APPLICATION OF IMPRESSED CURRENT SYSTEMS TO MITIGATE WATER WELL BIOFOULING

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ABSTRACT: Studies conducted by the Prairie Farm Rehabilitation Administration (PFRA) on the Canadian Prairies have shown that biofouling can reduce well yields and cause deterioration in water quality. Traditionally, chemical treatments have been used to mitigate the effects of water well biofouling, with variable results. A new and innovative method is now being investigated by PFRA, which exposes a biofouled aquifer environment to an applied electrical field. The application of this method has been successfully demonstrated in both the laboratory and in the field, demonstrating that an improvement in the specific capacity of a biofouled well can be achieved. However, further study is still required to determine the limitations and sustainability of this method.

RÉSUMÉ: Des études menées par l'Administration du rétablissement agricole des Prairies (ARAP) dans les Prairies canadiennes ont révélé que le bio-encrassement peut réduire le rendement des puits et détériorer la qualité de l'eau. Traditionnellement, on a eu recours à des méthodes de traitement chimique pour atténuer les effets du bio-encrassement des puits d'eau, avec plus ou moins de succès. L'ARAP se penche actuellement sur une nouvelle méthode innovatrice qui expose la natte aquifère bio-encrassée à un champ électrique appliqué. Cette méthode a été testée avec succès en laboratoire et sur le terrain. Au cours de la mise à l'essai, on a relevé une amélioration de la capacité spécifique d'un puits bio-encrassé. Cependant, d'autres études sont nécessaires pour déterminer les limites et la viabilité de cette méthode.

1. INTRODUCTION

A new and innovative method to mitigate the effects of biofouling on water wells is being investigated. The method consists of exposing a biofouled aquifer environment to an applied electrical field using an impressed current system. This system is physically similar to an impressed current system used for cathodic protection of steel structures. An anode is electrically coupled to the well screen or steel well casing, establishing an electrical field in the biofouled porous media around the well. The application of this method has been successfully tested in both the laboratory and in the field, demonstrating that an improvement in the specific capacity of a biofouled well can be achieved. Test results from a model well and two biofouled water wells are presented in this paper.

Characklis and Marshall (1990) describe the process of biofouling in an aqueous environment. Biofouling is a complex process that begins with preconditioning of a surface with organic molecules. A fraction of the planktonic (free floating) bacteria will adsorb into the conditioned surface layer and then will desorb (reversible adsorption). Some of the cells that remain may permanently adhere and become irreversibly adsorbed. These cells begin to grow, increase in number and migrate to produce secondary colonies.

Biofouling is associated with the development of biofilm, which consists of a diverse community of microbial cells embedded in a matrix of extracellular polymeric substances (EPS) or polymeric sugars produced by bacteria. These polymers appear as a highly hydrated capsule attached to the bacterial cell surface or as viscous, soluble slime (Characklis and Marshall, 1990). Some polysaccharides have the ability to hydrate water and further restrict the flow of free water in an aquifer by reducing the permeability of the porous media. The biofilm formed protects the microbial community but in the process can have a severe impact on a water well supply. Biofilm development in the groundwater environment begins to plug both the well screen and pore space in the adjoining aquifer resulting in decreased aquifer permeability. In time, the accretion of soil particles trapped by the biofilm and mineralization can further reduce well yield.

The pervasive effects of biofouling in a municipal well located at the City of North Battleford, Saskatchewan are illustrated in Figure 1. Microbiological testing with the Biological Activity Reaction Test (BART™) indicated the presence of highly aggressive slime forming bacteria in the well. Various chemical and mechanical treatments were initiated by the third year of operation to counteract the effects of biofouling. The projected trend line in Figure 1 shows the anticipated loss in the well's specific capacity.

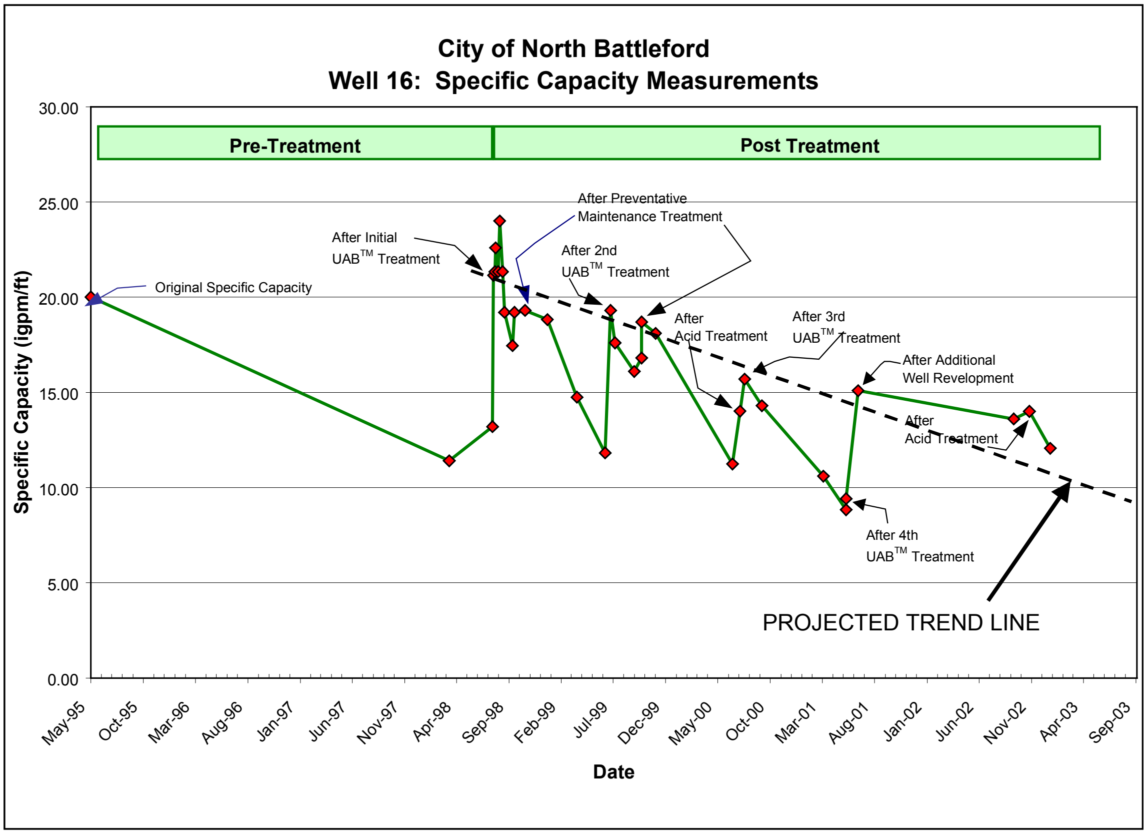

Figure 1. Effects of Biofouling on Specific Capacity

2. EVALUATION OF AN IMPRESSED CURRENT SYSTEM

Costerton (1994) and Wellman (1996) discuss the effects of an electrical field on killing biofilm bacteria by improving the efficacy of biocides and antibiotics. This phenomenon is referred to as the "bioelectric effect". Stoodley (1997) visually observed the effects of an electrical field on live biofilm in a test cell. Significant changes occurred to the structure of the biofilm on the surface of the anode and cathode electrodes but not to the structure of the biofilm elsewhere in the test cell. In these studies, it was observed that the thickness of the biofilm on the surface of the anode was reduced by 74% and expanded by 4% on the surface of the cathode. The phenomenon was reproduced with no current flow by alternately flushing the test cell with the pH of the electrolyte adjusted to a pH of 3 and 10 respectively. At a pH of 10, the biofilm was unaltered but became compacted to 69% of its original thickness at a pH of 3.

2.1 Model Well Construction

A model well was constructed in the laboratory to determine the effects of an applied electrical field on a biofouled porous media environment. The intentions were to biofoul the model well as quickly as possible, expose the test cell to an applied electrical field, and then observe the change in permeability by monitoring piezometers during pump tests. Biofouling was facilitated by recirculating water in the model well daily for 30 minutes every 8 hours, and feeding the bacteria weekly with a rich nutrient mix.

The components used to construct the model well shown in Figure 2 are identified as follows: 1) 75mm diameter stainless steel well screen electrically insulated except for a 75 mm length of exposed well screen at bottom of cell; 2) four high silicon cast iron anodes; 3) nine piezometers to measure head loss during pump tests; 4) feeder ring for circulating well water during pump tests and for providing nutrients to bacteria. Not shown are redox probes, reference electrodes, pump, control valves and flow meter. Also shown are the locations of piezometers B1, B2 and B3. The well was constructed from a 600 mm diameter PVC pipe about 1.2 m in length and backfilled with clean sand and water obtained from a biofouled well. The well water was tested with BART™ biodetectors and showed a highly aggressive consortium of slime producing bacteria. The anodes were used to impress a cathodic current onto the well screen, and were placed in the same plane as the exposed section of well screen in order to maximize the effect of the applied electrical field. DC current and voltage were supplied with a power supply capable of producing both constant voltage and current.

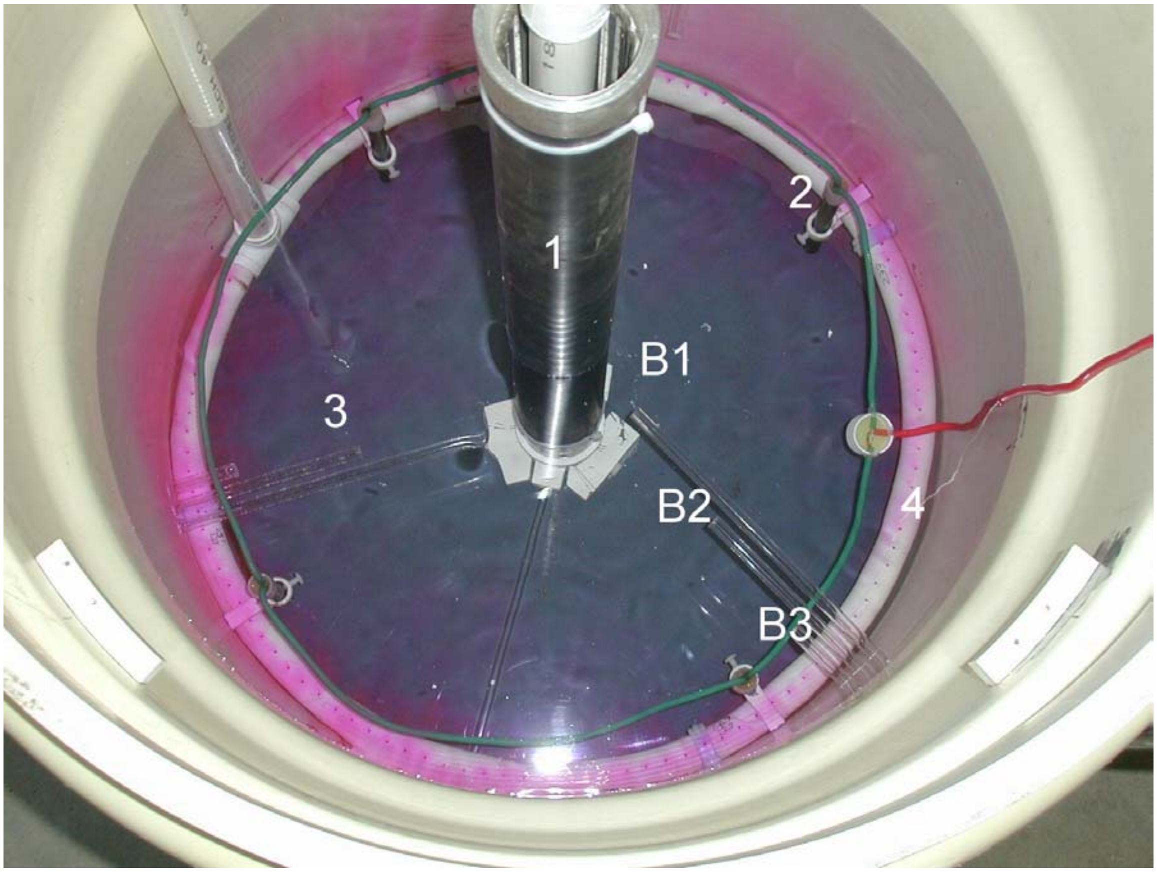

Figure 2. Model Well Design

2.1.1 Model Well Performance

Nine piezometers were installed to monitor the performance of the model well. A series of pump tests were carried out weekly using seven flow rates ranging from 0.5 to 3.5 litres per minute (l/min.), in increments of 0.5 l/min. The bacteria were fed a rich nutrient mix upon completion of each pump test. Figure 3 shows the chronological order of events, nomenclature, observed effects of the applied electrical field and nutrient loading on biofouling for a pumping flow rate of 0.5 l/min. Pump test curves for the other flow rates are essentially mirror images of Figure 3. Monitoring piezometers during pump tests was key in determining the effect of the electrical field and nutrient loading on biofouling and their subsequent effects on hydraulic conductivity. Increased drawdown shown in Figure 3 is concurrent with increased severity of biofouling. Piezometers B1, B2 and B3, which were in line with the exposed section of well screen, show the drawdown levels at 25 mm, 150 mm and 300 mm respectively from the well screen.

2.1.2 Effect of Electrical Field

Biofilm development began on Day 32 when nutrients were first added to the model well as shown in Figure 3. On Day 131, power was applied to the anodes when the model well was judged sufficiently biofouled.

DC voltage and current levels were initially set at 5 volts and 0.5 amperes, which corresponded to an electrical field strength of 16.4 volts per metre (V/m) and a current density of 2.74 milliamperes per square centimetre (ma/cm^2). Unfortunately, the flow meter used to control pumping rates was damaged on Day 131 and pump tests could not be performed for a period of 23 days. On Day 154, a pump test showed the drawdown level inside the well screen was within 43% of the pre-biofouled drawdown level. On Day 196, the drawdown level inside the well screen had decreased to within 5% of the pre-biofouled drawdown level.

Power was reapplied to the anodes on Day 648 using the same levels of voltage and current applied on Day 131. Pump tests showed drawdown levels recovered to within 63% of the pre-biofouled levels on Day 651 and to within 44% of the pre-biofouled levels on Day 658.

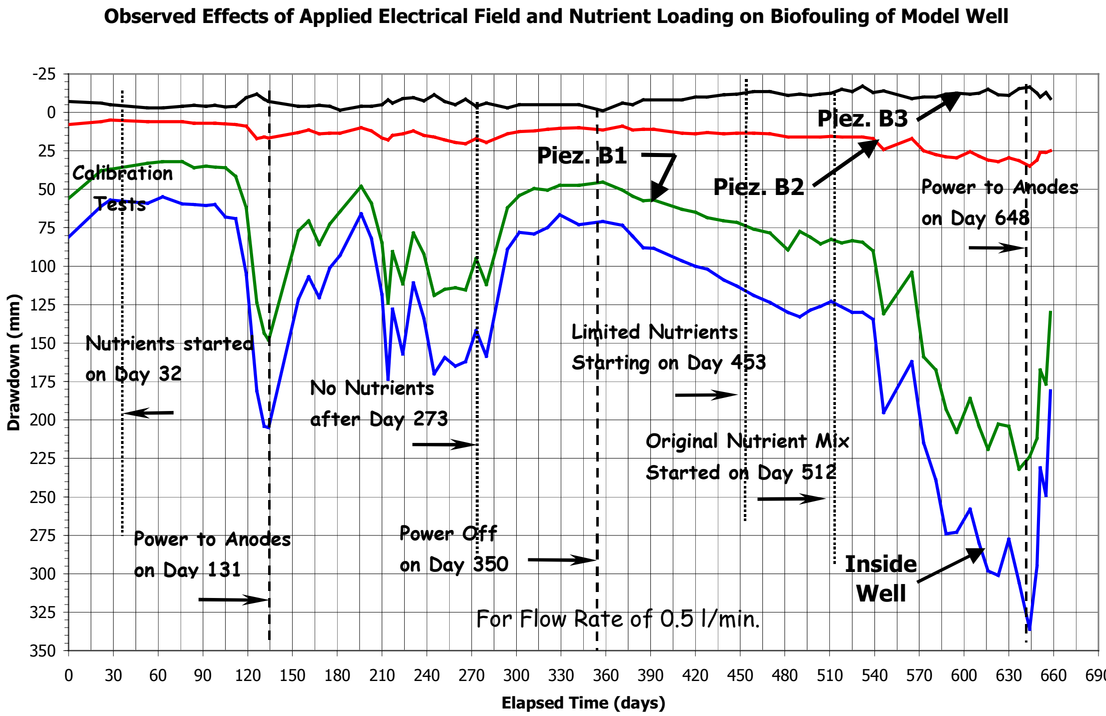

Figure 3. Drawdown Levels in Model Well

2.1.3 Effective Radius of Biofouling

The severity and extent of the biofouled environment around the well screen intake is apparent when the drawdown levels of the piezometers are compared to the drawdown level inside the well screen. The magnitude of the drawdown recorded at piezometer B1 was always less than the drawdown inside the well screen, but always mirrored the drawdown inside the well screen. Piezometer B2 showed a slight amount of drawdown while piezometer B3 generally showed a negative drawdown indicating a piezometric level higher than the static water level in the model well. Piezometer B3 is located near the feeder ring which returns water from the recirculating pump.

2.1.4 Effect of Nutrient Loading

The effect of nutrient loading on drawdown can be observed in Figure 3. Bacteria were fed a rich nutrient mix between Day 32 and Day 273. Feeding was discontinued on Day 273 and drawdown levels recovered considerably during this period in the presence of the electrical field until the power to the anodes was shut off on Day 350 and drawdown levels started to slowly increase. On Day 453, nutrient feeding was reintroduced to biofoul the model well in order to reapply the electrical field for a second time. At first, a leaner nutrient mix was fed to the bacteria in order to reduce the number of solvated ions that contributed to an increase in the ionic strength when the rich nutrient mix was used. However, ongoing pump tests showed that the rate of biofouling was too slow and a decision was made to begin feeding the rich nutrient mix on Day 512. On Day 637, the model well was considered fully biofouled since pumping rates greater than 0.5 l/min. could not be sustained. As described in section 2.1.2, drawdown levels started to decrease rapidly upon reapplication of the electrical field on Day 648.

2.2 Discussion of Model Well Results

The model well was constructed solely to demonstrate the effect of an applied electrical field on a biofouled water well environment. There were a number of inherent problems with the model well as it is nearly impossible to simulate a real well in the laboratory. The model well is a closed system and fresh water was not introduced during pump tests. The model was also not designed to obtain discrete water samples to properly measure changes in pH, conductivity, ionic strength, dissolved oxygen levels, organic carbon levels, and changes in water chemistry particularly in the biofouled zone around the well intake. Thus, water samples were only available for analysis at the point of discharge from the pump and these were deemed of limited value.

Electrolysis of water occurs when the anode and well screen are coupled and a positive current is discharged off the anode. Electrolysis at the well screen results in the production of hydrogen gas and alkaline conditions due to the production of hydroxyl ions. Similarly, electrolysis at the anode results in the production of oxygen and acidic conditions due to the production of protons. The authors cannot speculate on the pH gradient that may have developed between the well screen and anodes since pH probes were not installed. As mentioned previously, Stoodley (1997) visually observed a reduction in the volume of the biofilm on the surface of the anode in a test cell or when the pH of the electrolyte was made acidic with virtually no volume change at the cathode.

The piezometers in the model well showed that a significant decrease in drawdown levels occurred inside the well screen and at piezometer B1 where alkaline conditions may be apparent. The reduction in drawdown suggests the biofilm shrank in the presence of the electrical field. It is noted that the decrease in drawdown was not instantaneous suggesting the mechanism causing a possible volume change in the biofilm is a time dependent process.

3.0 FIELD DEMONSTRATION OF AN IMPRESSED CURRENT SYSTEM

Laboratory testing showed the applied electrical field was able to mitigate the effects of biofouling. The next step was to then field test the applicability of this process in a real water well environment. Two biofouled wells located in Saskatchewan were selected for field demonstrations, one at the Town of Qu'Appelle and the second well at the City of North Battleford.

3.1 Town of Qu'Appelle Well 4

Well 4 was put into operation in 1981 by the Town of Qu'Appelle. Subsurface conditions at this well site consist of sand and gravel from the surface to a depth of about 14 m. The well is 200 mm in diameter and consists of a 9.2 m of welded steel casing with an attached 3.8 m length of stainless steel well screen. The well had an original specific capacity of 22.4 imperial gallons per minute per foot of drawdown (igpm/ft). By February 2002, the specific capacity had deteriorated to 4.4 igpm/ft. Microbiological testing with BART^{TM} biodetectors indicated the presence of highly aggressive slime forming bacteria around the well. This well is normally operated from October to April and is then on standby for the remainder of the year.

The impressed current system at this site consisted of a cathodic protection rectifier with a maximum DC output of 100 volts and 14 amperes, and two 1.5 m by 50 mm high silicon iron anodes. These anodes contain up to 5% chromium by weight. As a precaution, mixed metal oxide (MMO) anodes were attached to the silicon iron anodes as alternative anodes in the event that chromium levels exceeded provincial guidelines for potable water during the time that the anodes were energized. However, water analyses in the following months showed chromium levels were below detectable limits. MMO anodes are metal rods with a titanium substrate coated with mixed metal oxide catalyst that activates the titanium.

Two anodes were originally installed at this well. Each anode was placed approximately at the mid-depth of the well screen, spaced 180 degrees apart, and about 4.5 m away from the well screen. The anodes were energized on May 9, 2002 as shown on Figure 4. The rectifier output could only be controlled by adjusting voltage output through a series of voltage taps so precise control was not possible. In addition, current output could not be controlled. Voltage levels were increased in 10-volt increments approximately every 2 to 3 weeks, from May 9, 2002 to August 2, 2002. During this period, pump tests showed that the specific capacity had increased by about 7.5%. Measurements showed the voltage and current output were 47 volts and 8.7 amperes, which corresponded to an estimated electrical field strength and current density of 10.4 V/m and 0.096 ma/cm^2. From August 2, 2002 to September 2, 2002, no further improvements occurred. The lack of improvement was considered a technical problem, since the current could not be focused directly onto the well screen but most likely was being projected to the entire length of the steel casing and well screen.

On September 2, the original anodes were replaced with two new anodes located at half the distance from the well screen in order to redirect the current closer to the well screen. The anodes were energized and the voltage output increased to 60 volts. Subsequent pump tests showed the improvement in specific capacity had doubled as a result. The improvement occurred even though groundwater levels were dropping as shown in Figure 4. Measurements showed that the voltage and current output levels were 58.5 volts and 7.0 amperes, which corresponded to an estimated electrical field strength and current density of 25.4 V/m and 0.077 ma/cm^2. An accurate estimate of the current density is difficult to obtain since the projected surface area of the well casing and well screen as seen by the current is not known. Voltage levels were later increased to 80 volts but no further improvement occurred. However, the groundwater levels were also dropping significantly during this time, which directly affects the specific capacity. Testing is continuing at this site.

3.2 City of North Battleford Well 17

Well 17 was originally placed into service in 1995. At this site, subsurface conditions consist of sand and gravel from the surface to a depth of about 21 m. The well is 305 mm in diameter well and consists of 8.5 m of welded steel casing with an attached 9.45 m length of stainless steel well screen. A pump test performed in 1995 showed Well 17 had an original specific capacity of 20.0 igpm/ft. By June 2001, the specific capacity had deteriorated to as low as 10.5 igpm/ft. However by July 2001, the well's specific capacity was restored to 18.2 igpm/ft following an Ultra Acid Base (UAB^{TM}) treatment (PFRA and DBI, 1997**)** along with some redevelopment. In January 2003, just prior to installing the impressed current system the well's specific capacity was measured to be 17.2 igpm/ft. At this time, microbiological testing with BART^{TM} biodetectors also indicated the presence of highly aggressive slime forming bacteria around the well.

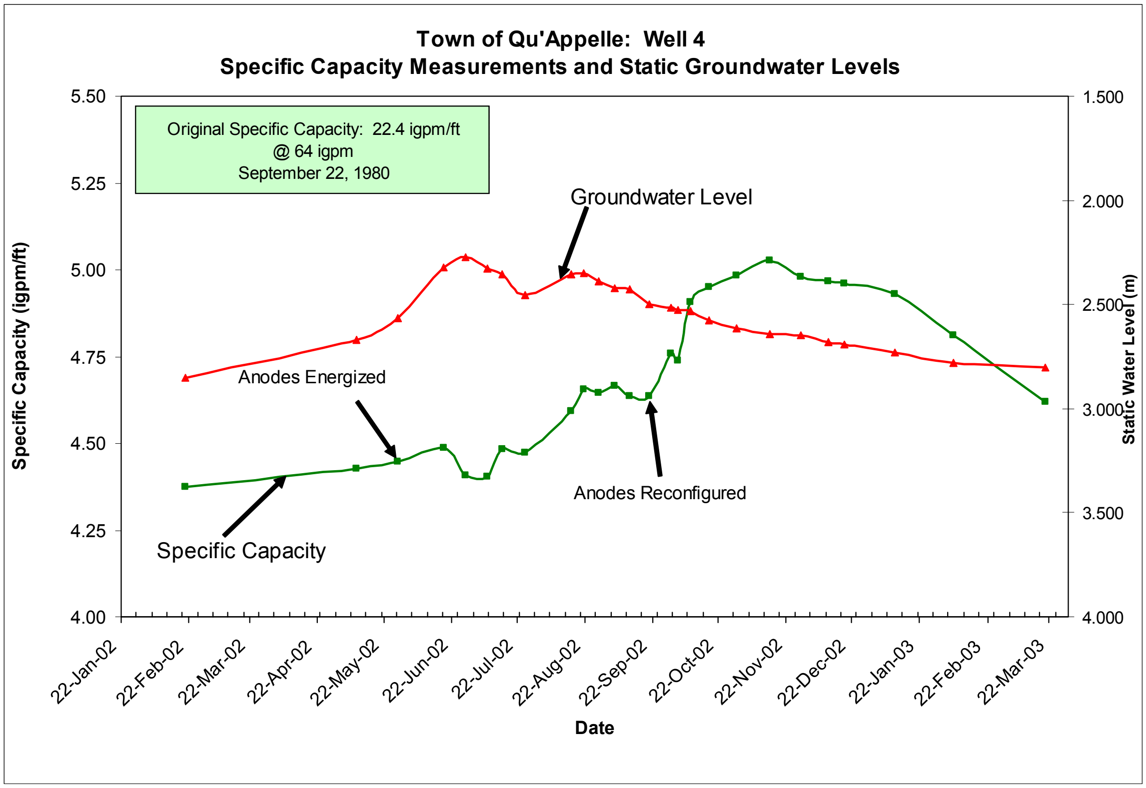

Figure 4. Specific Capacity Measurements and Groundwater Levels at Well 4

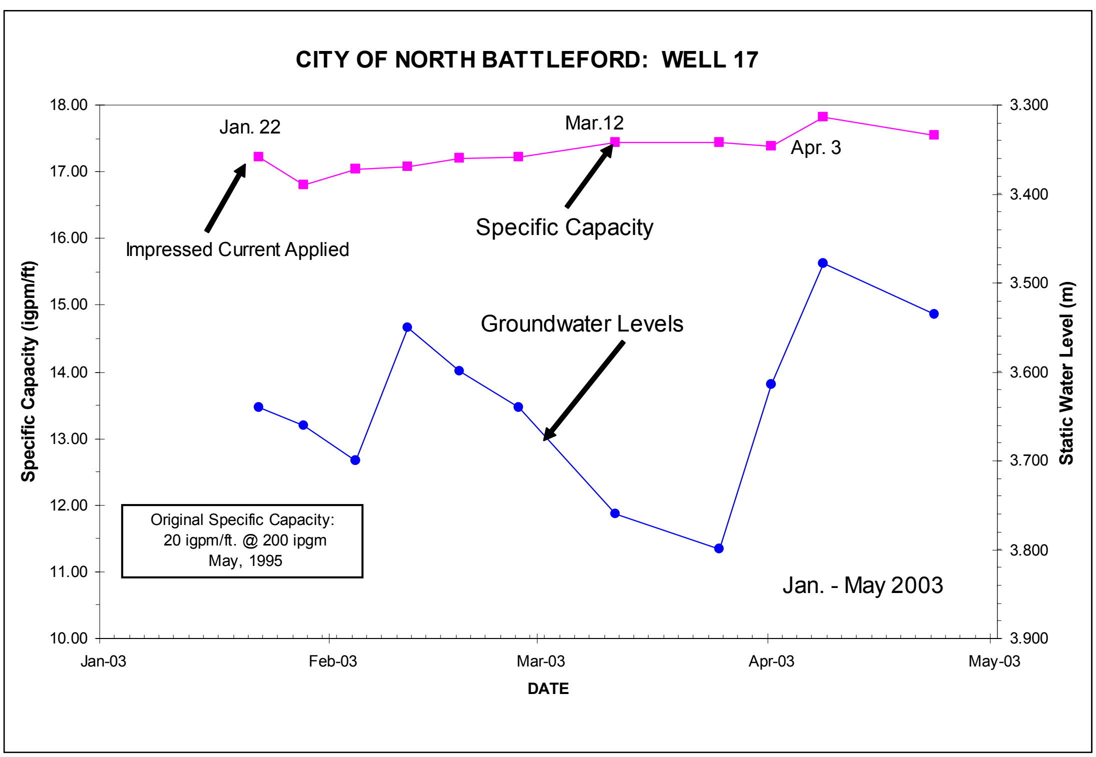

Figure 5. Specific Capacity Measurements and Groundwater Levels for Well 17

At this site, the impressed current system consisted of a cathodic protection rectifier with a maximum DC output of 100 volts and 14 amperes, and four anode strings each consisting of mixed metal oxide (MMO) anodes, 12.5 mm in diameter by 7.4 m in length. Each anode string was centered at the mid depth of the well screen; spaced 90 degrees apart and located 1.5 m away from the well screen. The anodes were energized on January 22, 2003 as shown in Figure 5. An initial voltage level of 20 volts was applied and incremented in 20-volt increments to 60 volts by April 3, 2003. Over this period the specific capacity increased to within 11% of the well's original specific capacity. Measurements showed a voltage and current output of 58.7 volts and 13.4 amperes, which corresponded to an estimated electrical field strength and current density of 39.1 V/m and 0.14 ma/cm^2. Testing is continuing at this site.

4. CONCLUSIONS

Observations in the laboratory and field show that an applied electrical field has a mitigating effect on biofilm. Drawdown levels decreased significantly in the model well and measurable increases in specific capacity were observed in the two-biofouled water wells. Tests have shown that the permeability of the biofouled porous media increases under the influence of an applied electric field suggesting the biofilm undergoes a reduction in volume. Although the mechanism by which the biofilm appears to shrink is not well understood, the process is time dependent. Studies on the two biofouled wells show the process is applicable for use in the field but longer-term observations are required to fully evaluate the process since seasonally fluctuating groundwater levels can obscure consistent measurement of small changes in the well's specific capacity. Further studies are planned to better understand the actual effect of the electrical field on biofilm in order to improve process effectiveness, to evaluate anode configuration, to optimize electrical field strengths and current densities, and to determine the sustainability of the process.

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