Microbial fouling control in groundwater extraction and treatment: Pilot studies of agents' efficacy and fate

Nicolas Dilliott, P.E.,[1] Brad Horn, P.E.,[2] Kevin Coons, P.E.[3]

[1]Engineering Analytics, Inc., 9820 Willow Creek Road, Suite 395, San Diego, CA 92131; E-mail: ndilliott@enganalytics.com

[2]Redux Technology, 280 Callegari Drive, West Haven, CT 06516; E-mail: bhorn@reduxtech.com

[3]Engineering Analytics, Inc., 9820 Willow Creek Road, Suite 395, San Diego, CA 92131; E-mail: kcoons@enganalytics.com

Abstract

Microbial fouling can pose major challenges in operations of groundwater remediation system extraction and treatment. Pipeline and unit operations biological fouling can lead to process upsets through reduced extraction rates, system fouling, reduced operating time, and increased maintenance costs. Extraction and discharge conditions may provide scenarios under which it is advantageous to consider treatment options that reduce disinfection by-product formation, are effective through non-oxidative pathways, mitigate inorganic deposition, and are effective in pre-treatment or early treatment stages. Two pilot tests were conducted to determine the efficacy and fate of two biological control agents (non-oxidizing and oxidizing) and five inorganic deposit control agents. The two biological control agents included: Tetrakis(hydroxymethyl) phosphonium sulfate (THPS – non-oxidative) and peracetic acid (PAA - oxidizing). The five deposit control agents included: Ethylenediaminetetraacetic acid (EDTA), citric acid, a terpolymer, phosphonic acid, and silicate. Groundwater from two aquifer units were tested with differing properties (microbial communities, ORP, and inorganic compounds). Results of the pilot tests for the biocides provided insights into the differing microbial community control efficacies, demand in differing groundwater conditions, and fate in groundwater treatment unit processes (oxidant media, advanced oxidation process, carbon filters, and reverse osmosis). Results of the pilot tests for the deposit control agents provided insights into chelation/complexation with the oxidative biocide PAA, efficacy in reducing inorganic oxidation from the biocide PAA, and fate in groundwater treatment unit processes. Results can assist designers and engineers that are investigating methods in mitigating microbial fouling and inorganic deposit formation in groundwater extraction and treatment processes.

Introduction

Microbiological fouling is common in groundwater extractions systems, particularly those at hazardous waste remediation sites, in part due to the presence of degradable contaminants. This paper presents work done to identify appropriate microbiocides for use at a Superfund site located in an urban setting in southern California. It describes initial vetting of available biocides, as well as subsequent field pilot work, and follow-up laboratory benchwork, to investigate efficacy, side effects and fate of selected biocides.

The subject site remedial system involves seven extraction wells screened in two aquifers bearing distinct and disparate quality groundwater. Extracted groundwater is pumped to a common pipeline, multiple miles in length with a maximum residence pipeline time exceeding 20 minutes. The design treatment process units at the time of study include oxidant multimedia media filtration, advanced oxidation, granular activated carbon adsorption, and reverse osmosis, with discharge to surface water. Initial testing of the extraction wells indicated the existence of biological communities that pose a high risk of fouling. These observations led the project team to initiate the work presented in this paper.

Site Characterization & Background

The extraction wells are located at multiple well sites and are intended to manage water in a shallow unconfined aquifer system (SAS) and a deep confined aquifer system (DAS). The wells provide containment of a regional plume of chemicals of concern that span multiple square miles. Testing of the target aquifers highlighted the different properties including but not limited to: ORP, inorganic compounds, microbial communities, and chemicals of concern (COC's).

Semi-quantitative microbial analyses were conducted as part of the extraction well testing program as shown in Table I. The results of these analyses indicated that there is a potential for aggressive microbial activity in the extracted groundwater. Based on this information, additional microbial samples were collected from selected extraction wells to further evaluate microbial activity and potential mitigation approaches including methods for chemical disinfection of influent groundwater.

Identification of Selected Biocides and Side effects

An initial review of potentially applicable biocides considered the biocide characteristics (including fate), system flow rate, water chemistry, treatment units, and discharge limitations among others. Biocides can generally be divided into oxidizers and non-oxidizers. While the latter may exhibit various mechanisms of disinfection, the former utilize a common mechanism, that of oxidation reactions which destroy biological molecules. Non-oxidizers tend to have more expensive use costs, and thus are limited in the scope of their application to industrial processes generally with limited water flows. Oxidizers are much more widely used in high flow applications (i.e. hundreds of gpm) such as drinking water and municipal wastewater treatment.

Biological Analysis:

	EW-2D-CR Casing 09:01	EW-2D-CR Aquifer 14:00	Detection Limit
Plate Count (colonies/ml)	>1,500	>1,500	NA
Anaerobic Growth (%)	50	10	NA
Sulfate Reducing Bacteria	Positive	Negative	NA
SRB Occurrence	*Excessive*	-	NA
Fe/Mn Oxidizing Bacteria	Negative	Negative	NA
ATP (cells per ml) Initial	217,000	336,000	1,000
ATP (cells per ml) 24 Hour	130,000	164,000	1,000
Bacterial Identification	*Pseudomonas stutzeri*	*Pseudomonas aeruginosa*	NA
Bacterial Identification	*Bacillus specie*	-	NA
Bacterial Identification	*Bacillus specie*	-	NA

	EW-2S-CR Casing 09:01	EW-2S-CR Aquifer 13:00	Detection Limit
Plate Count (colonies/ml)	>1,500	380	NA
Anaerobic Growth (%)	35	20	NA
Sulfate Reducing Bacteria	Positive	Positive	NA
SRB Occurrence	*Low*	*Very Low*	NA
Fe/Mn Oxidizing Bacteria	Negative	Negative	NA
ATP (cells per ml) Initial	113,000	40,000	1,000
ATP (cells per ml) 24 Hour	96,000	47,000	1,000
Bacterial Identification	*Pseudomonas aeruginosa*	*Acinetobacter beijerinckii*	NA

Table I. Initial microbial analysis of the studied wells EW-2S and EW-2D

This review was limited to biocides which could be delivered as a liquid to each well through a dedicated feed system, and it included consideration of the following microbiocides:

Oxidizing biocides:	chlorine dioxide (generated and stabilized solutions) hydrogen peroxide peroxyacetic acid (PAA) sodium hypochlorite
Non-oxidizing biocides	glutaraldehyde tetrakis(hydroxymethyl)phosphonium sulfate (THPS)

This list was consolidated to stabilized chlorine dioxide and peroxyacetic acid (PAA). Stabilized chlorine dioxide is essentially a buffered sodium chlorite solution, which is acidified by the presence of microbial activity, resulting in the release of chlorine dioxide, a very powerful oxidizing biocide. PAA is a widely used biocide seeing expanding application in various markets as a "green" alternative to common inexpensive halogen-bearing options.

A subsequent more detailed review of these two options included use cost estimates and estimates of the risk of detrimental side effects. This review involved investigation into the impact of oxidizing biocides on inorganic constituents expected to be present in the subject groundwater, potentially creating deposition and related operations problems, or increasing the toxicity of the chromium in extracted groundwater, complicating treatment. As a result of this concern, it was determined that subsequent field work include an evaluation of the effectiveness of deposit control agents that might ameliorate potential operations problems associated with use of an oxidizing biocide. Cost estimates resulted in the discounting of the use of stabilized chlorine dioxide. Also, field testing of the non-oxidizing biocide THPS (in addition to PAA) was proposed. THPS is widely applied in remedial and oilfield applications, where less expensive oxidizing biocides are ineffective due to certain water quality parameters.

Finally, a review of appropriate deposit control agents included considerations of fate and toxicity, efficacy in controlling iron and manganese deposition, and use costs. Many potentially effective deposit control agents were vetted for this study to derive a list of five preferential candidates. They include:

- EDTA (ethylenediamine tetra-acetic acid)
- Citric acid
- Dispersant terpolymer
- Phosphonic acid)
- Silicate

Field Pilot Procedures

The project team developed general conceptual procedures, which were then expanded into detailed (step-by-step) procedures for this field study. These detailed procedures were deemed by the authors to be too detailed to include in this paper, but can be provided upon request. In short, the field study comprised two distinct components, a biocide demand study and a deposit control study. Both components involved collecting fresh groundwater samples from two wells, screened separately in a shallow aquifer and a deep aquifer respectively, denoted EW-2S and EW-2D.

For the demand study, groundwater samples were dosed with three different doses each of PAA and THPS, creating six samples along with un-dosed control samples. Target dosing for PAA was 2, 5, and 14 ppm, and that for THPS was 12, 30, and 60 ppm. Aliquots of each sample were collected for seven-day testing using Biological Activity Reaction Tests (BART) and 'dipslides" for bacteria and fungi. Field measurements of concentration of biocide, and dissolved and total iron, were taken initially, and after one, 20, 60, 240 and 480 minutes. In addition, aliquots of these samples were collected for lab analyses of inorganics at one and 60 minutes. Inorganic analytes included calcium and magnesium, total and hexavalent chromium, total and dissolved iron (field filtered), and manganese.

The deposit control portion of this study involved dosing fresh groundwater samples with PAA and each of five different deposit control agents. Effectiveness of deposit control agents was determined using a combination of staged filtration using 0.45 micron and 0.1 filters, and bench scale greensand beds, with analysis for total and ferrous iron in the field. Aliquots of all samples were collected for laboratory analyses as well.

Historical data from all wells gave total iron levels ranging up to about 2 ppm, averaging about 0.75 ppm, but the subject wells at the time of this study were yielding ppb levels only. Thus, it was decided that deposit control studies would utilize an iron spike, using ferrous sulfate. On-site testing was done to arrive at an appropriate ferrous sulfate solution and dose volume to create approximately 2 ppm in initial samples for that study.

Pilot scale greensand beds were constructed on-site, based upon prior experimentation and scaling by the project team. Beds were treated per manufacturer recommendations, conditioned first with sodium hypochlorite solution, then purged with de-ionized water until bed effluent contained less than 0.5 ppm free chlorine. On-site testing showed this volume to be 3,600 mls or six bed volumes. Beds were dedicated to a particular deposit control agent studied, and were purged with subject sample prior to actually collecting lab samples or aliquots for field analyses. This purge volume was three bed volumes. Purge and sample flow rate was 300 mls/min, which simulates the Empty Bed Contact Time (EBCT) of the proposed full-scale greensand beds.

All sample collection and field analytical work was performed in a temporary on-site lab set up in a Connex box. The photo at right shows this arrangement with biocide and iron analysis done at the far station, greensand filtration in the mid-ground and sample collection, labelling and COC work done in the foreground.

Figure I. Greensand columns and filter field set-up.

Data Presentation

Field data and lab sample collection associated with this field study occurred during the week of February 13, 2023. Raw data collected from this study included: 1) Chronology of all site activities and field analyses, 2) BART and Dipslide testing results, 3) laboratory reports for off-site analytical work. All these sources of raw data were distilled into eight tables for simple presentation, and include all raw field and laboratory data. Raw data from this field study includes at least 1250 individual data values, a voluminous data set. This raw data was arranged into eight individual tables, and additional tables were derived through analyses and manipulation of raw data. Due to editorial limitations, this paper will not include all raw data tables: Rather, selected data upon which key results are based is included. Brief textual reference is made to data tables not included, and comprehensive data tables are available upon request.

Data Analysis & Discussion

The key data, and related results and conclusions from this field work, relate to 1) biocide efficacy and dose demand, 2) the impact of oxidizer on chromium, and 3) deposit control efficacy in the presence of oxidizer. These issues are discussed individually below.

Biocide Efficacy and Demand

Biocide efficacy is indicated primarily by BART & Dipslide Data. A summary of this data is presented in Table II below. It provides a numerical method of representing how each of two biocides performed based upon the comparison of BART/Dipslide results of control samples to those dosed with three different concentrations of two biocides. This numerical representation uses the days elapsed until the first indication of microbial growth in BART/Dipslide observations, given for control samples in the second column of Table II. The subsequent columns in Table II give the *additional days elapsed* before the first indication of microbial activity as a result of biocide addition. For example, the bacteria dipslide for the control sample for EW-2S (labelled as EW-2S-B1) did not show any sign of microbial activity until the second day of observation (see the second column for the row containing "Bacteria" data). The application of a low dose of peracetic acid (sample EW-2S-B2) extended the time before any indication of microbial activity by four days, giving a total of six days until first observation of microbial activity, in the latter test.

		PAA				**THPS**			
		Low Dose	Mid Dose	High Dose		Low Dose	Mid Dose	High Dose	
EW-2S	**B1***	**B2**	**B3**	**B4**		**B5**	**B6**	**B7**	
		(Additional days elapsed to first indication)				(Additional days elapsed to first indication)			
IRB	3	2	3	4	9	1	1	3	5
SRB	3	1	3	7	11	1	1	1	3
SLYM	1	1	1	0	2	1	1	1	3
Bacteria	2	4	4	5	13	-1	0	0	-1
Fungi	7	-1	-4	0	-5	-1	-1	-2	-4
	16	7	7	16		1	2	3	
EW-2D	**B1***	**B2**	**B3**	**B4**		**B5**	**B6**	**B7**	
		(Additional days elapsed to first indication)				(Additional days elapsed to first indication)			
IRB	4	0	0	1	1	0	0	2	2
SRB	4	2	0	3	5	1	1	2	4
SLYM	2	0	0	0	0	0	0	0	0
Bacteria	6	-2	-2	-4	-8	-4	0	0	-4
Fungi	6	0	0	-2	-2	0	-2	0	-2
	22	0	-2	-2		-3	-1	4	

Table II. Demand Study – BART & Dipslide Data Summary

* For B1 (control) values indicate the days elapsed to the first indication of bioactivity. Highlighted spaces denote those samples where no indication of bioactivity was observed for the duration of all observations

To aid in the interpretation of these numerical values, the right-most column (for each biocide) and the lowest row (for each well) give the sum of additional days elapsed for a specific test and specific biocide dose, respectively (with higher sums indicating better biocidal performance). For example, this sum for all doses of PAA for the bacteria dipslide test for EW-2S, is given as "13"

in sixth column in Table II. Also, the bottom row gives the sum of additional days elapsed for all tests for a specific dose of a biocide. For example, this sum is given as the number "8" for all tests on the low dose of PAA in EW-2S. These sums assist in interpreting the effects of one biocide compared to the other, or the overall microbial control of one dose versus another for a specific biocide, among other comparisons. Based upon data in these two tables, some conclusions can be itemized below. Note that the terminology employed here refers to the dipslide tests as indicating non-fastidious bacteria, and the BART tests indicating fastidious bacteria, with the latter category requiring special conditions for growth, and the former not necessarily so.

EW-2S Data:

- Overall, PAA clearly outperformed THPS.
- Overall, THPS gave relatively modest microbial control.
- PAA showed good direct correlation between dose and microbial control.
- While THPS gave worse control overall compared to PAA, it worked best on IRB at its highest dose.
- PAA gave best control of both fastidious and non-fastidious bacteria, while THPS gave only moderate control of fastidious bacteria and no control of non-fastidious bacteria.
- The lowest PAA dose gave better control than all doses of THPS.
- PAA gave four instances of no microbial indication during the observation period (see yellow highlights in Table II), while THPS gave none.
- THPS outperformed PAA in only one specific instance: SLYM at the highest dose of both biocides.

EW-2D Data:

- Overall microbial activity in the deeper aquifer is less prominent and dominated by fastidious bacteria.
- PAA and THPS performed equivalently in control of fastidious bacteria, with PAA controlling SRB better, and THPS controlling IRB better.
- PAA at all doses and THPS at its lowest dose appeared to serve as substrate for non-fastidious bacteria, reducing the days elapsed until first observations of microbial activity.
- THPS at mid and high dosing gave good control of non-fastidious bacteria.

Dipslide data for fungi were inconsistent and fungal growth was not controlled by either biocide in most cases. Dipslide data on control samples indicate the presence of fungi at less than 10 cfu/ml, a very modest level, particularly compared to those observed for all bacteria testing done. For this reason, the study authors conclude the risk of fungal growth contributing to microbial deposition to be modest.

The numerical method used here to rate biocide performance is not the only way to interpret BART/Dipslide data, it is simply convenient. This method ignores some more complex details of the raw data, such as how fast or how much, after first indication/observation, microbial activity *increases* in any particular test. Such detailed interpretive work was deemed beyond the scope of this study, the objectives of which focused on a qualitative comparison of two biocides. The numerical method used here was deemed sufficient for this objective.

Biocide demand can be defined as the amount of biocide consumed in cidal reactions. This value can be estimated by measuring biocide concentration, upon introduction to water samples and then at various times subsequent. In the case of PAA, this data gives a realistic estimate of the dose of biocide required to satisfy demand. In the case of THPS however, it indicates the demand for biocide, but not the appropriate dose: THPS is known to have a minimum threshold concentration below which no cidal effect is observed, generally identified in the range of 15 mg/l. In all cases, demand at sixty minutes was directly proportional to the initial dose. Determination of a reasonable dose requires consideration of not only the demand, or loss, at a given dose, but also the effectiveness of microbial control as measured by BART/Dipslide data.

Data collected in this phase of field work clearly showed the dramatic difference in oxidation-reduction potential between the shallow and deep aquifers. Residuals at 60 minutes for PAA suggest a less than 2ppm demand in EW-2S, but greater than the highest dose in EW-2D (due to increased demand associated with the low ORP of water samples from EW-2D). Residuals at 60 minutes for THPS suggest that no cidal activity occurred in the EW-2D sample at the lowest dose, indicative of a threshold concentration for cidal activity, with approximately 3 ppm demand in mid- and high dose of THPS. Residuals at 60 minutes for THPS in the EW-2S samples showed demand of about 3 ppm in all cases.

Impacts on Chromium

Laboratory analytical results from samples collected during the biocide demand study give information about key inorganic constituents, including hardness and the redox-sensitive metals chromium and iron. While some conclusions can be drawn from this analysis, these metals were only present at part per billion concentrations, so conclusions about oxidation are tempered by that fact. That said, chromium in the shallow aquifer was found to be already oxidized. Chromium in the deeper aquifer is present at much lower levels and did not oxidize to any significant extent due to PAA.

Deposit Control Efficacy

Laboratory analytical results from samples collected during the biocide demand study confirmed expectations about iron oxidation: Iron oxidation in the deep aquifer appears to occur with all doses of PAA, and low/mid dosing THPS, but appears suppressed at high dose THPS (which is known to be a mild iron sequestrant). Iron is substantially oxidized under all conditions in the shallow aquifer samples, which is unusual, but not unheard of in shallow aquifers. Hardness (calcium and magnesium) was included in analytical work because it presents a deposition threat and creates demand for deposit control chemistry. Hardness numbers were found to be consistent throughout, for each well, with much higher hardness in shallow aquifer.

Deposit control study lab data and subsequent analyses were used primarily to document the effect of deposit control agents on iron oxidation and mobility, with the intention of modeling the time period recovered groundwater is extracted from, and conveyed to, the proposed treatment plant, and then treated for iron removal by greensand, approximately thirty minutes.

While the data derived from this work includes the potential foulants calcium, magnesium, and manganese, the primary foulant studied was iron. This is because application of the oxidizing

biocide PAA is likely to cause deposition of redox-sensitive iron in particular, with little effect on the other inorganic foulants. Analysis of this data is given in Table III and IV below.

Deposit control chemicals can exert sequestration, dispersancy and crystal growth modification (or delay). Sequestration involves the formation of a soluble complex by reaction of an agent and a target foulant. Dispersancy involves the imparting of excess charge from agents to foulants resulting in an extension of turbidity by electrostatic repulsion of particulates. Crystal modification involves the sorption of an agent on crystal growth surfaces, interrupting the process of crystal particle growth.

For each deposit control agent, three sets of iron data were collected: initial state, after a 30-minute PAA/iron reaction time and after passing through greensand columns. Each of these data sets includes an unfiltered sample, and two filtered samples using 0.45-micron and 0.1-micron filters. This staged filtration process allows an assessment of particle formation and growth. Iron solubility is also often estimated by the use of filtration in the field, but this process tends to slightly overestimate solubility by including fine particulates, known as colloidal iron, as "dissolved". Staged filtration allows a better characterization of colloidal iron. Because iron oxidation reactions occur relatively rapidly, field testing for ferrous iron provides the best measure of soluble iron. Due to time constraints, and the sheer volume of samples in this study, ferrous iron testing was limited to spot checks, to allow some qualitative assessment of error introduced by assuming filtered samples reflect soluble iron levels.

A detailed analysis of data in Table III and IV will reveal one anomaly in filtered results, revealing a fault in the procedures: Filters were dedicated to each deposit control agent, but reuse for both 30-minute and post-greensand samples apparently affected filtered iron results for the latter.

While the data reflecting filtered samples in Tables III and IV are interesting and useful in assessing deposit control efficacy the most important conclusions can be drawn by focusing on the unfiltered data: 1) These data show the percent "mobility," which encompasses all iron which is dissolved, sequestered and/or retained in suspension, either naturally or due to the dispersancy of deposit control agents, during the 30- minute time of travel in the subject system pipeline and greensand treatment, and 2) They also show the percent removal of iron by greensand and the impact of deposit control agents on this critical process. Iron mobility was substantially improved for all deposit control agents tested. Iron removal by greensand was not impaired by deposit control agents with the exception of EDTA, which apparently created complexation bonding which passed through the greensand, making its use in the full-scale system unadvisable.

		Fe (ug/l)		
Control	EW-2S-D1A-001	1780		initial
	EW-2S-D1A-001-F45	64.4	96.4%	% filtered
	EW-2S-D1A-001-F10	14.6	99.2%	% filtered
	EW-2S-D1A-030	1810	100.0%	% mobile
	EW-2S-D1A-030-F45	80.6	95.5%	% filtered
	EW-2S-D1A-030-F10	52.3	97.1%	% filtered
	EW-2S-D1A-END	6.26	99.7%	% removed
	EW-2S-D1A-END-F45	0.0	100.0%	% filtered
	EW-2S-D1A-END-F10	0.0	100.0%	% filtered
EDTA	EW-2S-D2-001	1860		initial
	EW-2S-D2-001-F45	1390	25.3%	% filtered
	EW-2S-D2-001-F10	1500	19.4%	% filtered
	EW-2S-D2-030	1850	99.5%	% mobile
	EW-2S-D2-030-F45	1330	28.1%	% filtered
	EW-2S-D2-030-F10	1500	18.9%	% filtered
	EW-2S-D2-END	1280	30.8%	% removed
	EW-2S-D2-END-F45	1040	18.8%	% filtered
	EW-2S-D2-END-F10	995	22.3%	% filtered
Citric Acid	EW-2S-D3-001	1870		initial
	EW-2S-D3-001-F45	1670	10.7%	% filtered
	EW-2S-D3-001-F10	1630	12.8%	% filtered
	EW-2S-D3-030	1850	98.9%	% mobile
	EW-2S-D3-030-F45	1660	10.3%	% filtered
	EW-2S-D3-030-F10	1670	9.7%	% filtered
	EW-2S-D3-END	79.3	95.7%	% removed
	EW-2S-D3-END-F45	109	0.0%	% filtered
	EW-2S-D3-END-F10	124	0.0%	% filtered
Terpolymer Dispersant	EW-2S-D4-001	1780		initial
	EW-2S-D4-001-F45	1590	10.7%	% filtered
	EW-2S-D4-001-F10	1640	7.9%	% filtered
	EW-2S-D4-030	1860	100.0%	% mobile
	EW-2S-D4-030-F45	1740	6.5%	% filtered
	EW-2S-D4-030-F10	1730	7.0%	% filtered
	EW-2S-D4-END	25.9	98.6%	% removed
	EW-2S-D4-END-F45	8.27	68.1%	% filtered
	EW-2S-D4-END-F10	10.3	60.2%	% filtered
Phosphonic Acid	EW-2S-D5-001	1780		initial
	EW-2S-D5-001-F45	1740	2.2%	% filtered
	EW-2S-D5-001-F10	1760	1.1%	% filtered
	EW-2S-D5-030	1840	100.0%	% mobile
	EW-2S-D5-030-F45	1690	8.2%	% filtered
	EW-2S-D5-030-F10	1710	7.1%	% filtered
	EW-2S-D5-END	10.6	99.4%	% removed
	EW-2S-D5-END-F45	242	0.0%	% filtered
	EW-2S-D5-END-F10	24.1	0.0%	% filtered
Silicate	EW-2S-D6-001	1810		initial
	EW-2S-D6-001-F45	22.3	98.8%	% filtered
	EW-2S-D6-001-F10	889	50.9%	% filtered
	EW-2S-D6-030	1760	97.2%	% mobile
	EW-2S-D6-030-F45	22.8	98.7%	% filtered
	EW-2S-D6-030-F10	957	45.6%	% filtered
	EW-2S-D6-END	0.0	100.0%	% removed
	EW-2S-D6-END-F45	0.0	0.0%	% filtered
	EW-2S-D6-END-F10	4.8	0.0%	% filtered

Table III. DCC Study EW-2S Lab Data Summary

		Fe (ug/l)		
Control	EW-2D-D1B-001	1860		initial
	EW-2D-D1B-001-F45	86.5	95.3%	% filtered
	EW-2D-D1B-001-F10	429	76.9%	% filtered
	EW-2D-D1B-030	1860	100.0%	% mobile
	EW-2D-D1B-030-F45	94.9	94.9%	% filtered
	EW-2D-D1B-030-F10	557	70.1%	% filtered
	EW-2D-D1B-END	0	100.0%	% removed
	EW-2D-D1B-END-F45	0	0.0%	% filtered
	EW-2D-D1B-END-F10	4.22	0.0%	% filtered
EDTA	EW-2D-D2-001	1950		initial
	EW-2D-D2-001-F45	1710	12.3%	% filtered
	EW-2D-D2-001-F10	1750	10.3%	% filtered
	EW-2D-D2-030	1910	97.9%	% mobile
	EW-2D-D2-030-F45	1780	6.8%	% filtered
	EW-2D-D2-030-F10	1760	7.9%	% filtered
	EW-2D-D2-END	1100	42.4%	% removed
	EW-2D-D2-END-F45	1070	2.7%	% filtered
	EW-2D-D2-END-F10	1020	7.3%	% filtered
Citric Acid	EW-2D-D3-001	1830		initial
	EW-2D-D3-001-F45	1780	2.7%	% filtered
	EW-2D-D3-001-F10	1800	1.6%	% filtered
	EW-2D-D3-030	1820	99.5%	% mobile
	EW-2D-D3-030-F45	1780	2.2%	% filtered
	EW-2D-D3-030-F10	1790	1.6%	% filtered
	EW-2D-D3-END	49.9	97.3%	% removed
	EW-2D-D3-END-F45	402	0.0%	% filtered
	EW-2D-D3-END-F10	176	0.0%	% filtered
Terpolymer Dispersant	EW-2D-D4-001	1860		initial
	EW-2D-D4-001-F45	1670	10.2%	% filtered
	EW-2D-D4-001-F10	1700	8.6%	% filtered
	EW-2D-D4-030	1800	96.8%	% mobile
	EW-2D-D4-030-F45	1680	6.7%	% filtered
	EW-2D-D4-030-F10	1710	5.0%	% filtered
	EW-2D-D4-END	176	90.2%	% removed
	EW-2D-D4-END-F45	222	0.0%	% filtered
	EW-2D-D4-END-F10	321	0.0%	% filtered
Phosphonic Acid	EW-2D-D5-001	1920		initial
	EW-2D-D5-001-F45	1750	8.9%	% filtered
	EW-2D-D5-001-F10	1780	7.3%	% filtered
	EW-2D-D5-030	1980	100.0%	% mobile
	EW-2D-D5-030-F45	1830	7.6%	% filtered
	EW-2D-D5-030-F10	1790	9.6%	% filtered
	EW-2D-D5-END	4.63	99.8%	% removed
	EW-2D-D5-END-F45	100	0.0%	% filtered
	EW-2D-D5-END-F10	12.8	0.0%	% filtered
Silicate	EW-2D-D6-001	1940		initial
	EW-2D-D6-001-F45	97.5	95.0%	% filtered
	EW-2D-D6-001-F10	1120	42.3%	% filtered
	EW-2D-D6-030	1850	95.4%	% mobile
	EW-2D-D6-030-F45	82.3	95.6%	% filtered
	EW-2D-D6-030-F10	1090	41.1%	% filtered
	EW-2D-D6-END	6.46	99.7%	% removed
	EW-2D-D6-END-F45	0.0	100.0%	% filtered
	EW-2D-D6-END-F10	0.0	100.0%	% filtered

Table IV. DCC Study EW-2D Lab Data

Conclusions

Key conclusions that are the primary target of this field work are discussed here.

Comparison of biocides and their demand: While both THPS and PAA showed some level of microbial control, PAA showed substantially better control at much lower dose than THPS in the shallow aquifer groundwater. Due to the ORP demand in the deep aquifer, the distinction in performance was not as dramatic. Data suggested that PAA may have served as a microbial nutrient source, which is a common concern in systems using PAA with high retention times. This is because PAA degrades over time to yield hydrogen peroxide and acetic acid, with the latter potentially serving as substrate for microbial growth. Interestingly, THPS also may have had this effect at low dose (possibly below the cidal threshold). It should be noted that the retention time involved in the BART and Dipslide testing is on the order of days, while the pipeline residence time of the proposed remediation system, which is the target of biocidal action, is less than 30 minutes. Aside from these issues, the two contending biocides performed roughly equally in the deep aquifer groundwater.

Oxidation of Iron by PAA: Data from this study did clearly show that oxidation of iron with the use of PAA is of concern, and consideration of its use must accompany consideration of the application of deposit control chemical.

Assessment of Deposit Control Chemicals: Deposit control chemicals generally performed as expected in terms of retaining mobility of iron. Some distinction occurred in terms of subsequent removal of iron using greensand in the presence of deposit control chemical, with EDTA keeping a substantial portion of iron mobile through greensand. The four remaining deposit control chemicals studied gave excellent iron mobility but did not for the most part interfere with removal of iron in greensand. They were retained for further consideration pending fate analysis and cost comparisons.

Additional Studies

As a follow-up to the field study, the team performed laboratory bench scale tests to better understand the fate of biocides and deposit control chemicals on planned unit operations. This work excluded EDTA, but included all other reagents included in the field study. It involved running a solution of each reagent through bench-scale greensand and activated carbon columns, with subsequent measurement of the fate of regents through these processes. It also involved an assessment of the ultraviolet transmittance (UVT) of each regent solution. This parameter is important in determining any negative impacts of chemical additives to the advanced oxidation treatment unit. Analysis of the data from this additional study is being finalized.

References

Ash, Michael and Iren ed, Handbook of Water Treatment Chemicals, Gower, Brookfield VT, 1996

Atkins, P.W., Physical Chemistry, Oxford University Press, Oxford, UK, 1978

Bodek, Igmar et al editors, Environmental Inorganic Chemistry, Pergamon Press, 1988

Budavari, Susan et al ed., The Merck Index, Merk & Co, Rahway, NJ, 1989

Callahan, Michael et al, Water related Environmental Fate of 129 Priority Pollutants, Volume I, EPA Contract # 68-01-3852&67, 1979

Dean, John A. ed., Lange's Handbook of Chemistry 13th edition, McGraw Hill, NY, 1985

Deutsch, William J., Groundwater Chemistry: Fundamentals and Applications to Contamination, 1997, Lewis Publishers/CRC, 1997

Kemmer, F. N., The Nalco Water Handbook, 2nd Edition, McGraw-Hill Book Company, New York, 1988

Kim, N.H. et al, Enhanced Bactericidal Action of Acidified Sodium Chlorite Caused by the Saturation of Reactants, Journal of Applied Microbiology, 2014 Volume 116, pages 1447—1457

Nikolaidis, et al, Vertical Distribution and Partitioning of Chromium in a Glaciofluvial Aquifer, Groundwater Monitoring and Remediation, Summer 1994, pages 150-159

Patterson, James W., Industrial Wastewater Treatment Technology, 2nd ed, Butterworths, Boston, 1985

Rogers, Nathan D., "Chromium Oxidation by Disinfectants and Oxidants Used in Drinking Water Treatment" (2016). All Graduate Theses and Dissertations. 5028. https://digitalcommons.usu.edu/etd/5028

Schmidt, R.L., Thermodynamic Properties and Environmental Chemistry of Chromium, 1984, Pacific Northwest Laboratories (Battelle), PNL 4881

Sienko, Michell J. & Plane, Robert A., Chemistry: Principles and Application, McGraw Hill, NY, 1970

Silderberg, Martin S., Chemistry: The Molecular Nature of Matter and Change, McGraw Hill, NY, 2009

Ulmer, Nancy Sue, The Effect of Chlorine on Chromium Speciation in Tap Water, EPA Water Research Engineering Laboratory, EPA/600/M-86/015, June 1986