate the effectiveness of well treatments at reducing the biological activity, and to signal when further preventative maintenance or well treatments would be required. The BART™ was developed by DBI and provides a quick and easy indication of the presence and relative "aggressivity" of the biofouling bacteria present in the water well environment (DBI, 1999).

5.3 Well Design Considerations

Another challenge is to design a rural farm well that is easily accessible for monitoring and for conducting regular preventative maintenance. A "user-friendly" well would hopefully encourage regular monitoring and allow for the effective application of preventative maintenance procedures. Due to the design of the average farm well, conducting pump tests to obtain specific capacity data and to collect water samples directly from the well, is usually very difficult. To overcome this problem, a hydrant could be installed in close proximity to the well, as shown in Figure 3. This would facilitate the performance of periodic pump tests, which would provide the necessary data to forewarn of any potential problems.

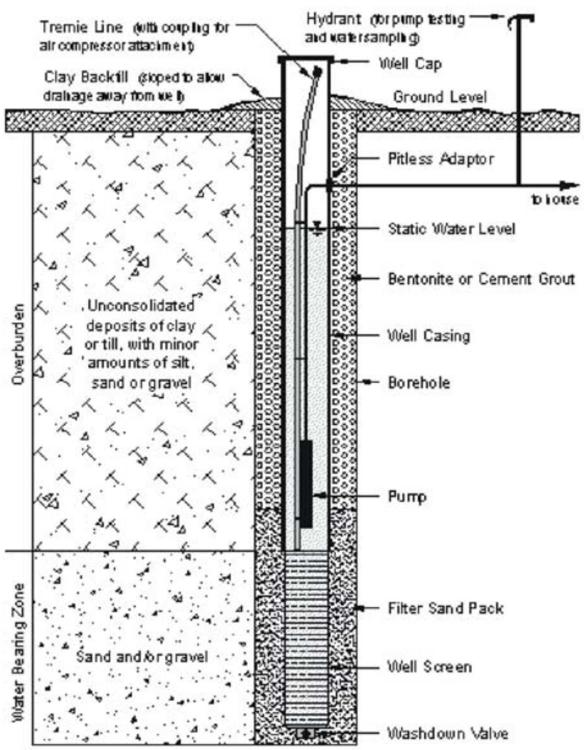

Figure 3. Well Design Considerations

Another simple design adaptation is to install a tremie line with an appropriate fitting to allow connection to an air compressor, as shown in Figure 3. Treatment chemicals can be introduced directly into the well intake area, and air-lift pumping can be conducted to disrupt and remove biofilms from the well. This tremie line could also be used to monitor water levels in the well.

6. WELL REHABILITATION

Once a well becomes severely plugged, the next challenge is to apply an appropriate treatment to restore the yield or quality of the groundwater supply. Studies conducted by DBI indicate that well treatments should be performed before a well has experienced a 40% loss in specific capacity or the biological aggressivity has increased by two orders of magnitude (Keevill, 2000). Most conventional well treatment methods use acids to remove mineral incrustations and employ "shock" chlorination techniques to treat for the presence of coliform bacteria or bacterial slime deposits. These treatments are often applied with limited knowledge on the type of problem that may actually exist, and therefore, the treatment process is sometimes ineffective or produces marginal results.

For biofouled wells, the treatment must penetrate and disperse the biofilms, before an acid can effectively dissolve any mineral deposits or a disinfectant can traumatize any bacteria present. Although there are many commercially-available treatment products designed to rehabilitate biofouled wells, not much documentation is available on the effectiveness of these treatments for water wells on the Canadian Prairies.

6.1 Evaluation of Well Treatments

To better understand the effectiveness of well treatments, PFRA has established laboratory methods to evaluate the effect of commonly-used treatment chemicals on the permeability of biofouled aquifer material (Stewart, 2000). Also, through a joint-venture arrangement between PFRA and Droycon Bioconcepts Incorporated (DBI), a new and innovative treatment process for biofouled wells, known as the Ultra Acid Base (UAB™), was developed (PFRA and DBI, 1997). DBI had previously been involved in the successful development of the Blended Chemical Heat Treatment (BCHT™), which had been applied to biofouled wells in the United States under the sponsorship of the U.S. Army Corp of Engineers (Keevill, 1997).

6.1.1 Ultra Acid Base™ Treatment Process

The Ultra Acid Base (UAB™) treatment process is unique in that it utilizes heat in its chemical applications (Keevill, 1998). This treatment method involves the application of heated water and treatment chemicals to more effectively penetrate and disrupt the biomass. The chemical solutions are heated to about 80 ^{0}C before being introduced into the well and are then maintained at about 65 ^{0}C in the well.

Heat increases the effectiveness of the treatment chemicals, and therefore, lower chemical concentrations are required. The heated chemical solution also moves into the cooler surrounding groundwater by convective flow, thereby moving further into the aquifer than traditional chemical applications (Alford and Cullimore, 1999). This was observed during the field testing of the UAB™ treatment process, where temperatures of 20 ^{0}C were measured in piezometers located about 3 metres from the well. Heat is also effective at traumatizing the bacteria, making them more vulnerable to treatment and removal.

A non-phoshate based surfactant is used in the chemical application phases of the UAB™ process. The surfactant penetrates and disrupts the biofilms, increasing the effectiveness of the treatment chemicals. During the chemical applications, a pH shift of 7 units is obtained in the well by raising the pH to 9 in the first phase of treatment and then lowering the pH to 2 in the subsequent phase. This dramatic shift in pH, over a very short time period causes severe disruption of the biofilms and is lethal to most bacteria. Upon completion of the chemical applications the dispersed biofilms and other plugging material are removed by conventional well redevelopment techniques.

6.1.2 Ultra Acid Base™ Treatment Results

The UAB™ treatment technology was jointly field tested and evaluated by PFRA and DBI. The treatment process was first applied to rural farm wells in M.D. of Kneehill, Alberta, with specific capacity improvements ranging from 38 to 170 per cent (PFRA, 1999b). For these wells, the original specific capacity was not known, so the absolute effectiveness of the treatment could not be determined.

Further testing of the UAB™ treatment process was conducted at two municipal test sites, where the specific capacities had declined to 10 and 15% of original. After treating these biofouled wells, the specific capacities improved to 20 and 40% of original, respectively (PFRA and DBI, 1998; PFRA 1999a). At two other municipal test sites, where specific capacity declines of 30-40% were reported, the treatment process was able to restore the specific capacity of these wells to near original levels (PFRA, 2000). Although the UAB™ treatment was extremely effective, at these latter two sites, the wells reverted back to their pre-treatment state within a year of treatment. Severe biofouling is suspected at these sites, and it appears that a single treatment is unable to completely breakdown and remove the accumulated biomass.

In the case of the well shown in Figure 4, successive treatments have become progressively less effective at removing the biomass that has become established around well. The projected specific capacity trendline indicates that even with annual treatments, the specific capacity may soon fall below 50% of original.

One possible explanation for the incomplete recovery in specific capacity, is the inability of the treatment process to effectively penetrate and disrupt the entire area of biological plugging. During the treatment process, the volume of chemical solutions introduced into the well should be able to treat an effective radius of 0.3-0.6 metre

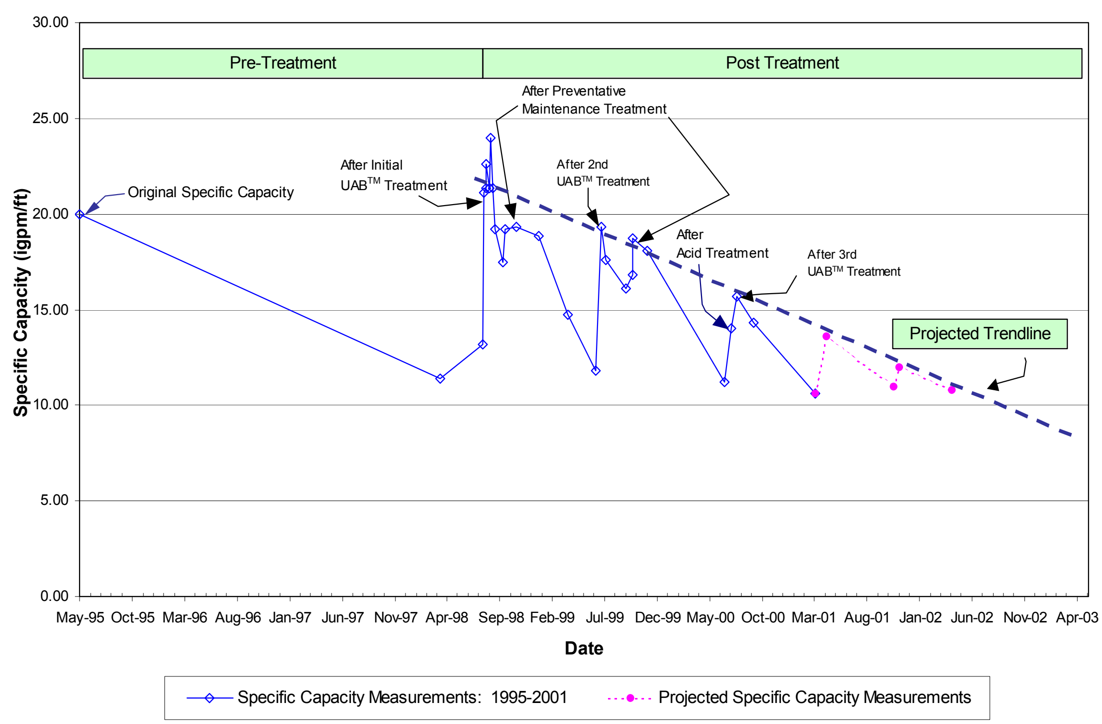

Figure 4. Projected Specific Capacity Measurements

around the well intake area. Beyond this radius, the treatment chemicals would be less effective on any plugging material. Also, the biofilms located at the edge of the treatment radius may be forced further into the aquifer and would be more difficult to reach after successive treatments, resulting in a decreasing recovery of the specific capacity.

Another possible explanation is that there was incomplete breakdown and removal of the biofilms. The treatment process may have been unable to reduce the biofilms to sizes that could be easily mobilized through the pore spaces of the aquifer material. Therefore, increased residency times for the treatment chemicals may be required to reduce the biofilms to particle sizes that can be more effectively removed.

Clearly, these field test results indicate that there are still numerous challenges that need to be overcome in dealing with the treatment of biofouled wells.

7. CONCLUSIONS

The various field and laboratory studies conducted under SWWI were primarily directed at identifying and addressing the microbiological challenges on water well infrastructure on the Prairies. These studies were able to provide a better understanding of issues related to biofouling, and led to the development of innovative treatment and preventative maintenance techniques. However, in this process, many new challenges arose in effectively dealing with water well biofouling.

Laboratory and field testing, conducted by both PFRA and DBI, have shown that severely biofouled wells are difficult to restore to their original state. This stresses the need to develop and implement preventative maintenance techniques that are effective at controlling biofilm development.

Studies have indicated that preventative maintenance should be performed before a well has experienced a 20% loss in specific capacity or the biological aggressivity has increased by one order of magnitude. Also, well treatments should be performed before a well has experienced a 40% loss in specific capacity or the biological aggressivity has increased by two orders of magnitude.

Additional research is necessary to better understand the particle-size reduction required to mobilize the biofilm through the pore spaces of the aquifer material, as part of a well treatment process. As well, further research is required to determine the required residency times for treatment chemicals in the aquifer to effectively reduce the biofilms to particle sizes that can be mobilized and removed.

Regular monitoring is a key element in forewarning of any potential water well problems. Rural well owners need to be instructed on appropriate well designs prior to construction, so that the required data can be collected and preventative measures implemented in an efficient and timely manner. Cooperation between various sectors of the groundwater industry and water well users will be required to develop a cost-effective "user-friendly" well.

To face the many challenges identified in this paper, as well as other issues related to preserving and extending the life of water well infrastructure on the Prairies, continued collaboration between government agencies, the groundwater industry, educational institutions, researchers and water well users is required.

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REFERENCES

Alford, G., and R. Cullimore, 1999. The Application of Heat and Chemicals in the Control of Biofouling Events in Wells. The Sustainable Well Series; Series Editior: R. Cullimore. Lewis Publishers, Boca Raton, Florida.

Borch, M.A., S.A. Smith, and L.N. Noble, 1993. Evaluation and Restoration of Water Supply Wells. American Water Works Association Research Foundation. Denver, Colorado.

Byrne, J.M., 2000. Climate Variability/Change Issues for the Canadian Prairies and Beyond. Proceedings from the 12th Annual Meeting, Conference and Trade Show of the Saskatchewan Soil Conservation Association, Regina, Saskatchewan.

Coote, D.R., and L.J. Gregorich (editors), 2000. The Health Of Our Water – Toward sustainable agriculture in Canada. Research Planning and Coordination Directorate, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ontario.

Cullimore, D.R., 1993. Practical Manual of Groundwater Microbiology. Lewis Publishers, Chelsea, Michigan.

Cullimore, R., 2000. Microbiology of Well Biofouling. The Sustainable Well Series; Series Editior: D. R. Cullimore. Lewis Publishers, Boca Raton, Florida.

Cullimore, D.R., and T. Legault, 1997. Microbiological Investigations of Water Wells In The Municipal District Of Kneehill, Alberta. Droycon Bioconcepts Incorporated, Regina, Saskatchewan.

DBI, 1999. Biological Activity Reaction Test (BART ™) User Manual. Droycon Bioconcepts Incorporated, Regina, Saskatchewan.

Environment Canada, 1997. The Canada Country Study, Volume 3: Responding to Global Climate Change in the Prairies. Ottawa, Ontario

Johnston, L.A., 2001. Investigation and Sustainable Management of Microbially Induced Biofouling in Porous Media using Electro-Motive Forces. Master of Science Thesis in Enivronment and Management, Royal Roads University, Victoria, British Columbia.

Jaques, D., and H. Rohde, 2001. Rural Municipality of Mount Hope # 279 – Water Well Inventory And Microbiological Activity Assessment. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Adminstration, Earth Sciences Unit, Regina, Saskatchewan.

Keevill, B., 1997. Implementation of the BCHT™ (Blended Chemical Heat Treatment) Process to Rehabilitate Clogged/Biofouled Groundwater Wells. Fourth Year Engineering Thesis, University of Regina, Saskatchewan.

Keevill, B., 1998. Implementation of the UAB™ (Ultra Acid-Base) Process to Rehabilitate Biofouled Water Well #15 for the City of North Battleford (A Pilot Project) Droycon Bioconcepts Incorporated, Regina, Saskatchewan.

Keevill, B., 2000. Sustainable Groundwater Well Initiative – Development of an effective treatment and preventative maintenance technology for biofouled groundwater wells. Master of Science Thesis, Royal Roads University, Victoria, British Columbia.

Lebedin, J., H. Rohde, D. Jaques, M. Hammer, 2000. Rural Water Well Infrastructure Assessment On The Prairies: An Overview of Groundwater Development and Reliance Trends. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit, Regina, Saskatchewan.

Maathuis, H. (SRC), and L. H. Thorleifson (GSC), 2000. Potential Impact of Climate Change on Prairie Groundwater Supplies: Review of Current Knowledge. SRC Publication No. 11304-2E00. Saskatchewan Research Council, Saskatoon, Saskatchewan.

Mansuy, N., 1999. Water Well Rehabilitation: A Guide to Understanding Well Problems and Solutions. The Sustainable Well Series, Series Editior , D. R. Cullimore. Lewis Publishers, Boca Raton, Florida.

PFRA, 1997. Groundwater and Water Wells in the Municpal District of Kneehill, Alberta. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit, Regina, Saskatchewan.

PFRA, 1999a. Town of Qu'Appelle Well Treatment Evaluation Project. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit, Regina, Saskatchewan.

PFRA, 1999b. Field Testing of Ultra Acid-Base (UAB™) Water Well Treatment Technology in the Municipal District of Kneehill, Alberta. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit, Regina, Saskatchewan.

PFRA, 2000. City of North Battleford Well Rehabilitation Project – Summary Report. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit, Regina, Saskatchewan.

PFRA and DBI, 1997. Development of Ultra Acid-Base (UAB™) Water Well Treatment Technology. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit and Droycon Bioconcepts Incorporated, Regina, Saskatchewan.

PFRA and DBI, 1998. City of North Battleford Well 15, 1997 Field Test of UAB™ Water Well Treatment Technology. Agriculture and Agri-Food Canada, Prairie Farm Rehabilitation Administration, Earth Sciences Unit and Droycon Bioconcepts Incorporated, Regina, Saskatchewan.

Smith, S.A., 1995. Monitoring and Remediation Wells: Problem Prevention, Maintenance and Rehabilitation. Lewis Publishers, Boca Raton, Florida.

Stewart, B., 2000. Common Well-Aquifer Maintenance Chemicals And Their Influence On Aquifer Permeability – A Laboratory Assessment. Proceedings of the 1st Joint CGS-IAH Conference, Montreal, Quebec.

Wellman, N., S. M. Fortun and B.R. McLeod, 1996. Bacterial Biofilms and the Bioelectric Effect. Montana State University, Bozeman, Montana.