OBSERVATIONS ON IMPRESSED CURRENT SYSTEMS TO MITIGATE WATER WELL BIOFOULING

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ABSTRACT
Studies have been initiated by PFRA to investigate a nonchemical treatment process for biofouled water wells. An experimental process that mitigates the clogging effects of biofilm by exposing the biofilm to an applied electrical field is being evaluated. Laboratory model studies show the clogging effect of the biofilm can be mitigated on the surface of a well screen and in the surrounding porous media. Field studies have shown promise and warrant further study.

RÉSUMÉ
L'Administration du rétablissement agricole des Prairies a entrepris une étude visant à mettre au point un processus de traitement non chimique des puits d'eau ayant subi un encrassement biologique. On évalue présentement un processus expérimental qui atténue l'effet d'obstruction du film biologique présent dans les puits en exposant ce dernier à un champ électrique. Les essais effectués en laboratoire montrent qu'il est possible d'atténuer cet effet d'obstruction du film biologique à la surface du filtre pour puits et dans le milieux poreux environnant. Les études réalisées sur le terrain sont prometteuses; leurs résultats indiquent qu'il faut pousser plus loin.

1. INTRODUCTION

Since 1996, PFRA, through its Sustainable Water Well Initiative, has undertaken several studies to better understand the effects of microbiological activity in the water well environment. These studies have shown that microbiological activity in the water well environment can lead to bio clogging of the well screen and surrounding porous media with biofilm, resulting in a decline in well yield and water quality. Donlan (2002) describes biofilm as an assemblage of microbial cells irreversibly associated with a surface and enclosed in a matrix of extracellular polymeric substances (EPS) produced by the bacteria that consists primarily of polysaccharide. Biofilm is commonly referred to as bacterial slime. Well yield can be further reduced as the biofilm traps soil particles and mineralization occurs over time. Generally, a bio clogged water well is treated with conventional chemical treatment processes and physical agitation of the biofilm by using a surge block or by airlift pumping. Although, chemical treatments and physical methods are sometimes effective, the results are often variable and short lived (Lebedin, pers. comm., 2004).

During the last three years, PFRA has investigated a nonchemical treatment process that exposes the biofilm to an applied electrical field. These studies revealed that the clogging effects of biofilm were mitigated in laboratory-scale experiments by more than 90% and to a lesser extent in field test sites. (Globa and Rohde, 2003). An impressed current system, similar in concept to cathodic protection systems for controlling corrosion of underground structures, is being used to apply a direct current from strategically located anodes onto a well screen (cathode). Preliminary laboratory studies have shown that the clogging effect of the biofilm exposed to the direct current field is mitigated on the surface of the well screen, as well as the surrounding porous media.

This process has been shown to be less effective in field trials since none of the systems discussed herein are optimized for anode location and current densities when compared to laboratory test models. The current density is defined as the magnitude of the current flowing to the surface of the well screen. Anodes need to be strategically located to ensure most of the current is directed towards to the biofouled well intake area. Nonetheless, early field observations have shown that the process can measurably increase the specific capacity of the wells, or maintain well efficiency, based on their previous operating history.

This paper will present additional test results and observations from the original work carried out on a model well and two field trial sites. (Globa and Rohde, 2003), along with some new studies completed on a flow-through model cell constructed for confocal laser scanning microscopy (CLSM) studies.

2. OBSERVATIONS FROM LABORATORY MODEL STUDIES

Laboratory studies were performed to determine the effects of an applied electrical field on biofouled porous media using two conceptually different models: a model well and a flow-through model cell. Operation and test results are described below.

2.1 Model Well

A model well constructed to demonstrate the effect of exposing a bio clogged porous media to an applied electrical field is shown in Figure 1. The construction, operation and bio clogging of the model well have previously been described (Globa and Rohde, 2003). Head losses that developed during pumping operations were monitored with nine strategically located piezometers. Three of these piezometer locations (B1, B2 and B3) are shown in Figure 1. Piezometers B1, B2

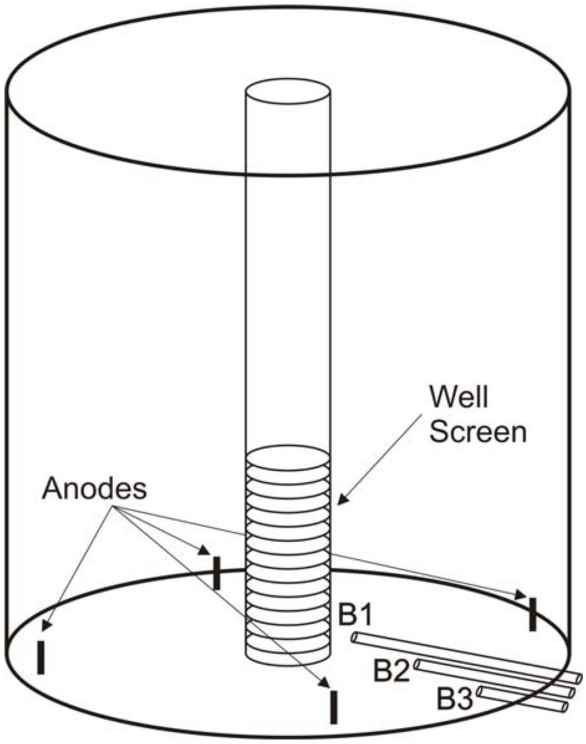

Figure 1. Model well design

and B3 were positioned 25 mm, 116 mm and 207 mm respectively from the well screen. Four high-silicone pencil anodes are positioned on the inner surface of the model well, in-line with a 75 mm diameter well screen, at the point where the screen is exposed. The upper portion of the well screen is electrically insulated with a neoprene sleeve to ensure that current flow is targeted onto a defined surface area of the screen. Basic monitoring procedure consisted of reading piezometers on a weekly basis during pump tests, at pumping rates between 0.5 to 3.0 l/min., in 0.5 l/min. increments. The model well was inoculated with slime producing bacteria obtained from a bio clogged water well.

2.1.1 Observations from Model Well Testing

Test results and events recorded over a 1016-day test period are shown in Figure 2. Biofilm development began on Day 32, which represents pre biofouled drawdown levels recorded by the piezometers at the time nutrient feeding began. On Day 131, anodes were energized when the model was judged to be sufficiently bio clogged. The DC voltage and current levels were set at 5 volts and 0.5 amperes. Observations show that the drawdown (head loss) incurred by the biofilm development in the model decreased by about 95% over a 65 day period, when compared to the pre biofouled drawdown levels. Thereafter, head losses began to increase significantly, with periods of fluctuating head loss, until nutrient feeding was stopped. Upon termination of nutrient feeding, the head losses began to decrease significantly. The nutrient feed used in the model well is specially formulated to encourage a rapid increase in EPS and is not representative of a typical water well environment. On Day 350, the anodes were de energized and observations showed that head losses slowly started to increase again. On Day 512, nutrient feeding was reestablished to biofoul the model well for a repeat demonstration. A pumping rate of 0.5 l/min could not be sustained after Day 648 due to severe head losses incurred by biofilm development. Anodes were then reenergized using the previous voltage and current settings. Observations show that the drawdown incurred by biofilm development in the model decreased by about 91% over the next 110 days, compared to the pre biofouled drawdown level observed on Day 32. Nutrient feeding was stopped on Day 862 and testing will continue until the anodes are depleted.

Details of the model well's circulation system are not shown in Figure 1. However, water was pumped from inside the well screen and recirculated under pressure back through a circulation ring located on the inside circumference at base of the model well. Nutrients were also added through this circulation ring. The drawdown levels recorded by piezometers B1, B2, B3 and inside the well screen are shown in Figure 2. These drawdown levels suggest that the zone of bio clogging did not extend significantly more than 100 mm from the well screen surface. Piezometers B2 and B3 indicate that little bio clogging occurred beyond piezometer B2 even though a rich nutrient supply was available for production of EPS by slime forming bacteria. Discharge of a positive current from the anodes would result in a flow of electrons to the well screen surface resulting in a reductive or anaerobic environment near the surface of the well screen based on anticipated redox reactions. As discussed later in Section 3.2, BART^{TM} (Biological Activity Reaction Test) testing at Well 17 showed the bacterial consortium in the region of the well screen had changed from aerobic to anaerobic, which indicated development of a reductive environment.

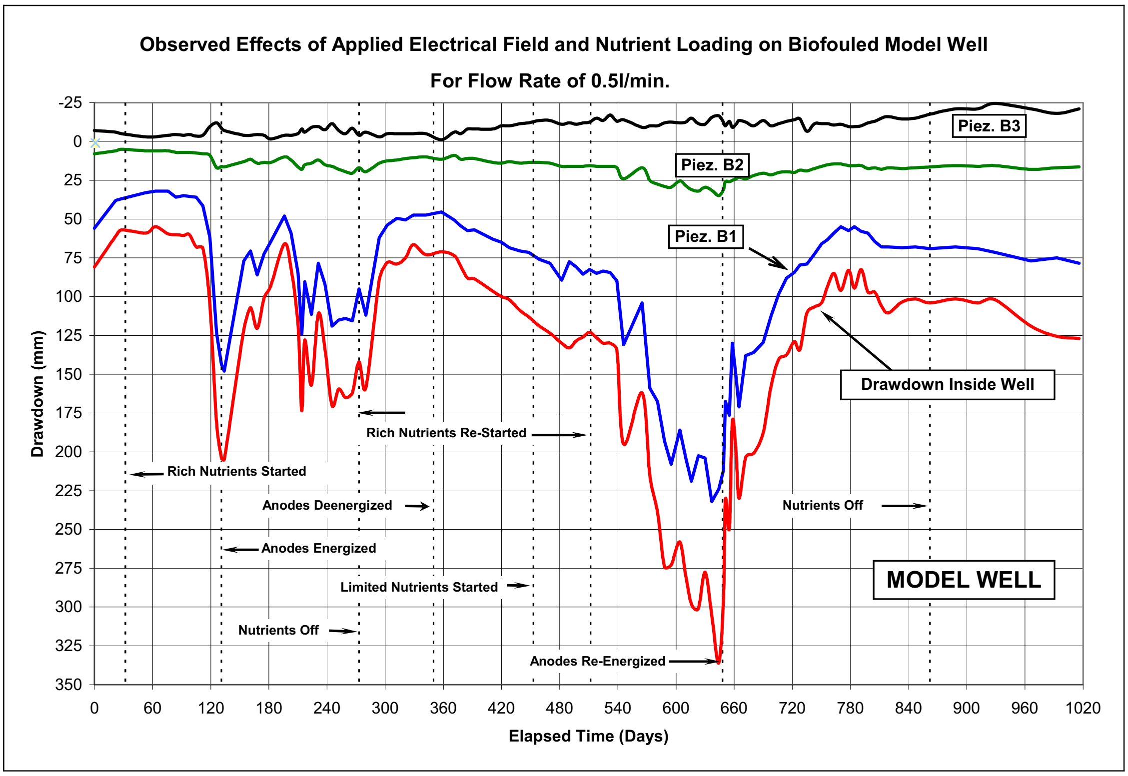

Figure 2. Model Well Test Data

2.2 Flow-Through Model Cell

A flow-through model cell, shown in Figure 3, was constructed to examine biofilm exposed to an electrical field with a confocal laser scanning microscope. Fluorescein (0.1%) was added to allow visualization of the biofilm material and porous media by negative staining. The cell consisted of an electrified channel equipped with an anode and cathode in the upper part of the model, along with a non electrified control channel. Raw river water flowed through both channels under gravity flow and drained out at the cathode end without recirculation. Both channels were filled with fine-grained filter sand. Differential head losses were monitored with pressure transducers located at either end of the two channels.

2.2.1 Observations From Flow-Through Model Cell

The test results and events recorded over a 6.6-day period are shown in Figure 4. Initially, raw river water was passed through both channels for the first 3 days, with some head loss development. It is expected that the river water contained sufficient bacteria and nutrient for initial EPS development. A slime-forming bacterium (Klebsiella oxytoca) was then added to the river water feed at the start of Day 3, which resulted in the increased head loss observed on Day 4. A nutrient medium was then added on Day 4.4 to encourage more rapid biofilm development, which dramatically increased head loss over the next 10 hours (Day 4.8). The anode was then energized and the current output was incremented by increasing the power supply voltage output from 2.5 to 5 volts near Day 5.5.

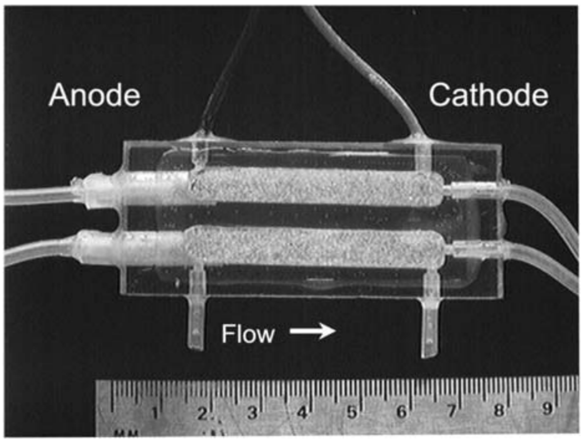

Figure 3. Flow-Through Cell Model

The head loss incurred by biofilm development dissipated completely within the next 3 hours in the electrified channel when compared to the control

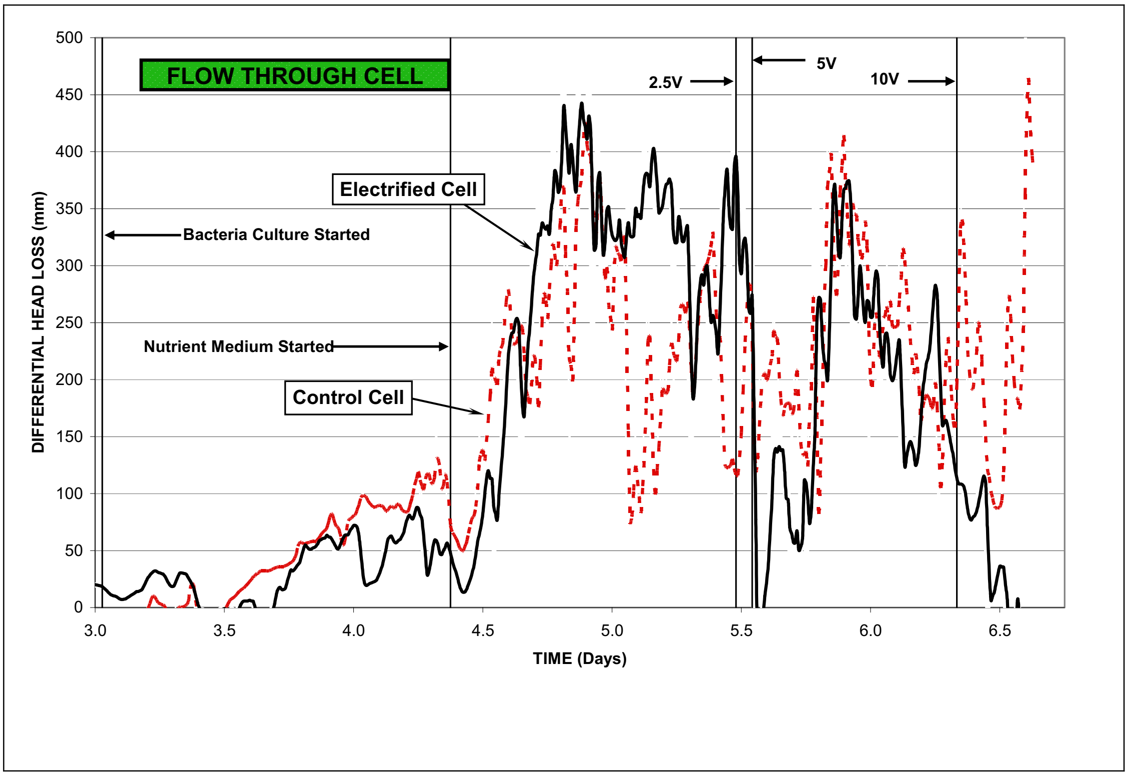

Figure 4. Flow Through Cell Test Data

channel. About 9 hours later (Day 5.9), the head loss again dramatically increased in both channels, even though the current was still flowing through the electrified cell. The current was then increased to about 50 milliamperes by incrementing the power supply to 10 volts. The head loss dissipated completely in the electrified channel about 3 hours later (Day 6.45), but increased dramatically in the control channel. The test was terminated on Day 6.6.

Testing showed that the applied electrical field had a very positive effect on mitigating the clogging effects of the biofilm when compared to the head loss observations in the control channel. However, it was difficult to explain the occasionally oscillating head losses observed in both channels, until the CLSM images were studied.

2.2.2 Observations from Confocal Laser Scanning Microscopy Studies

CLSM images were obtained throughout the test to observe biofilm development and the effect of an applied electrical field on the biofilm. A series of time elapsed images showed free floating masses of biofilm and also biofilm tightly adhered to sand grains before and after the application of current in the electrified channel. Images obtained near the cathode showed the free floating biofilm plugging pore space between sand grains which likely accounted for the transient head loss increases observed at various times through out the test. Images later on showed biofilm in the pore spaces being released over a short period of time as the current was applied and then incremented. There were insufficient observations to determine if the electrical field resulted in a measurable reduction of the tightly adhering biofilm on the sand grains. Figure 5 shows CLSM images of biofilm reduction in the pore space between two negatively stained sand grains shown in the upper left and right corners of both images over an elapsed time of 350 minutes. The image on the right also shows residual attached biofilm.

Figure 4 shows that differential head loss frequently fluctuated widely in both the electrified and control channels. The CLSM images suggest these fluctuations were likely the result of free floating biofilm temporarily clogging pore spaces near the cathode end of both channels that were totally released in the electrified channel. However, unlike the electrified channel, Figure 4 suggests a permanent minimum residual head loss, in the order of 100 mm, developed in the control channel.

3. OBSERVATIONS FROM FIELD WELL TESTS

Two biofouled wells were selected to demonstrate the applicability of the laboratory process developed to

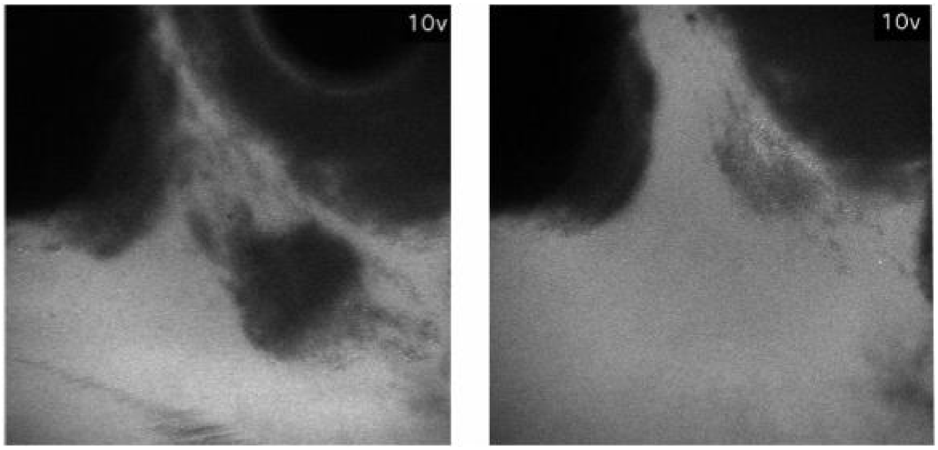

Figure 5. Confocal Laser Scanning Microscopy Images

mitigate the clogging effects of biofilm. The history, background and preliminary performance of impressed current systems installed at these wells were previously presented (Globa and Rohde, 2003). The systems at both wells were installed to demonstrate the process in the field. However, the systems did not have the current capacity to have a greater effect on mitigating the biofilm as demonstrated under laboratory conditions.

3.1 Town of Qu'Appelle Well 4

Well 4, owned by the Town of Qu'Appelle, is located approximately 40 km east of Regina, Saskatchewan and was put into operation in 1981. This well had an original specific capacity of 22.4 imperial gallons per minute per foot of drawdown (igpm/ft) that deteriorated to 4.4 igpm/ft by February 2002. BART^{TM} tests indicated the presence of highly aggressive slime forming bacteria and the well was deemed severely biofouled. Also, during the first five minutes of each pump test, the water had a greenish-black discharge and a hydrogen sulphide odour. This was only observed when the well was off line for 24 hours to allow the static water level to stabilize prior to each pump test. An impressed current system with a maximum DC output of 100 volts and 14 amperes was installed and energized in May 2002, in order to generate the applied electrical field. The current was slowly incremented until a maximum current output was obtained in September 2002. At that time, new anodes were installed and placed closer to the well screen that resulted in a 100% improvement in the specific capacity within a week.

Figure 6 shows the specific capacity and static groundwater levels from July 2000 to the end of April 2004. Normally, specific capacity is dependent on the saturated thickness in an unconfined aquifer, which is the case at Well 4. However, test data for Well 4 suggests that the specific capacity was relatively insensitive to changes in the static water level. In May 2002, an impressed current system was installed and energized, and between May and November 2002, a 14% gain in the specific capacity was observed. By April 2004, a 22% gain in the specific capacity had occurred compared to May 2002. This test data not only suggests that the applied electrical field improved the specific capacity of Well 4, but also implies that the improvement to date has been sustainable without the need for any additional chemical treatments.

3.2 City of North Battleford Well 17

Well 17, owned by the City of North Battleford, is located approximately 400 km northwest of Regina, Saskatchewan and was put into operation in 1995. Figure 7 shows that the original specific capacity of the well was 20 igpm/ft, and by July 1999 the specific capacity had dropped to 13.7 igpm/ft. BART^{TM} tests indicated the presence of highly aggressive slime forming bacteria and the well was deemed to be biofouled. As a result, a number of chemical and physical treatments were carried out by the City to restore the capacity of the well between 1999 and 2001. However, by June 2001, the specific capacity had fallen to 10 igpm/ft. Traditional treatments were effective in restoring some of the lost capacity but were very limited in duration. In January 2003, an impressed current system with a maximum DC output of 100 volts and 14 amperes was installed and energized. In the first month of operation, BART^{TM} tests showed the bacterial consortium had changed from aerobic to anaerobic indicating that a reductive environment had developed.

During the operation of the impressed current system, specific capacity and static water levels were closely monitored from January 2003 to end of April 2004. Although there was no significant gain or loss in specific capacity, pump tests suggested an improvement trend was starting to develop in the fall of 2003 reaching a peak in December 2003 during a period of decreasing

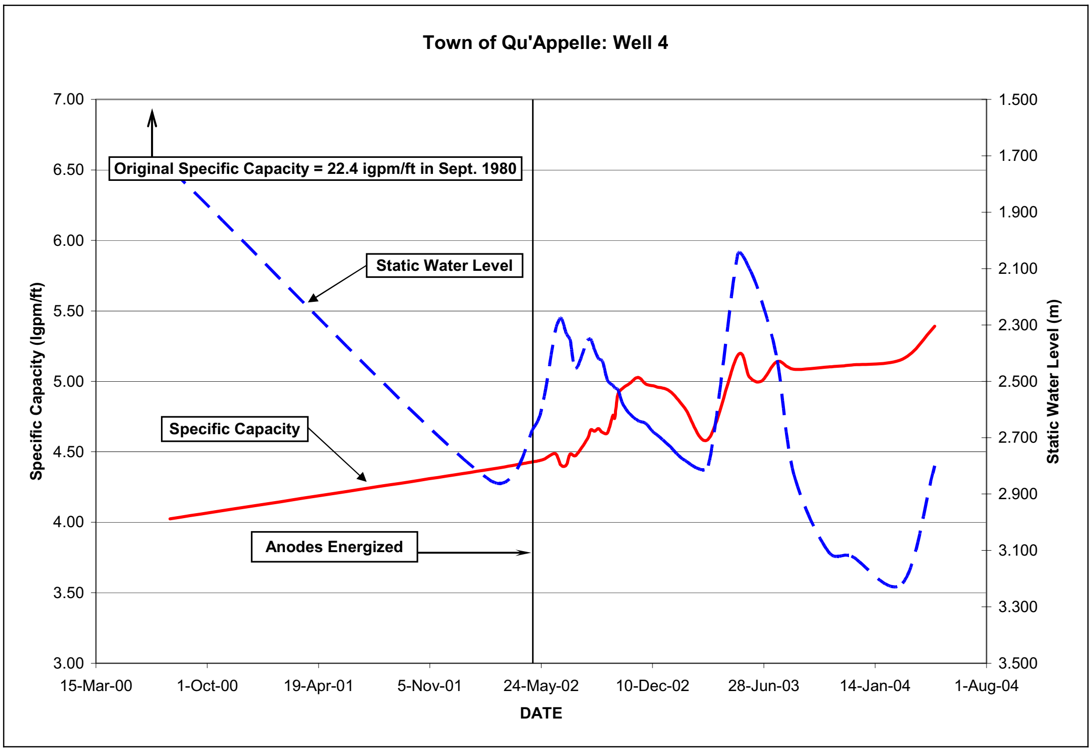

Figure 6. Specific Capacity and Groundwater Levels for Well 4

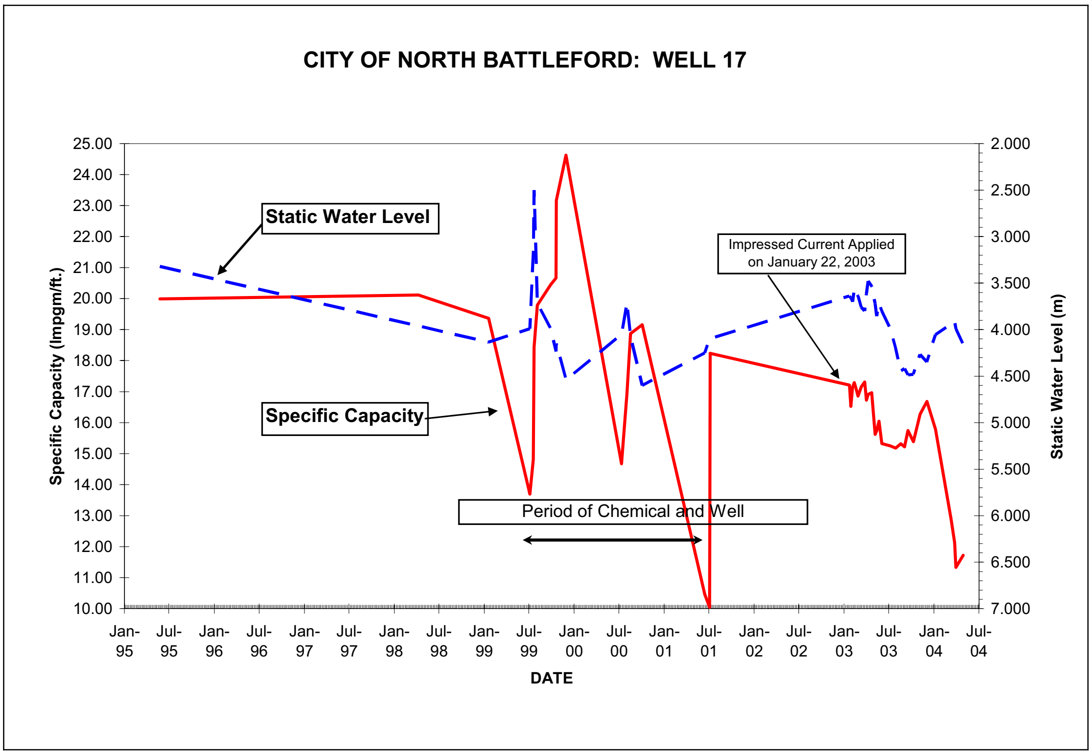

Figure 7. Specific Capacity and Groundwater Levels for Well 17

groundwater levels. Due to inclement weather, the next pump test could not be performed until March 2004, which revealed that the specific capacity had decreased dramatically. Well 17 is part of a battery of seven wells operated by the City. Pump tests performed on the remaining wells showed that all wells, except for one, had experienced a similar decline. This event was not anticipated. The cause of the overall decline in the wells is uncertain at this time and is being investigated by the City. Meanwhile, Well 17 is being closely monitored.

4. CONCLUSIONS

Laboratory model studies have successfully demonstrated that clogging effects of EPS can be mitigated significantly with an applied electrical field using an impressed current system. The process appears time dependent for a given magnitude of current and can be enhanced at higher current densities as demonstrated by the flow-through cell model where the magnitude of current was incremented with time. The CLSM studies in conjunction with differential head loss measurements showed EPS in clogged pore spaces being removed under the effects of the impressed current over a short period of time. However, this also resulted in the migration of biofilm masses through pore throats resulting in additional transient plugging events. The effect of the impressed current systems, being observed at Well 4 and 17, has not been as dramatic as demonstrated in the laboratory. Nonetheless, the results are still promising, particularly at Well 4. It is thought that the process could be improved considerably in the field by increasing the current density on the well screen. Projects are underway to determine optimum current densities and strategic anode placement for use in the field. Model well studies suggest the biofouled zone only extends a short distance into the porous media, but still has a dramatic impact on the well's efficiency.

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