A Cautionary Tale: Well Rehabilitation in Elkhart, Indiana's South Wellfield

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Elkhart, Indiana's South Wellfield, one of three operated by the city's Department of Public Works and Utilities (DPWU), is developed in the glacio-fluvial outwash Yellow Creek tributary of the St. Joseph River aquifer. Hydrogeologic details are provided in the original wellfield testing report of 1964 (Keck Consulting for Peerless Midwest), and in Imbrigiotta and Martin (1981) and Arihood and Cohen (1997). This wellfield is developed with three high-capacity screened "gravel-wall" wells to-date, and supplies a conventional aeration/pressure-filtration water treatment plant. Over time, these wells have experienced performance decline, adversely affecting the economy of the plant and its operations, with periodic attempts to restore production capacity.

Elkhart is not alone in experiencing these problems and the "ups and downs" of addressing them. All well problems and the wellfield maintenance and rehabilitation history related here are experienced by wellfield managers and operators elsewhere in Indiana (and regionally and internationally). By relating our experiences in the South Wellfield, we hope to assist the audience by (1) providing encouragement <u>not</u> to let wells degrade in performance, (2) introducing unfamiliar (but well-demonstrated) methods that are available to recover performance in severely impacted wells, (3) reviewing the results of rehabilitation in an imperfect world, and (4) reviewing options to avoid or slow well performance decline in the future.

An Evaluation of Well Performance History

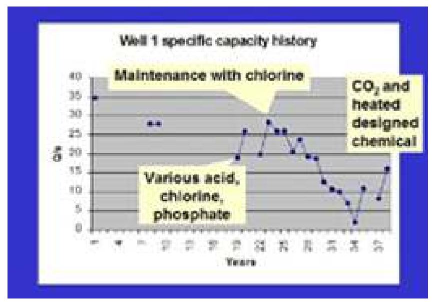
Wells in the South Wellfield have experienced a decline in performance since at least 1971, when the first rehabilitation was conducted on Well no. 1 (the northern-most of three) (Figure 1). Each of the wells were treated several times. In 1997, a team of Greeley & Hansen, Engineers, Panterra Corporation, and Smith-Comeskey Ground Water Science (subcontracting to Panterra) was asked by Elkhart DPWU to evaluate the problem and propose options for rehabilitation or replacement of Well no. 1.

From the outset, the problem was attributed to "iron bacteria" and treated for such periodically. In its 1998 analysis, a biofouling cause was confirmed by Smith-Comeskey. A review of the treatment history since 1971 showed that, despite repeated treatments, a pattern of continual decline was evident. However, this decline was reversed somewhat by rehabilitation events. Specific capacity (yield per drawdown Q/s) is a readily calculated indicator of hydraulic performance change in wells.

Well no. 1, having the lowest initial specific capacity of the three (35 gpm/ft), declined below the optimal pumping economics point most quickly. Rehabilitation was first attempted six years after completion with no improvement, and then was permitted to decline in performance to uneconomical levels before a series of treatments from 1981 to 1989 kept specific capacity in the mid- to upper 20s-gpm/ft range. Treatment effectiveness then fell off rapidly, with specific capacity falling to as low as 2 gpm/ft, despite conducting alternative methods of treatments, until the well was effectively abandoned in 1995. The following table summarizes treatments in well no. 1:

Date	Treatment	Before Q/s[1]	After Q/s
Dec. 1971	acidization (A-6), phosphate (P-6, B-6), surging	28[2]	27.9
Sept. 1982	acidization (A-6), phosphate (P-6, B-6) with HTH, surging[3]	18.9	26
Sept. 1985	phosphate (P-6) with HCl acidization and A-6, surging	20	28.3
Dec. 1987	P6 + HTH, light acidization , alternating, surging	26	26
Nov. 1989	phosphate and acidization, chlorine and wetting agent. phosphate + wetting agent, surging	20.7	23.7
Oct. 1991	phosphate with Cl_2, wetting agent, acidization alternating, surging	19.1	18.6
Mar. 1992	surged and caustic soda added.	12.5	10.65
1993	Sonar Jet treatment.	10	7
1995	Aquafreed treatment.	2	11

(1) Q/s = specific capacity (yield Q in gal/min per drawdown s in feet). (2) Original Q/s = 34.6 (3) Treatments typically included alternating treatment chemical types and surging. Several 100 pounds of chemical typically used.



Specific capacity history of Well no. 1, S. Wellfield

Wells no. 2 and 3, with higher initial specific capacities (51.2 gpm/ft and 88.6 gpm/ft, respectively), appeared to decline in performance more slowly. Well 2 was not rehabilitated until 21 years after original construction and specific capacity had fallen to 63 % of original. Well no. 3 had a similar history, but was permitted to drop to <40% of original Q/s in 14 years.

On both wells no. 2 and 3, two rehabilitations each were performed in 1987 to 1991 once problems were recognized by the DPWU water staff . Chemicals used are as indicated. The following summarizes results:

	Well 2			
Events	Treatment	Before Q/s	After Q/s	% original Q/s
1987	acidization, phosphate, surging	34	44	86
1991	acidization, phosphate, surging	33	41 (1)	80
	Well 3			
1987	acidization, phosphate, surging	34	62.5	71
1991	acidization, phosphate, surging	48	65.6 (2)	74

(1) Q/s for 898 gpm. (2) Q/s for 932 gpm.

For well no. 2, the 1987 treatment restored Q/s to 86 % of original, but Q/s declined to below the 1986 pre-cleaning value by 1991. The 1991 treatment restored Q/s to 82 % of original. However, note that the Q/s reported was for 898 gpm, and not 1420 gpm. Specific capacity for any well at any point in time declines with increased pumping rate (Driscoll, 1986). An estimated Q/s for 1420 gpm at that time would have been less than 25 gpm/ft. Q/s then was permitted to decline precipitously to 23 gpm/ft at 800 gpm prior to cleaning in September 1998.

For well no. 3, the 1987 treatment restored Q/s to 71 % of original, but performance declined to 53 % of original by 1991. The 1991 treatment restored a reported Q/s (for 932 gpm) to 74 % of original. An estimated Q/s for 1240 gpm at that time would have been something less than 49 gpm/ft. Q/s then was permitted to decline precipitously to < 20 gpm/ft at 393 gpm prior to cleaning in September 1998.

Two technical notes on specific capacity values:

(1) Not all specific capacities are equal: Attempting to objectively compare specific capacity data in files (while useful) can be an "apples to oranges" exercise for several reasons, including:

(a) Q/s for different pumping rates are not really equivalent. If they are charted together (e.g., a Q/s for 898 gpm and a Q/s for 1240 gpm), large differences can be masked or success overstated.

(b) If only final Q/s numbers (and no actual step test drawdown data or curves) are available, it is impossible later to calculate changes over time in the well loss function (the C slope) or the aquifer loss (B intercept), respectively, using common well hydraulics analysis techniques (e.g., as documented in Kruseman and de Ridder, 1994).

(c) Errors in yield and drawdown measurement: Some typical causes include inaccurate flowmeters or orifice weirs and drawdown errors.

(d) Incomplete tests: Not run to completion or run at various pumping rates that are difficult to compare.

(e) Not taking into account regional changes: For example, since the water table or potentiometric surfaces vary seasonally and with outside stresses, a deeper pumping water level for a given discharge rate may not reflect a change in the well performance.

(2) Specific capacity can be a crude tool: While being a crucial single calculation for wellfield performance monitoring, specific capacity in a sense is a crude tool in charting well performance change. As in artificially constructed filters, a large amount of biofouling (biomass and associated organic matrix and inorganic debris) can build up in an aquifer around wells before a head loss across the screen surface (reflected in lowered specific capacity) is detected. Initially, as in biological filtration (e.g., Goldrabe et al., 1993; Wang et al., 1995) biofilms have relatively little impact on aquifer or gravel pack pore volume. As "debris" such as iron oxides build up, pore spaces become more restricted and head losses begin to

rise, eventually to be reflected in lowering specific capacity values.

A note about aquifer biofouling potential and effects: It is now well understood that aquifers have native microbial communities. Glacial-fluvial aquifers such as the Yellow Creek unit typical harbor abundant and diverse microflora that cause biofouling. The sediments provide abundant pore volumes. When they were deposited, abundant and readily biodegradable organic material (BOM) and nutrient resources were also deposited, which are then cycled in the ecosystem indefinitely by microbial communities, supplemented by recharge. Wells in such aquifers also experience more profound impacts from biofouling compared to the other important aquifer type found in Indiana: carbonate rock aquifers. The reason is that sand and gravel pore spaces are more easily plugged, compared to the fractures, channels and vugs of limestones and dolomites. It is also important to note a contrast with engineered biological filters: Experience (e.g., Ahmad et al., 1998) shows that maintaining biological filter performance is dependent on effective, high-intensity backwashing. While this is also true for wells in aquifers, the backwashing (well development) options for wells are more restricted in their ability to reach and remove biofouling.

Contributing Factors in Well Performance Decline in the South Wellfield

An analysis of the history of treatment performance and well performance decline in these wells shows several contributing factors:

(1) The aquifer and well conditions have clogging potential. The working mechanisms are a combination of fine sediment in-migration from the glacio-fluvial formation (mixed particle sizes) and biofouling. Fine sediment migrates toward the well. Biofouling forms theoretically in a cylindrical band from the depth into the formation where iron oxidizes to the screen face. While biofouling does reduce hydraulic conductivity, it clogs more effectively as it traps in-migrating particles.

(2) The wells were permitted to decline in performance below the point where full performance recovery was possible. Below about 75 to 85 % of original or target specific capacity, it requires a great amount of development energy to restore performance, and most especially to remove nutrients and residual debris to slow the return to well decline after cleaning.

Tragically, Elkhart's wellfield operations team from the mid-1980s to early 1990s had a well maintenance monitoring and treatment plan in place that could have halted decline earlier. However, this plan was permitted to lapse for several reasons. This kind of intermittent well maintenance history is more the exception than the rule in wellfield management.

Choices of treatment methods in the past. Prior to 1998, phosphate-containing surfactant compounds were used in each treatment in large quantities. These were selected with the best of intentions based on information provided by chemical suppliers and short-term (<10 year) experience in wellfields (including Elkhart's) that showed good initial results. However, phosphorus-containing surfactants are suspected of ultimately being counterproductive in well rehabilitation use due to residual phosphate (a limited nutrient in ground water) left behind. P is adsorbed to clays by cation exchange and available for bacteria to use in metabolism and cell growth and development (e.g., Borch et al. 1993, Smith 1995, and Layne Inc. internal corporate communication).

A condition commonly observed in sand-and-gravel wells treated repeatedly over time using phosphorus-containing compounds is a change in the type of biofouling present. It is transformed from a low-biomass filamentous form toward a bulkier, slimy type of biomass that is more difficult to remove using conventional rehabilitation methods. This change results in an acceleration of the performance decay in such wellfields. The change from short-term success to long-term acceleration of decline seems to be illustrated by the Q/s history graph supplied by Peerless Midwest for well no. 1. Successes in the 1980s are followed by rapid declines in performance persisting to the present.

Evidence of a possible change in biofouling in the DPWU South Wellfield was provided by a review of color downhole videos performed on Well no. 1. While in the past, the problem was described as "iron bacteria" (filamentous iron-related biofouling), recent videos showed a more gray, flocculent, slimy growth. Smith-Comeskey's 1998 tests using BART methods (Droycon Bioconcepts) and microscopy (methods per *Standard Methods*; Smith, 1992; Smith, 1996) confirmed potential for intense slimy growth. Additionally, active denitrifying microflora were detected. These oxidize FeII to FeIII anaerobically, opening up the possibility of a deep-set FeIII clog.

(4) Insufficient or inappropriate well redevelopment methods. As in filter backwashing, mechanical development action is crucial to well rehabilitation success, both to mix chemicals with target compounds and to set fine particles in motion to cause them to enter the well to be removed. Both the quality (method efficiency and force) and the quantity (duration of

application) are important. Redevelopment methods that are "good enough" for many wells may not be adequate for difficult wells.

(a) The effectiveness of conventional mechanical development used in past treatments was difficult to evaluate based on file information, but the approach to treatment prior to 1998 was more focused on chemical application than development action. Less-than-optimal redevelopment likely resulted in incomplete removal of clogging mass from the gravel pack and formation.

(b) Other treatments were tried on well no. 1 on the recommendations of contractors. It is unclear exactly how each contributed, but these are possibilities:

A caustic and chlorine treatment was attempted in 1992 and 1993 with no improvement. This treatment may have resulted in accelerated mineral precipitate formation that could add to hydraulic inefficiency in the gravel pack.

A Sonar-Jet™ treatment (acoustic shock-wave development), conducted in 1993, resulted a large decline in specific capacity when attempted. This was probably due to shock wave force pushing abundant soft debris and fine sediment back to the outside boundary of the gravel pack.

An Aqua Freed™ treatment (injecting liquid and gaseous carbon dioxide) was attempted in 1995 and Q/s was improved from about 2 gpm/ft to the already low 1992 value (~11 gpm/ft). However, it is likely that with the accumulated and impacted sediment-biofouling build-up in the near-well formation, the injection force of this treatment may also have added to proposed compaction problem in the gravel pack. In any case, conditions in the well at that time probably limited the effectiveness of this treatment (Smith personal communication with N. Mansuy). Both these technologies are discussed in other articles on the Ground Water Science site.

Summing up:

(1) There was a two-fold clogging potential in the wellfield (both sediment and biofouling) that would ultimately result in performance decline.

(2) Past management did not have the information or plan to act in a proactive fashion to act before performance decline, permitting decline to go on beyond the point where it was easiest to reverse, and an existing maintenance plan was abandoned prematurely.

(3) Numerous treatments selected and used, with varied success. While in some cases effective in the short-term, some treatments seem to have contributed to accelerating the expected long-term decline in performance.

1998 Treatments

Because (1) the wells appeared to be fundamentally sound, and (2) the cost of rehabilitation to restore performance was favorable compared to new construction, the team recommended rehabilitation over either well reconstruction or abandonment and new construction. Target yields and specific capacities were calculated based on pumping goals (production needed and maximum drawdowns) and power efficiency (using Helweg et al, 1983's formulas).

Based on the analysis of causes, a Blended Chemical Heat Treatment (BCHT) program (process documented in Leach et al., 1991; Smith, 1995; Alford and Cullimore, 1999) was recommended to break through the expected clogging material and restore performance. The BCHT process (which employs a mixture of chemicals, heated upon injection) has a history of effectiveness on difficult well clogs promoted by the slime-forming biofouling, similar to that detected in the South Wellfield tests.

In this case, in the specification developed by Smith-Comeskey for Panterra, the treatment comprised a combination of acetic acid (amended to reduce pH to <2) and nonphosphate polyelectrolyte (ARCCsperse CB-4 and PM-30, ARCC, Daytona Beach, FL), jetted in at 180 F (at the nozzle), with a program of extensive mechanical development using double surge block and airlift pumping. This program was used on both wells 1 and 3.

Due to cost differences and as a comparison, well no. 2 was treated with hydrochloric acid, calcium hypochlorite and development. Phosphate-containing compounds were not used in any treatments, replaced as surfactants by the ARCCsperse products.

Well no. 1:

Well no. 1 was in extremely poor shape prior to cleaning (Q/s = 8.2 at 402 gpm). After the initial chemical charge, with minimal development, specific capacity fell to 5 gpm/ft. This was probably due to development action collapsing clogging material against the screen, but it resulted in some short-term hand-wringing. Surging and airlift began a recovery over one week to 16.1 gpm/ft at 737 gpm, an economically viable level of performance for 1 million gpd, based on calculations. While not the target result, the well could then pump 737 gpm at a 45-ft drawdown instead of 402 gpm (maximum) at over 70 ft drawdown. Our assessment was that the result was neither at its potential nore complete.

The effectiveness of development was hindered by (1) a delay in commencement of development after chemical loading due to scheduling (under BCHT, development is most effective when commenced while the solution is still hot), (2) some stoppage in development subsequently due to mechanical problems and process "choke points", and (3) (initially) the effectiveness of development with the tools at hand.

One "choke point" was acid neutralization. This was built into the project plan to assure that well-cleaning discharge to sanitary sewer was at an acceptable pH. The system used proved to be time-consuming and contributed to stoppages in redevelopment. The tank capacity for neutralization was underestimated, and a more efficient neutralization system would have helped. Development had to stop when discharge tanks (2800 gal. total capacity) were full, while pumped fluid was being neutralized. In the case of well no. 1, we may have been able to use less chemical, reducing the neutralization effort, but that the time, we expected a deep, massive clog.

Wells 3 and 2:

Well no. 3 provided the most effective immediate response to the BCHT approach. After one chemical treatment pass and three days of development, Q/s was restored to 55 gpm/ft at 770 gpm from 15.6 gpm/ft at 686 gpm. Q/s reached 61.3 gpm/ft on July 23, 1998, when a large amount of silica sand was pumped in. The screen was repaired, reducing Q/s somewhat. Overall, performance was restored to somewhat less than 1987 post-treatment levels by the end of treatments in 1998.

Well no. 2 was treated differently, using hydrochloric acid, alternating with an alkaline (soda) and chlorine steps, with three days development. Success in immediate redevelopment response here was also evident in increased specific capacity: from 22.8 gpm/ft at 800 gpm to 38.7 gpm/ft at 1002 gpm.

Comparing the effectiveness of the two chemical regimes will require evaluation over time. Acid-amended acetic acid has been shown in over 3000 well applications to perform better than hydrochloric acid and chlorine on very advanced slime-forming biofouling. However, in wells where the clogging is not compacted, as in well no. 2, various chemical treatments can have similar results. History with aggressive biofouling well environments shows that the benefits of both BCHT (and the amended acetic acid chemical choice) and effective redevelopment come with delayed decline in performance after rehabilitation, rather than in obvious immediate effects.

Rehabilitation Follow-Up

Long-term effectiveness of these treatments in the South Wellfield will depend upon follow-up by the Elkhart DPWU. The following recommendations were made to the DPWU:

(1) An immediate short-term follow-up should be additional low-intensity redevelopment of each well in the South Wellfield in the next two years to complete the work begun with the 1998 rehabilitation actions. It is our assessment that treatment is not finished in these wells. Each well should respond to additional development and light chemical treatment by increasing in performance if it is not permitted to decline in performance first.

Real world influences: Elkhart has two other wellfields with performance decline. As with almost any wellfield, allocating fixed resources will be the fundamental challenge.

(2) For further benefit, a program of professionally developed, DPWU administered, maintenance evaluation and treatment is essential in the South Wellfield, and by extension, all three wellfields. A continued resumption in performance decline can be expected if no maintenance treatment actions are taken. The lapse in preventive maintenance treatments after 1992 almost certainly contributed to the state of the wells prior to the 1998 treatments.

Real world influences: A "New Jerusalem" of preventive maintenance may take time to achieve with other priorities and fixed resources, but this is certainly achievable and a worthy, cost-effective goal.

(3) To best achieve these goals, all monitoring, treatment, and repair activities should be planned as part of a system-wide strategic wellfield maintenance program that is both systematic and effective.

(4) Within the maintenance plan, personnel training and wellfield equipment modification are recommended to make the process easier and more effective.

Real world influences: The municipality, the contractor, and the consultants all have limited time and staff resources to allocate over many tasks.

(5) A non-contractor advisory role on major treatment events: Professional assistance in this area by people highly experienced in well maintenance and rehabilitation helps to assure that a wellfield operator's objectives and best interests are served.

Real world influences: This is different than the approach that has evolved in Indiana and the region over decades and the expense for such advice has to be justifiable in cost benefits.

Prospects for Success?

The Elkhart experience clearly shows what happens when wells are permitted to decline in performance. Having to rehabilitate multiple wells in the midst of a dry 1998 in Elkhart was a serious matter. The methods of rehabilitation and a success history for maintenance are demonstrated and documented. Most importantly, at present, the will to re-implement a systematic wellfield maintenance treatment program appears to be in place in the DPWU.

Real world influences: In almost all wellfield settings, implementation of successful well maintenance programs has historically (as in Elkhart) suffered because program success depends on the will of one or a few motivated people. When they leave employment, as at Elkhart, programs languish. Success in the future will depend on both the elements involved in the proposed maintenance program and its institutional perpetuation over time.

The experience in Eklhart's South Wellfield should not be considered unique. Prospects for success in well maintenance in other wellfields also depend on the kind of analysis, review and planning documented here. As Elkhart has, any water supplier can benefit from (1) honest and complete scrutiny of successes (complete and incomplete), lapses and failures in its maintenance history, and (2) taking advantage of the many improvements now available in the practice of well analysis, treatment and maintenance.

Sad note: We have since learned that Well 1 was retired and replaced by a new well. It could have been saved, if the subsequent redevelopment had been implemented, saving money.

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