Evaluation of Silica Removal Alternatives Mint Farm Regional Water Treatment Plant

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Introduction

The City of Longview (City) and Beacon Hill Water and Sewer District (District), of Washington State developed the Mint Farm Regional Water Treatment Plant (MFRWTP) which includes a new groundwater wellfield, and treatment facilities for iron and manganese removal from the source water. The Mint Farm supply began operating on January 31, 2013. Soon thereafter, some customers began experiencing objectionable taste, odor and color of their drinking water when the new source was introduced, replacing the previous surface water supply system. The City and District received extensive customer input and conducted water quality monitoring, flushing, distribution system ice pigging, and in some cases, main replacement to address many of the concerns.

Most of the discoloration problems were addressed in 2013. However, concerns remained over taste and odors and silica coating on glassware, showerheads, appliances, and other products the water contacted and was allowed to dry upon.

The taste and odor issues were identified as most likely the result of chlorinating organic nitrogen compounds in the well water, and hydrogen sulfide reversion from polysulfide compounds in customer's premise piping where reducing conditions may be present.

As a result, the City and District decided to install a system to add dissolved oxygen to the water supply to mitigate both the taste and odor issues and provide additional stability to distribution system pipe scaling potential.

To address the silica issues, the City and District requested an alternatives treatment strategies evaluation including laboratory testing be conducted to determine potential solutions to reduce the silica entering into the distribution system from the groundwater supply. Upon discussion with the City and the District, it was decided to conduct an evaluation of the following five treatment alternatives:

1. Electrocoagulation
2. Aluminum precipitation
3. Lime softening
4. Reverse osmosis
5. Ion exchange

Bench (Laboratory) testing using water from the MFRWTP was conducted on the first four alternatives in order to witness and document the effectiveness of each treatment process and to provide information in order to determine the appropriate size of capital facilities and determine ongoing O&M needs. Ion Exchange effectiveness and costs were developed using two ion exchange models developed by the

DOW Chemical Company and Purolite and were not bench tested. Each of the alternatives are discussed below.

Introduction to Silica Removal

The groundwater supply for the MFRWTP is provided by water pumped from the underground formation known as the Columbia River Basalt group. This formation is a large igneous formation that underlies a large area of the Pacific Northwest, including the Columbia River channel, in Oregon and Washington States[1]. Silicon concentrations in the Columbia River Basalts are approximately 50% of the minerals makeup.[1]

Total silica measured in water is in either the reactive or colloidal form. The City of Longview has tested for reactive silica and colloidal silica and has found that in the Mint Farm supply, all of the measureable silica is in the reactive form.

The reactive portion of the total dissolved silica can be measured using the standard molybdate colorimetric test. The reactive form is silicon dioxide dissolved in water, creating the compound monosilicic acid (H_4SiO_4), as shown in Equation 1:

$$SiO_2 + 2H_2O \quad H_4SiO_4 \qquad \text{Eq. 1}$$

Silica is relatively un-ionized at most natural pH levels, but can dissociate to $H_3SiO_4^-$, as shown in equation 2, at pH above 9.

$$pK_a = \frac{[H_3SiO_4^-][H^+]}{[H_4SiO_4]} = 9 \text{ to } 10\text{, depending on the silica concentration.} \qquad \text{Eq. 2}$$

Monosilicic acid attracts four additional water molecules beyond the two that make up part of the molecular structure in the hydrated state. The structure exists as shown in Figure 1.

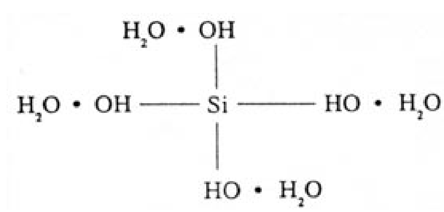


Figure 1. Monosilicic acid structure[2]

The colloidal species is generally thought to be either silicon that has polymerized with multiple units of silicon dioxide, or silicon that has formed loose bonds with organic compounds or with other complex inorganic compounds -- usually aluminum and calcium oxide structures.

Silica Treatment Options

Several technologies have been used for silica removal in industrial water applications, and some in municipal applications. Treatment systems to remove silica in municipal applications nearly always have other treatment objectives like softening or total dissolved solids reduction. The City of Longview's objective is solely the reduction in silica content, but some of the treatment options provide these additional benefits.

The treatment technologies investigated included electrocoagulation – filtration, precipitation-filtration, lime softening, reverse osmosis, and ion exchange. Each of these technologies has its benefits and drawbacks as discussed below.

Electrocoagulation

Electrocoagulation has been used for several years in reverse osmosis (RO) pretreatment, cooling tower, and produced water applications[6]. WaterTectonics, of Everett, WA also has optimized removal using the addition of aluminum precpitates[7]. Other vendors also provide equipment for EC treatment, although WaterTectonics was consulted due to their locale, and sites that have their system installed in SW Washington.

Precipitation

Sandia National Laboratories[4] recently tested a number of precipitates for silica removal in cooling tower water, including aluminum sulfate, aluminum chloride, sodium molybdate, polyaluminum chloride, magnesium chloride, lime softening and sodium aluminate. The results showed that several precipitates could achieve greater than 75% removal, as shown in Table 1.

Table 1

Sandia National Laboratory Silica Precipitants that achieved greater than 75% Removal

Precipitant	Best % Silica Removed	Efficiency as ppm SiO2/ppm Al	Optimizing Conditions	Other Considerations
Sodium Molybdate*	95%	0.05	pH<4	Expensive
PAX 18 (Proprietary polyaluminum chloride)	99%	0.43	pH 8.0 – 8.2	Proprietary, large NaOH demand
$AlCl_3$** (Aluminum chloride)	92-98%	0.41 – 0.44	pH 8.0 – 8.2	Acidifying, NaOH demand
$NaAlO_2$ (Sodium aluminate)	94%	0.47	pH 8.0 -8.2	Slightly alkalizing, small H_2SO_4 demand

*Sodium Molybdate and another precipitate (PAX10) were only tested on concentrated tower water, while data from other candidates comes from tap water. Larger amounts of SiO_2 are available for capture from tower water. (PAX10 did not remove more than 50% of the silica)

**The efficiency range for AlCl3 reflects difference between alkali pretreatment (pH >11) or not, with the pretreatment giving a slightly better outcome

Lime Softening

Lime softening has been widely used in industrial applications, primarily for cooling tower and boiler feed applications. In lime softening, silica is removed by adsorption onto magnesium precipitates, which generally occur at higher pH (above 10.5, and often require addition of a magnesium source)[2]. The most efficient way to add magnesium is through the addition of magnesium chloride.

Reverse Osmosis

Reverse osmosis (RO) works effectively for silica removal for both colloidal and reactive forms. Membrane fouling is an issue above 200 ppm in the concentrate, so multiple stages are difficult to implement, and the concentrate volumes are often large (20 to 30% of the feed rate).

Ion Exchange

Ion Exchange has been used effectively for silica removal[5]. Silica can only be removed in its ionized state, so pH adjustment above 9.5 is required. Strong base anion exchange resin in the hydrogen form is the most effective means of removal. Removal efficiencies and selectivity are similar to bicarbonate alkalinity. A specific type of two stage ion exchange has been developed, and it is referred to as a *desilicizer*. An anion desilicizer consists of a strong cation exchange resin in the sodium form (a water softener) followed by a strong base anion exchange resin in the hydroxide form. Demineralizers are also used for silica removal. Each type of ion exchange is subject to resin fouling from silica and can experience chromatographic peaking as sulfate, nitrate, chloride or other more selective anions displace the silica.

Bench Testing

Bench testing of Electrocoagulation, Lime Softening, Precipitation, and flow through testing of Reverse Osmosis membranes, using water collected from the Mint Farm, and their abilities to remove Silica are discussed below. Based on the previous water supply from the Fishers Lane Water Treatment Plant where Silica content was approximately 20 to 25 mg/L, the goal set for these treatment evaluations was to obtain a 50 to 75-percent reduction of Silica delivered from the Mint Farm supply system. This meant the goal of Silica content after treatment would be 14 to 28 mg/L.

Electrocoagulation Bench Testing (by Vendor)

Electrocoagulation has been used extensively in water treatment for mining water treatment, oil and gas produced water, industry process, industrial wastewater and stormwater applications, but there are very few municipal installations that use electrocoagulation for drinking water treatment. Because of that limited experience, the City contracted with a leading electrocoagulation company; WaterTectonics, of Everett, WA to conduct bench testing and help in developing Capital and Operations and Maintenance (O&M) costs for this option. Their testing report is included as Attachment A to this technical memorandum.

WaterTectonics (WT) testing used a bench-top EC unit, using aluminum (AL) anodes. In addition, WT checked the EC results using chemical precipitation with multiple aluminum based coagulants. Raw and filtered water samples were obtained from the City of Longview for the testing. 500 milliliter (mL) samples were tested using batch treatment laboratory scale EC at a constant current and varying treatment times. WT calculated theoretical Al doses based on their EC treatment conditions. Chemical precipitation was conducted in a similar manner. The pH was corrected to the City's treatment goal of approximately 7.7. Rapid mixing and flocculation were simulated in the 500 mL sample jars, then the samples were allowed to settle and the supernatant was filtered using 8 micron filter paper. Figure 2 shows the results of the EC silica reduction of treated water. Figure 3 shows the comparison of the EC results with multiple precipitates used by WT.

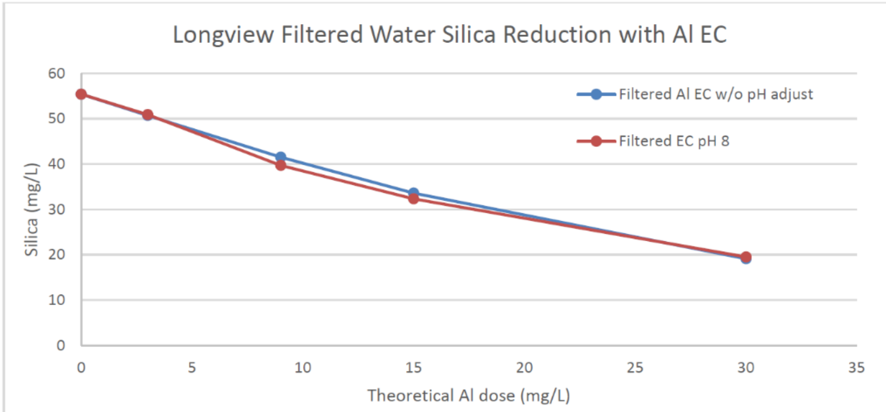


Figure 2 – WaterTectonics Bench Scale EC treatment of Longview Filtered Water for Silica Reduction

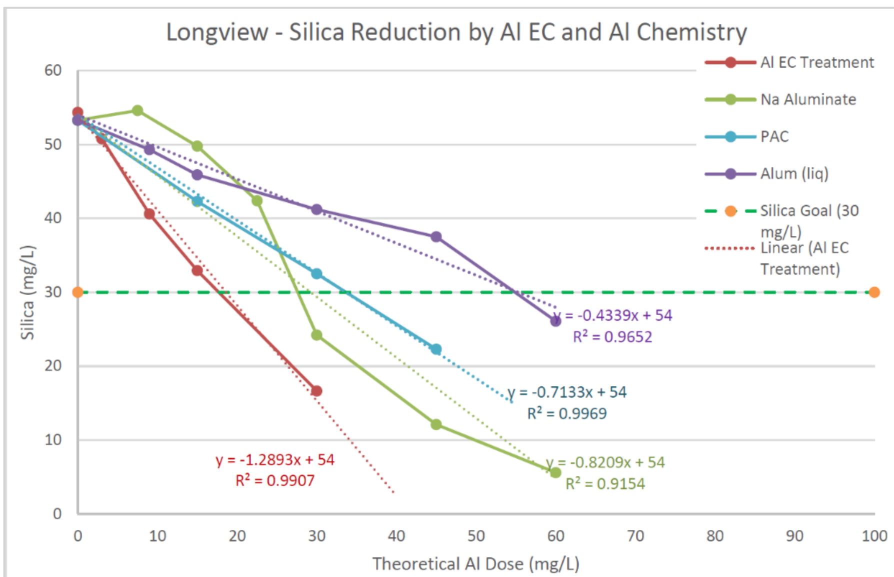


Figure 3 – WaterTectonics Bench Scale EC and Chemical treatment comparison

The results indicate that EC was more effective than Chemical Precipitation when comparing them on the basis of Aluminum dose. The EC treatment also did not require pH adjustment as the chemical treatment alternatives did.

The silica goal, as shown as the green dashed line on Figure 3, represents approximately a 50% reduction in silica from the Mint Farm system, but the testing clearly shows that removal of 75% or greater can be obtained.

CH2M Bench Testing

CH2M also obtained samples of raw water and filtered water from the Mint Farm system. Raw water was used for testing the lime softening and precipitation options, whereas the filtered water was used for the reverse osmosis flow through testing.

Water Characterization

The characterization of raw and filtered waters as currently treated, is shown in Table 2.

Table 2. Mint Farm Raw Water and Filtered Water Characterization

Parameter	Units	Raw Water	Filtered Water
Barium	µg/L	13.6	19.8
Boron	µg/L	<100 U	29.3 J
Calcium	µg/L	33,000	30,400
Iron	µg/L	957	<10.0 U
Magnesium	µg/L	9,140	8,770
Manganese	µg/L	630	0.41 J
Potassium	µg/L	3,960	4,110
Total Silica	µg/L	56,900	54,300
Reactive Silica	µg/L	59,000 S	68,000 S
Sodium	µg/L	11,700	14,400
Strontium	µg/L	93.2	92.5
Hardness, Ca	mg/L as $CaCO_3$	82.4	75.9
Hardness, Mg	mg/L as $CaCO_3$	37.6	36.1
Hardness, total	mg/L as $CaCO_3$	120	112
Alkalinity, total	mg/L as $CaCO_3$	47.3	102
Alkalinity, bicarbonate	mg/L as $CaCO_3$	<5.00 U	102
pH	Units	7.45	7.5
Turbidity	NTU	3.78	0.31
Conductivity	µS/cm	296	305
Total Dissolved Solids	mg/L	211	223
Ammonia	mg/L-N	0.16	<0.10 U
Nitrate	mg/L-N	<0.010 U	0.0098 J
Nitrite	mg/L-N	<0.010 U	<0.0030 U
TKN	mg/L-N	0.52	0.26
Chloride	mg/L	28.4	32.2
Sulfate	mg/L	1.08	1.18
Fluoride	mg/L	<0.20 U	0.19 J
TOC	mg/L	1.52	1.04
Hardness, Ca	mg/L as $CaCO_3$	86	80.0
Hardness, Mg	mg/L as $CaCO_3$	32	28.0
Hardness, total	mg/L as $CaCO_3$	118	108
J	= Estimated value below reporting limit.		
S	Reactive Silica is a wet chemistry method that is not as accurate as the method for measuring Total Silica. These results indicate that essentially all of the Total Silica is in the reactive or ionized form.		
U	= Not detected at specified detection limit.		

Laboratory Materials

Reagents used in the bench testing are included in Attachment B, along with all of the bench testing results conducted by CH2M. Bench tests were conducted using 2 liter cells and a Phipps & Bird six-gang Jar Tester. Rapid mixing was simulated using 300 revolutions per minute (RPM) for 1 minute. Three stage flocculation was simulated at 60, 40 and 20 RPM for 10 minutes per stage. Flocculation observations and photos are included in Attachment B.

Lime Softening

Figure 4 shows the results of lime softening jar tests without magnesium chloride addition. Silica was slightly removed as pH increased from 10.2 to 11, but none of the results achieved 50% or 75% removal.

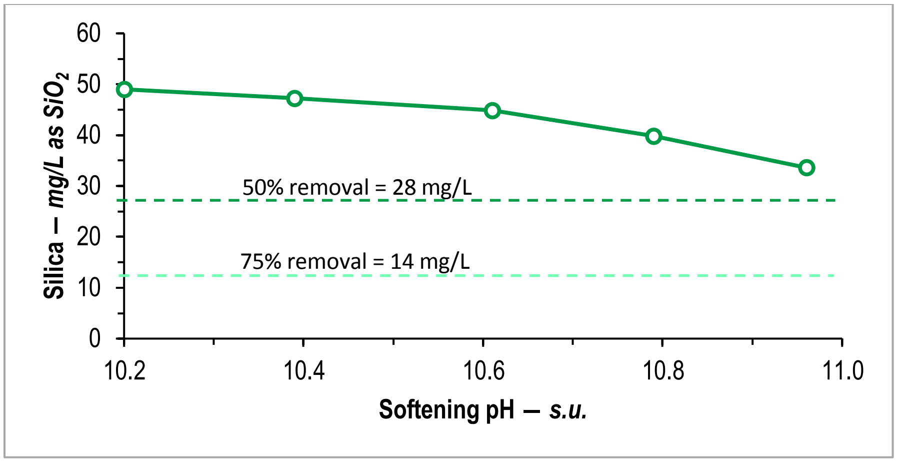


Figure 4, Silica removal vs pH of lime softening, no magnesium chloride removal

The second set of jar tests was performed with lime softening at pH 11 and the addition of 50 mg/L of magnesium chloride as magnesium. The mixing was varied from 15 minutes to 120 minutes. Figure 5 shows the silica concentration for the various mixing times. The figure shows that lime softening with magnesium chloride reduced silica by at least 50% after 30 minutes of mixing time, but even with 120 minutes of mixing, 75% removal was not achieved. Finished water pH was calculated using WaterPro™ software with carbon dioxide reduction. The resulting softened water at pH 7.8 was approximately 80 mg/L as $CaCO_3$, which represents a 33% reduction from the raw water.

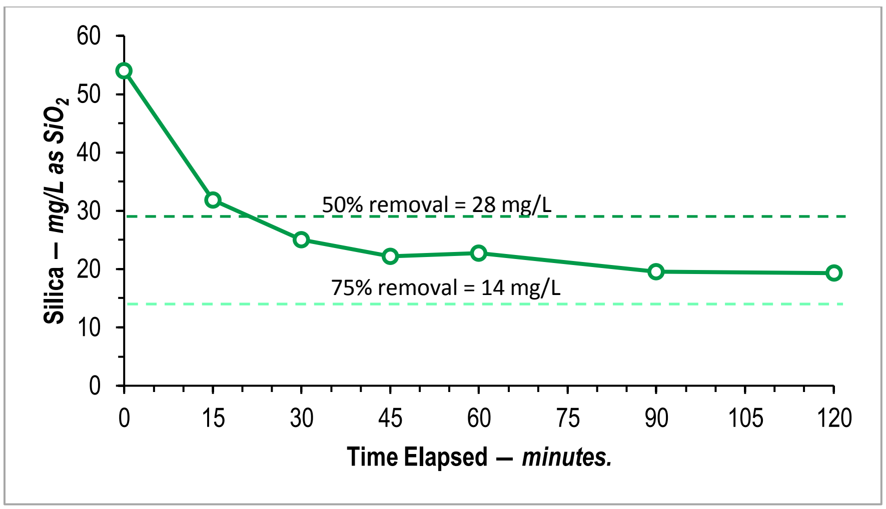


Figure 5. Reactive silica with lime softening and magnesium chloride addition, various mixing times

Precipitation

Jar tests were conducted using sodium aluminate and aluminum sulfate (alum). The best results were obtained with pH adjustment to approximately 8.0 to 8.2. Figure 6 shows the precipitation results for alum and sodium aluminate. The sodium aluminate reduced silica by more than 75% for each of the three doses shown (40, 80 and 120 mg/L as Al). The alum significantly reduced silica, but not as effectively as sodium aluminate. Sodium aluminate increases pH, so pH reduction was accomplished with sulfuric acid. Alum lowers the pH, so pH adjustment was conducted with sodium hydroxide.

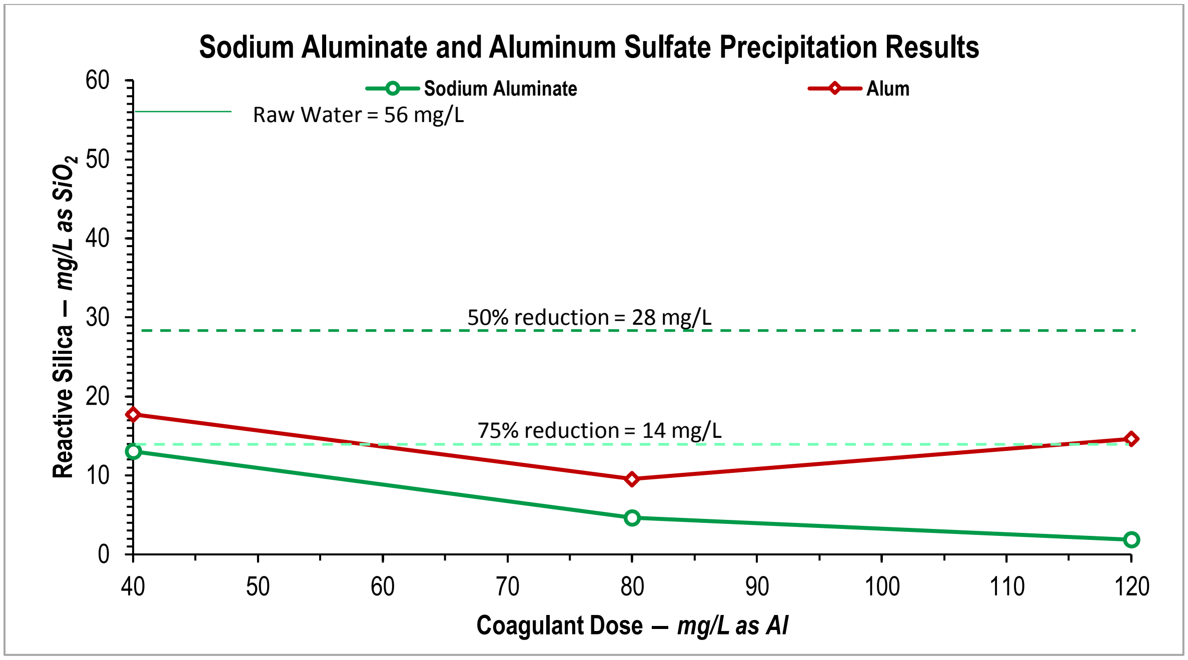


Figure 6. Silica levels with Precipitation using Aluminum Sulfate and Sodium Aluminate with pH adjustment

Reverse Osmosis

Reverse osmosis was tested using a flow through RO skid, shown in Figure 7. The RO membrane was a Hydronautics model ESPA2-2540 cartridge. This membrane is a low pressure RO membrane, typically used for brackish water treatment. Typical feed pressures are 200 to 300 psi. The molecular weight cutoff for this membrane is 50 daltons, so it is expected to remove silica, but may not remove salts. The reactive silica and total dissolved solids (TDS) in the Feed water (pre-RO filtered water from the Mint Farm WTP), Permeate (post-RO finished water to customers) and the Concentrate (waste stream), are shown in Figure 8. A comparison of water quality for each of the three RO water streams is included in Table 3. The RO membrane essentially removed all of the silica from the feed stream, and all of the TDS. The RO membrane was operated at a 61% recovery rate. This recovery rate means that 39% of the feed water was expelled as concentrate, or as a waste stream. In some low salt RO applications the recovery rate can be much lower, however with silica there are concerns over membrane fouling, and this recovery rate would also be expected at full scale.

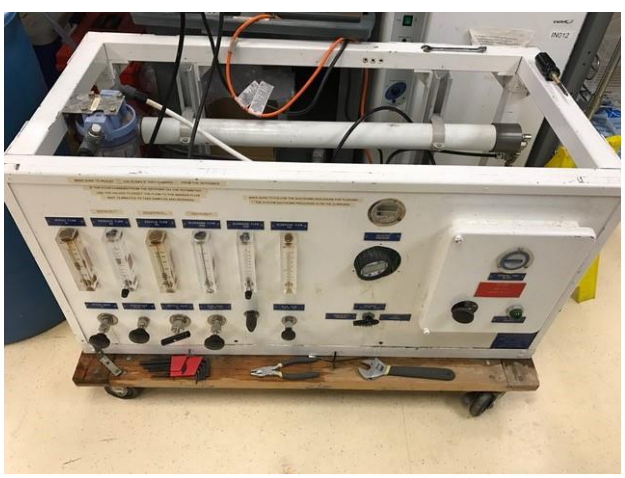


Figure 7. Flow through RO Skid with Hydronautics ESPA2-2450 RO cartridge

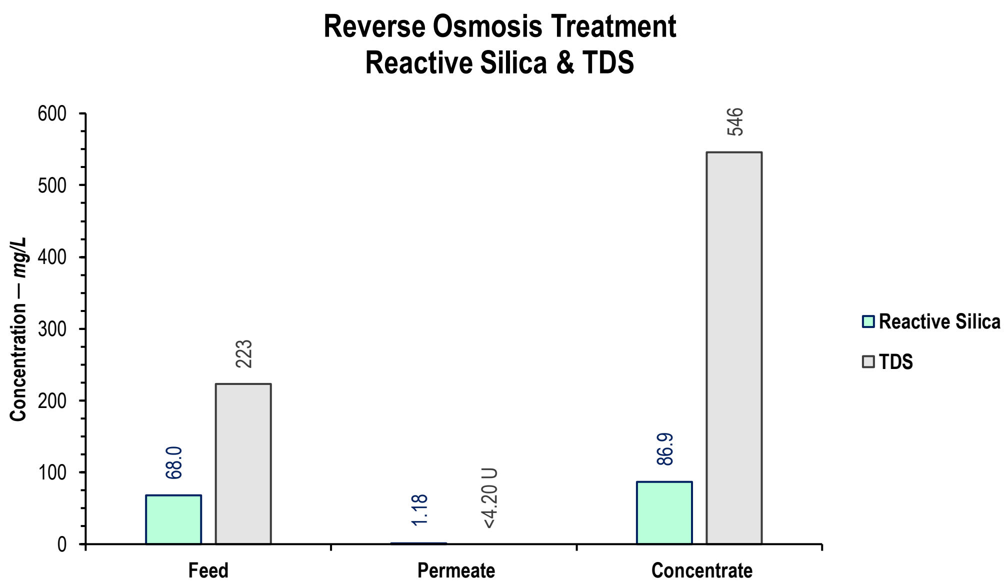


Figure 8. Silica and Total Dissolved Solids for Reverse Osmosis feed, permeate and concentrate streams

Table 3. Comparison of RO Feed Water, Permeate, and Concentrate Streams

Parameter	Units	RO Feed — *61% Recovery*	RO Permeate — *61% Recovery*	RO Concentrate — *61% Recovery*
Barium	µg/L	19.8	<0.25 U	68.2
Boron	µg/L	29.3 J	21.2 J	37.3 J
Calcium	µg/L	30,400	<200 U	82,500
Iron	µg/L	<10.0 U	<10.0 U	<10.0 U
Magnesium	µg/L	8,770	52.2 J	22,900
Manganese	µg/L	0.41 J	<0.025 U	1.23
Potassium	µg/L	4,110	300 J	10,500
Total Silica	µg/L	54,300	1,190	145,000
Reactive Silica	µg/L	68,000 S	1,180 S	86,900 S
Sodium	µg/L	14,400	1,160	35,200
Strontium	µg/L	92.5	<2.50 U	238
Hardness, Ca	mg/L as $CaCO_3$	75.9	<0.50 U	206
Hardness, Mg	mg/L as $CaCO_3$	36.1	0.21	94.3
Hardness, total	mg/L as $CaCO_3$	112	0.21	300
Alkalinity, total	mg/L as $CaCO_3$	102	<5.00 U	251
Alkalinity, bicarbonate	mg/L as $CaCO_3$	102	<5.00 U	251
pH	Units	7.5	7.9	7.0
Turbidity	NTU	0.31	0.15	0.49
Conductivity	µS/cm	305	8.16	749
Total Dissolved Solids	mg/L	223	<4.20 U	546
Ammonia	mg/L-N	<0.10 U	<0.10 U	<0.10 U
Nitrate	mg/L-N	0.0098 J	<0.0028 U	0.014
Nitrite	mg/L-N	<0.0030 U	<0.0030 U	<0.0030 U
TKN	mg/L-N	0.26	0.24	0.79
Chloride	mg/L	32.2	0.89	84.8
Sulfate	mg/L	1.18	0.72	3.04
Fluoride	mg/L	0.19 J	0.065 J	0.51
TOC	mg/L	1.04	<0.20 U	2.56
Calcium	mg/L	32.0	0.40	84.9
Magnesium	mg/L	6.80	<0.24 U	18.5
J	= Estimated value below reporting limit.			
S	=Reactive Silica is measured through wet chemistry and is not as accurate as the Total Silica test. Reactive Silica is used to determine how much of the Total Silica is ionized.			
U	= Not detected at specified detection limit.			

Conceptual Designs and Cost Estimates

The current Mint Farm Water Regional Water Treatment Plant process flow diagram is shown in Figure 9. Conceptual designs and cost estimates are provided herein for the following treatment options:

1. Electrocoagulation
2. Aluminum precipitation
3. Lime softening
4. Reverse osmosis
5. Ion exchange

Each of these options, along with modified process flow diagrams to show how the options are integrated into the existing Mint Farm plant, are discussed below. In order to evaluate all of the options on an even platform, several cost assumptions have been made and are applied to each option.

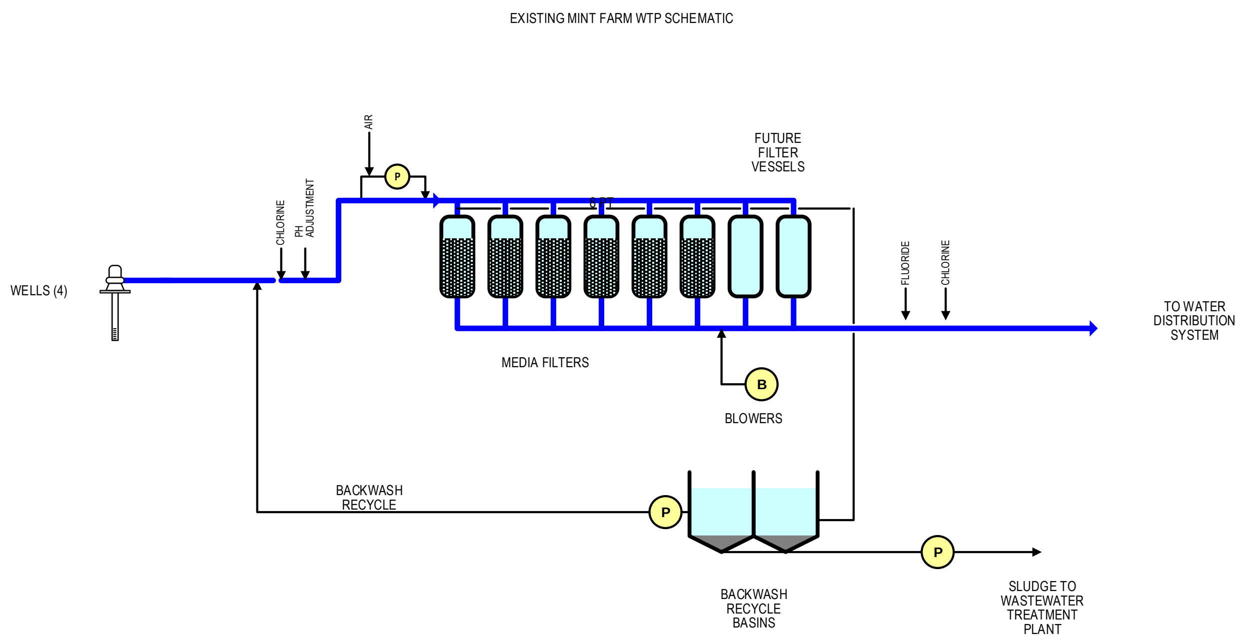


Figure 9. Existing Mint Farm Regional Water Treatment Plant Process Schematic

Electrocoagulation

WaterTectonics provided capital equipment costs, which are included in Attachment A. The modified process flow diagram is shown in Figure 10. New equipment includes:

- Twelve electrocoagulation cells (10 online and 2 redundant), which would be housed in a new CMU building
- Twelve power supplies
- An inline (in pipe) rapid mixer, in a CMU building
- Two trains of flocculation basins with 30 minutes of hydraulic residence time, covered
- Two trains of high rate clarifiers using lamella plates, covered
- In plant pump station in a CMU building
- Sludge thickener and dewatering (centrifuge with polymer feed) in a CMU building

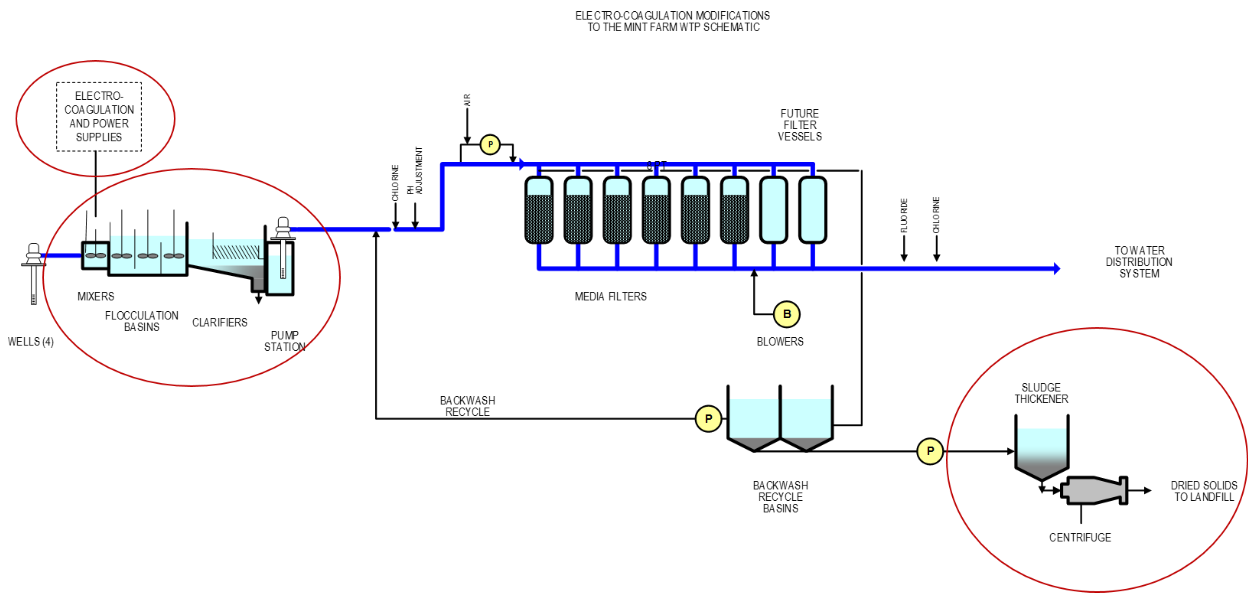


Figure 10. Electrocoagulation Modification to the Mint Farm Regional Water Treatment Plant

Precipitation

The precipitation modification for silica is shown in Figure 11, and includes the following modifications.

- A new chemical feed building (CMU building) with sodium aluminate and sulfuric acid feed systems
- An inline (in pipe) rapid mixer, in a CMU building
- Two trains of flocculation basins with 30 minutes of hydraulic residence time, covered
- Two trains of high rate clarifiers using lamella plates, covered
- In plant pump station in a CMU building
- Sludge thickener and dewatering (centrifuge with polymer feed) in a CMU building

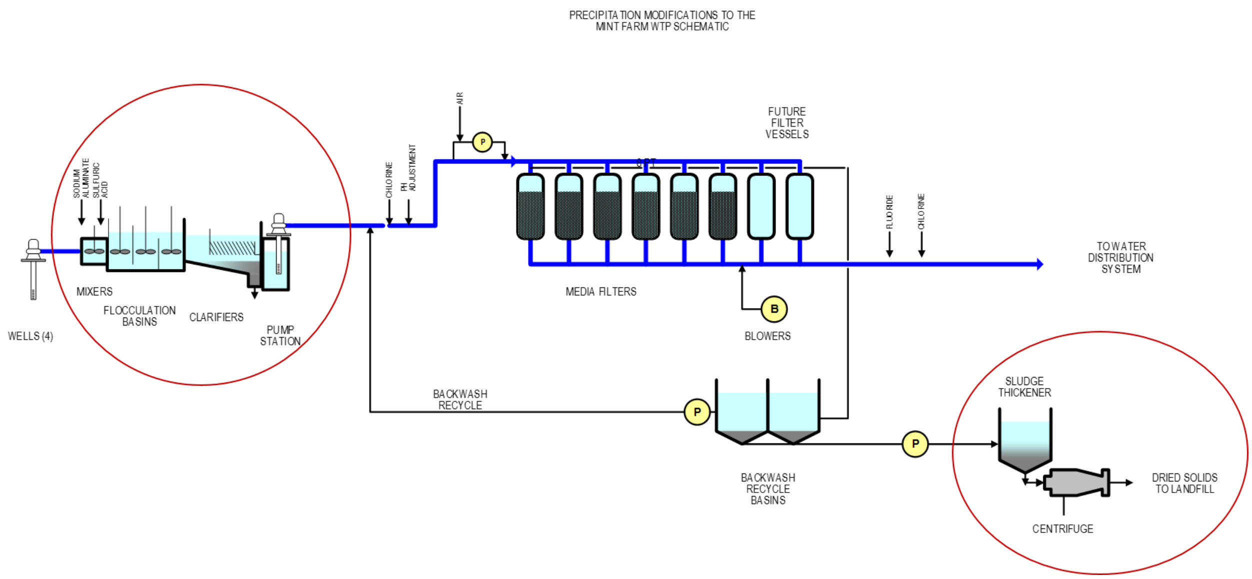


Figure 11. Precipitation Modification to the Mint Farm Water Treatment Plant

Lime Softening

Lime softening modifications are shown in Figure 12 and include the following modifications:

- A new chemical feed building (CMU) with lime, soda ash and magnesium chloride feed systems
- Two center-feed, upflow, sludge contact clarifiers
- In plant pump station in a CMU building
- Sludge thickener and dewatering (centrifuge with polymer feed) in a CMU building

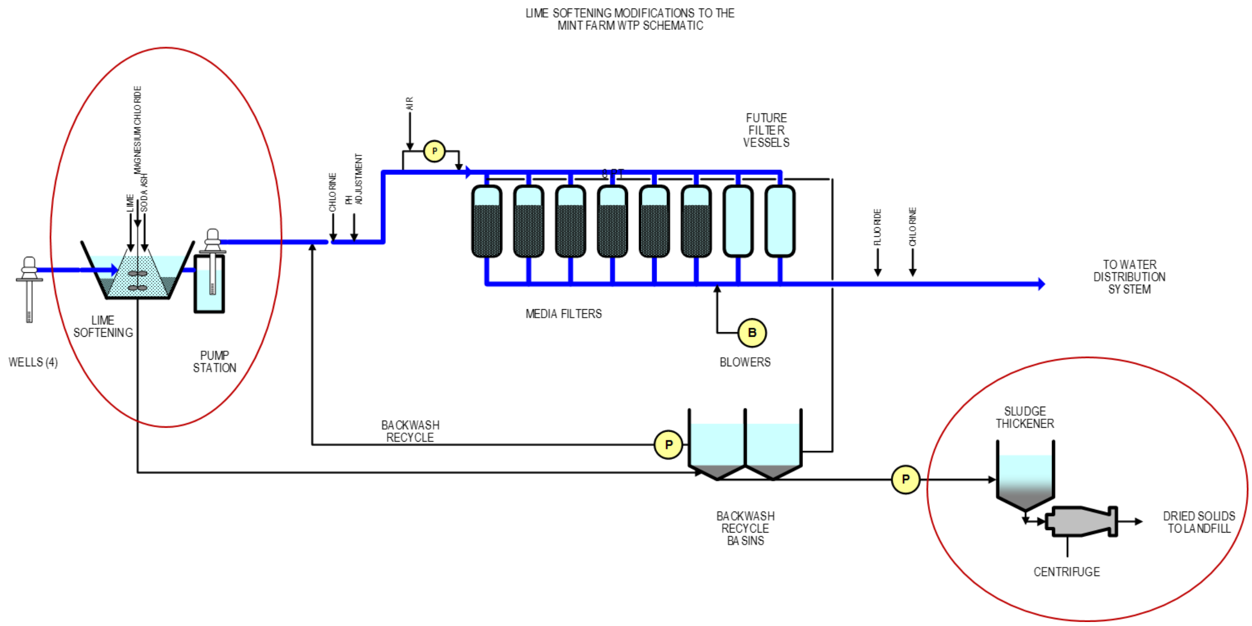


Figure 12, Lime Softening Modifications to the Mint Farm Regional Water Treatment Plant

Ion Exchange

Ion exchange modifications to the Mint Farm Water Treatment Plant are shown in Figure 13, and include the following:

- Cation and anion exchange softeners
- Regeneration equipment for salt and sodium hydroxide
- Well pump modifications

It is assumed that the ion exchange system will be a pressure filter system, requiring modifications to the well pumps to provide an additional 50 feet of total dynamic head, thereby not requiring intermediate pumping. In addition, this alternative assumes the liquid regeneration waste will be conveyed to the sanitary sewer (TDS of the waste stream is estimated at 15,000 mg/L).

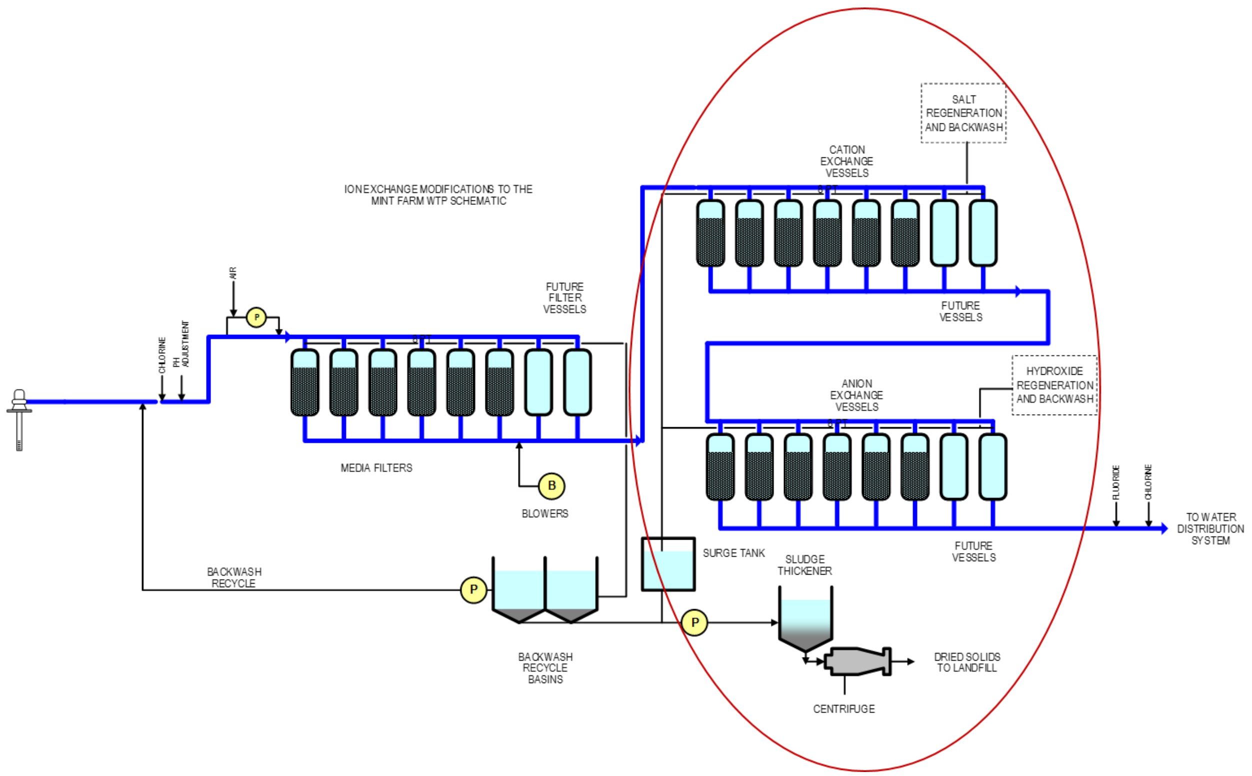


Figure 13. Ion Exchange modifications to the Mint Farm Water Regional Treatment Plant

Reverse Osmosis

The reverse osmosis modifications to the Mint Farm water treatment plant are shown in Figure 14, and include:

- Single Stage, Low Pressure RO, with clean in place system, energy recovery, and in plant pumping system, sized for 9 mgd permeate (12 mgd) feed and blended 75% RO water with 25% filtered water in a CMU building.
- A discharge pipe, and outfall to the Columbia River, which will require a new NPDES discharge permit.
- A sodium bisulfite feed system for de-chlorination prior to the RO system.

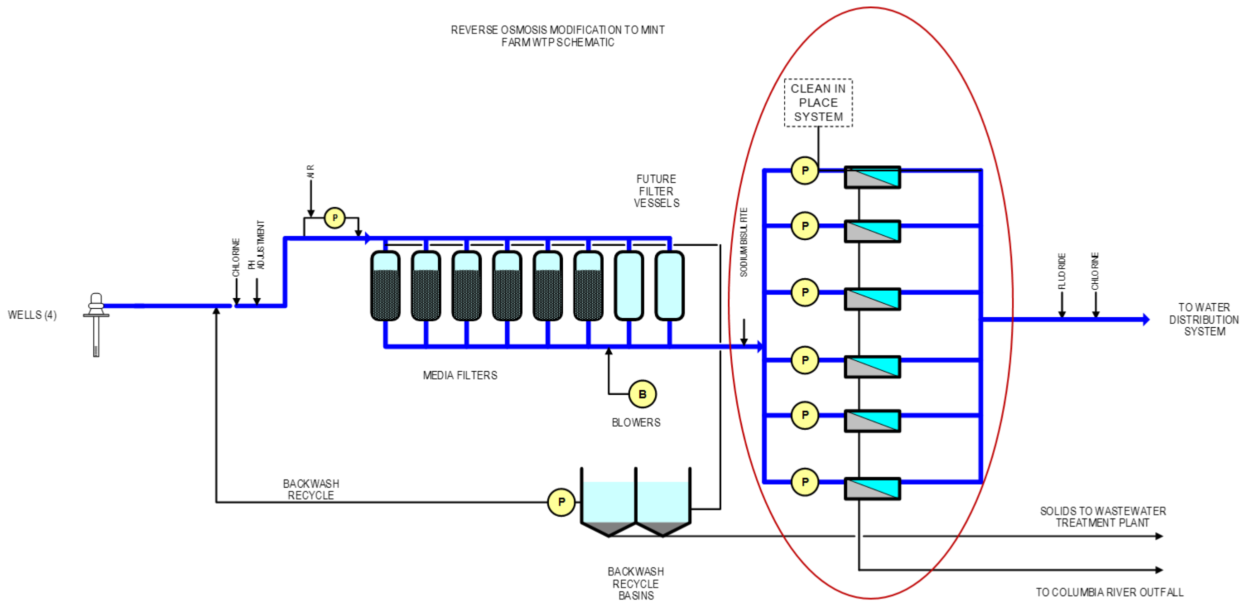


Figure 14. Reverse Osmosis Modifications to the Mint Farm Regional Water Treatment Plant

Cost Estimates

Cost estimates were prepared for each of the five alternatives for silica removal:

1. Electrocoagulation
2. Aluminum precipitation
3. Lime softening
4. Reverse osmosis
5. Ion exchange

Capital costs are presented first, followed by annual operations and maintenance costs (O&M) and then a 20-year lifecycle cost assessment.

Capital Cost Estimates

Cost assumptions for all alternatives

The following cost assumptions are provided for all options. Cost Estimate Details are shown in Attachment C.

- All facilities are housed in a CMU Building, except for flocculation and clarification facilities, which are concrete basins with building covers on top of the basins.
- Capital facilities are sized for 12 mgd.
- Capital and O&M costs are developed in March 2017 dollars.
- The construction cost index for Vancouver, WA was used (98.1% of national average).
- Tax has been included at 8.1% of the construction subtotal.
- Equipment installation was assumed to be 25% of the equipment purchase cost.
- Contractor markups are a total of 18% of the construction subtotal, and include mobilization, bonding and insurance (5%), profit (5%) and overhead (8%).
- Contingency is estimated at 25% of the total construction cost.
- Engineering, Services during construction, commissioning and start up are estimated at 20% of the construction cost including contingency.
- Capital cost financing is based on 20 years with an annual percentage rate of 4%.
- Ground improvements using preloading was assumed to be required at a cost of $500,000 for each alternative.

Capital cost estimates are summarized in Table 4. Detailed Cost estimates are included as Attachment C.

Table 4. Capital Cost Estimates for Mint Farm Water Treatment Plant Modifications for Silica Removal

Treatment Alternative	Electro-coagulation	Precipitation	Lime Softening	Ion Exchange	Reverse Osmosis
Preloading	500,000	500,000	500,000	500,000	500,000
Well Pump Modifications				700,000	
Electrocoagulation	5,665,000*				
Rapid Mix	550,000	550,000			
Flocculation	698,000	698,000			
Clarifier	2,317,000	2,317,000			
Chemical Feed		905,000	1,792,000		301,000
Ion Exchange				9,110,000	
Solids Contact Clarifier			1,702,000		
Pump Station	777,000	777,000	777,000		
Reverse Osmosis/Pumps System					14,661,000
Sludge Thickener	844,000	1,147,000	1,409,000		
Dewatering	4,226,000	4,320,000	4,691,000		
Outfall, Transmission					393,000
Subtotal	15,577,000	11,214,000	10,871,000	10,310,000	15,855,000
Contractor Markups (18%)	2,804,000	2,019,000	1,957,000	1,856,000	2,854,000
Contingency (25%)	3,894,000	2,804,000	2,718,000	2,578,000	3,964,000
Tax (8.1%)	1,262,000	908,000	881,000	835,000	1,284,000
Construction Subtotal	**23,537,000**	**16,945,000**	**16,427,000**	**15,579,000**	**23,957,000**
Location Adjustment Cost (98.1% of Construction Subtotal)	23,090,000	16,623,000	16,115,000	15,283,000	23,502,000
Design, SDC, Start-up (20%)	4,618,000	3,325,000	3,223,000	3,057,000	4,700,000
Total	**$27,708,000**	**$19,948,000**	**$19,338,000**	**$18,340,000**	**$28,202,000**

* - See Detail provided in Table 5

The capital costs were developed using CH2M's parametric cost estimating system. The cost estimates utilize materials estimates for each unit process as shown in Attachment C. The cost estimating program does not include unit processes for Electrocoagulation, therefore a User Defined tab was developed for this unit process. The Electrocoagulation capital cost estimate includes the summary costs shown in Table 5 which includes information provided by WaterTectonics. In addition, the electro-coagulation process produces less solids, so the gravity thickener and dewatering unit process costs were reduced.

Table 5. Summary Costs for Electrocoagulation Unit Process

Cost Item	Cost Estimate*
Excavation, Foundations and Site-work	$12,000
Concrete for foundations and floors	92,000
Masonry (CMU) Building	780,000
Electrocoagulation Cells and Power Supplies (mid-point of high and low estimate provided by WaterTectonics)	2,650,000
EC Cells and Power Supplies Installation (25%)	663,000
Instrumentation and Control	280,000
Conveying Systems (Crane)	4,000
Mechanical	620,000
Electrical MCC Panels	286,000
Allowance for Miscellaneous items	278,000
Unit Process Total	**$5,665,000**

* Costs are rounded to the nearest $1,000.

Annual O&M Costs

Annual O&M costs were calculated based on the following assumptions:

- The average water treatment plant flow used was 4 mgd.
- One additional Full Time Equivalent operator would be required for each alternative.
- One FTE costs $108,000 per year in wages and benefits.
- Power costs were calculated at $0.08/kwh
- Consumable costs were provided for the EC anodes and the RO membranes only.
- Chemical costs are the same for each alternative which use chemicals.
- All other items were expected to last through the 20 year life cycle.
- Electrocoagulation (EC) consumables are based on costs provided by WaterTectonics at a unit cost of $11,021 per unit, and a consumption rate of 0.43/3 = 0.143 per day
- RO membranes replacement was estimated every 5 years at a total cost of $2,200,000
- Hauling and disposal of solids was calculated at $75 per ton
- Solids content of residuals was assumed to be 50%

Chemical costs and doses were calculated as shown in Table 6. Annual O&M Cost estimates for the first year are provided in Table 7.

Table 6. Annual Chemical Cost and Doses for Each Treatment Alternative

Chemical Name	Cost per dry ton		Electro-coagulation	Precipitation	Lime Softening	Ion Exchange	Reverse Osmosis
Sodium Aluminate, as Al	$1,692	Dose, mg/L		40			
		Cost per Yr		$618,000			
Sulfuric Acid	$392	Dose, mg/L		98			20
		Cost per Yr		$507,000			$151,000
Sodium Hypochlorite	$2,213	Dose, mg/L					2.5
		Cost per Yr					$107,000
Carbon Dioxide	$59	Dose, mg/L			80		
		Cost per Yr			$70,000		
Sodium Hydroxide	$1,226	Dose, mg/L				113	25
		Cost per Yr				$2,671,000	$591,000
Lime, Hydrated	$331	Dose, mg/L			80		
		Cost per Yr			$510,000		
Soda Ash	$298	Dose, mg/L			50		
		Cost per Yr			$287,000		
Magnesium Chloride	$845	Dose, mg/L			199		
		Cost per Yr			$3,241,000		
Sodium Chloride	$110	Dose, mg/L				133	
		Cost per Yr				$282,000	
Sodium Bisulfite	$1,090	Dose, mg/L					2.5
		Cost per Yr					$53,000
Total Chemical Cost Per Year (2017)			**$0**	**$ 1,125,000**	**$1,125,000**	**$4,108,000**	**$2,953,000**

Table 7. Annual O&M Costs for Silica Removal Alternatives (2017)

Alternative	Electro-coagulation	Precipitation	Lime Softening	Ion Exchange	Reverse Osmosis
Power Cost	$159,000	$1,000	$2,000	$2,000	$33,000
Labor Cost	108,000	108,000	108,000	108,000	108,000
Chemical Cost	-	1,125,000	4,108,000	2,953,000	902,000
Consumables Cost	577,000	-	-	-	440,000
Residuals Disposal Cost	59,000	77,000	105,000	255,500	
Total Annual O&M Cost	**$903,000**	**$1,311,000**	**$4,323,000**	**$3,319,000**	**$1,483,000**

Life Cycle Costs

Life Cycle Costs for operating the system for 20 years are presented in Table 8. This analysis includes the assumption that City/District would finance the new treatment for 20 years, with a financing of the capital cost at 4% interest, and inflation rate for the O&M costs at 3%, and assuming no increase in water demand (additional treatment needs). As shown, the lowest alternative lifecycle cost is Precipitation, although the lifecycle cost for Electrocoagulation is essentially the same.

Table 8. 20 Year Life Cycle Costs for Mint Farm Modifications, Silica Removal

Alternative	Electrocoagulation	Precipitation	Lime Softening	Ion Exchange	Reverse Osmosis
Annualized Capital Cost	$2,039,000	$1,468,000	$1,423,000	$1,349,000	$2,075,000
Annual O&M Cost	903,000	1,311,000	4,323,000	3,319,000	1,483,000
20-Year Life Cycle Cost	$65,044,000	$64,587,000	$144,621,000	$116,163,000	$81,349,000
Monthly cost per ERU – (Year 1)	$12.32	$12.23	$27.39	$22.00	$15.41

Monthly costs per ERU are based on a total of 22,000 ERU's between the City and District.

Evaluation Criteria

To provide a decision model, an evaluation method using non-financial criteria was developed. The criteria and weighting factors were provided by the City and District staff. Evaluations were scored by CH2M staff. The core evaluation criteria and weightings are shown in Table 9.

Environmental criteria were weighted as eight percent of the total and was comprised of chemical use, waste streams, and resources waste or carbon footprint. Economic Criteria was weighted at twenty seven percent of the total and included capital, annual O&M, and customer affordability. Water Quality Aesthetics and Health was weighted at thirty five percent of the total and included silica reduction, hardness reduction, and secondary impacts. Technical criteria was weighted at thirty percent of the total and included operability and reliability of the process, safety, distribution system impacts, and the overall footprint or site impact.

Table 9 – Evaluation Criteria and Weighting for Silica Removal Treatment Options

No.	Evaluation Criteria	Weighting Factor
1	Environment	**8%**
	a. Chemical use	2%
	b. Waste streams, solids handling, disposal methods (Columbia River outfall)	4%
	c. Resource waste - water use/inefficiency (RO), electricity (double pumping), carbon footprint	2%
2	Economic	**27%**
	a. Capital Cost	8%
	b. O&M Cost	8%
	c. Rate impacts (ability to fund)	11%
3	WQ Aesthetics/Health	**35%**
	a. Silica reduction	25%
	b. Hardness reduction	5%
	c. Secondary benefit or detriment (chloramine removal vs. mineral stripping)	5%
4	Technical	**30%**
	a. Operability & Reliability (proven technology)	10%
	b. Safety	5%
	c. Distribution system impacts	5%
	d. Ability to add WTP and/or silica removal capacity; Wellfield encroachment	10%

Evaluation of the Alternatives

Alternatives were rated 1 to 5 for each evaluation criteria. 1 was the worst outcome and a rating of 5 was the best outcome. The results of the evaluation are summarized in Table 10. Electrocoagulation was rated highest for chemical use (for lack thereof), followed by Precipitation and Reverse Osmosis. Lime softening and Ion Exchange were ranked the lowest.

For waste streams, Electrocoagulation and Precipitation were rated the highest. Lime softening and Ion Exchange were rated lower because of large amounts of sludge and regeneration waste, respectively. Reverse Osmosis was rated the lowest.

For efficiency, the ratings were similar to the waste streams ratings, with the exception of Ion Exchange which got a slightly higher rating since most of its regeneration waste is salt or chemical and not water.

Capital costs, O&M costs and rate impacts were rated based on their actual costs, discussed previously.

Silica reduction ratings were based on the testing conducted, with the exception of Ion Exchange, which was rated based on experience with Ion Exchange and demineralization systems at full scale operations.

Hardness reduction was also based on the testing results, and full-scale experience for Ion Exchange. Secondary benefits were rated highest for Lime Softening and Reverse Osmosis, based on the removal of organic nitrogen and other materials during pilot testing (note at full scale, Reverse Osmosis would include a 25% bypass, so some raw water minerals would still be present). Ion Exchange was rated the lowest, because the process would include the replacement of calcium and magnesium with sodium.

Electrocoagulation was rated the highest for safety, based primarily on the reduced amount of chemicals required, compared to the other options.

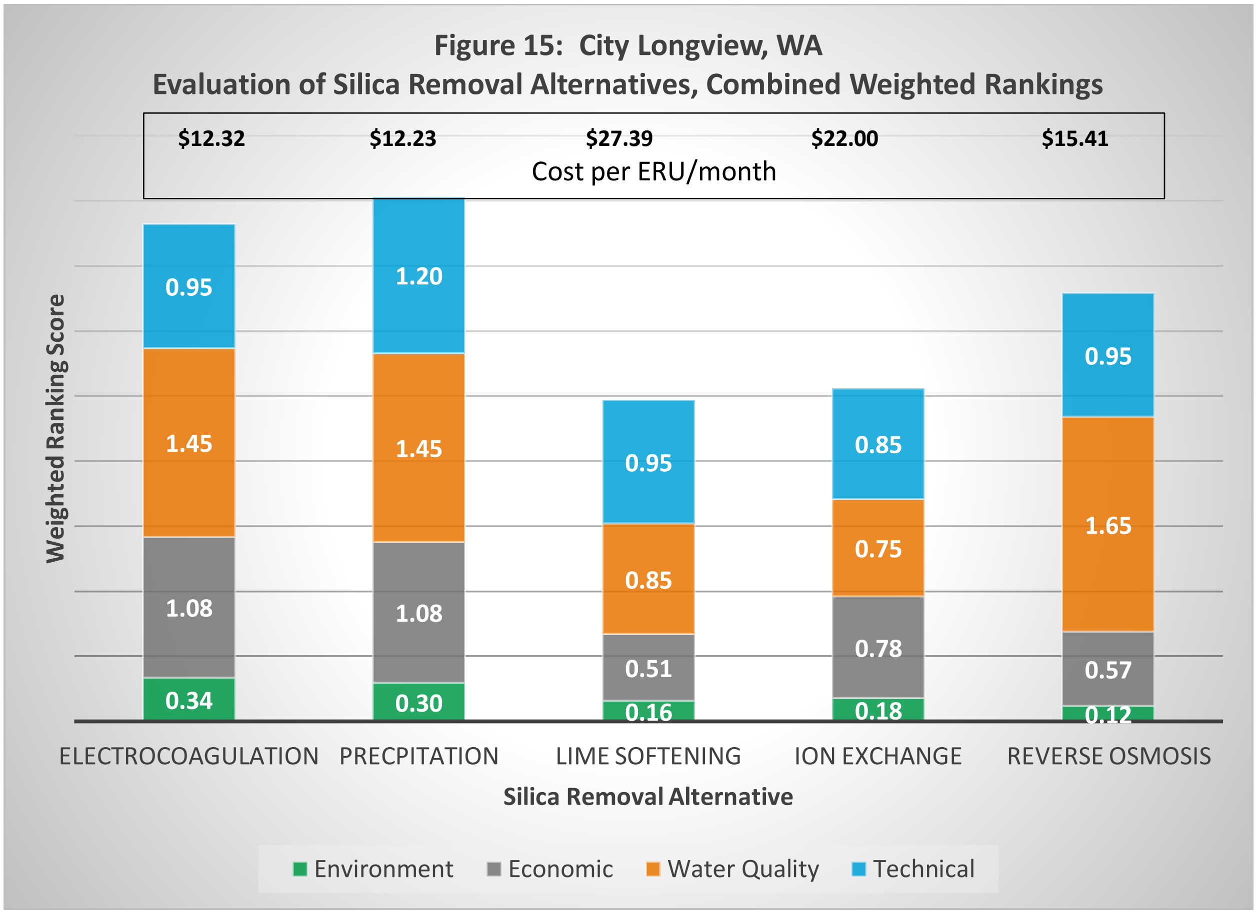
Distribution system impacts were very similar to the secondary benefit scores.

Footprints (building sizes) were rated based on their conceptual design footprints.

Table 10 – Evaluation Ratings (5 is best, 1 is worst)

No.	Evaluation Criteria	Weighting Factor	Electrocoagulation	Precipitation	Lime Softening	Ion Exchange	Reverse Osmosis
1	**Environment**	**8%**					
	a. Chemical use	2%	5	3	2	2	3
	b. Waste streams, solids handling, disposal methods (Columbia River outfall)	4%	4	4	2	2	1
	c. Resource waste - water use/inefficiency (RO), electricity (double pumping), carbon footprint	2%	4	4	2	3	1
2	**Economic**	**27%**					
	a. Capital Cost	8%	3	4	4	5	2
	b. O&M Cost	8%	5	4	1	2	1
	c. Rate impacts (ability to fund)	11%	4	4	1	2	3
3	**WQ Aesthetics/Health**	**35%**					
	a. Silica reduction	25%	5	5	2	2	5
	b. Hardness reduction	5%	1	1	3	4	4
	c. Secondary benefit or detriment (organic nitrogen removal vs. mineral stripping)	5%	3	3	4	1	4
4	**Technical**	**30%**					
	a. Operability & Reliability (proven technology)	10%	2	5	3	3	3
	b. Safety	5%	4	3	3	2	3
	c. Distribution system impacts	5%	3	3	4	1	4
	d. Ability to add WTP and/or silica removal capacity; Wellfield encroachment impact	10%	4	4	3	4	3

The individual ratings were then multiplied by their weighting factor to provide a weighted score. The combined weighted scores are shown in Figure 15, summarized by each category of evaluation criteria. Figure 15 also includes the cost per equivalent residential unit (ERU) per month.



Design Criteria and Plant Layout for Top Two Alternatives

As Electrocoagulation and Precipitation are both the lower cost and highest non-financial ranked alternatives, these two options were taken to the next step of further evaluation. Table 11 lists the preliminary design criteria for the silica removal facilities using Precipitation or Electrocoagulation. Both the precipitation and the electrocoagulation alternatives share the same design criteria for rapid mixing, flocculation, clarification, pumping and solids handling.

Table 11 – Preliminary Design Criteria for Silica Removal Facilities, Initial Capacity 12 MGD, Expandable to 18 MGD

Item	Precipitation	Electrocoagulation
	Rapid Mix, Flocculation and Clarification	
Rapid Mix, No Trains	2	2
Mixer HP, each	10	10
Velocity Gradient, G sec^{-1}	2,000	2,000

Item	Precipitation	Electrocoagulation
Mag meter, No	1	1
Flow control Valve, No.	1	1
Hoist, No	1	1
Building for Rapid Mixing	CMU, 880 SF	CMU, 880 SF
Flocculation Trains, No	2	2
Hydraulic Detention Time, min	20 at max flow	20 at max flow
Stages, No.	2	2
Flocculator, Type	Vertical Paddle Wheel	Vertical Paddle Wheel
Cover for Floc Basins	Roof Shelter, 1800 SF	Roof Shelter, 1800 SF
Lamella Plate Settler, No Trains	2	2
Plate dimensions	10’ x 5’	10’ x 5’
Plate loading rate, gpm/sf	0.3	0.3
Sludge Collector, No.	1 per train	1 per train
Side Water Depth	15’	15’
Cover	Roof Shelter, 6,300 SF	Roof Shelter, 6,300 SF
Chemical Building		
No. Chemicals Added	2	
Sodium Aluminate Bulk Tanks, No.	2 – 12’ by 16’	
Sodium Aluminate Chemical Pumps, No.	2	
Sodium Aluminate Solution Strength	48%	
Storage at average flow, Days	36	
Sulfuric Acid Bulk Tanks, No.	2	
Sulfuric Acid Chemical Pumps, No.	2	
Sulfuric Acid Solution Strength	93%	
Storage at average flow, Days	40	
Electrocoagulation Building		
No. of Power Supplies		12
No. of Electrocoagulation Cells		12
Building Size, Sq ft		5,000
Solids Handling		
Gravity Thickener, No	2	2
Sludge Depth, ft	5	5
Clearwater Depth, ft	10	10
Diameter, ft each	55	55
Loading rate, gpd/sf	300	300
Influent solids conc., %	0.25%	0.25%
Sludge Building, sq ft	CMU, 860 Sq ft	CMU, 860 Sq ft
Centrifuge, No	2	2
Inlet Sludge Concentration, %	3%	3%
Dewatered Cake, % solids	25%	25%
Polymer Dose, lbs/ton	10 to 20	10 to 20
Polymer Storage	3 – 400 gallon totes	3 – 400 gallon totes
Polymer Storage at average flow, days	40	40
Truck lane, length x width	70’ x 20’	70’ x 20’
Pump Station		
No. Pumps	3	3
Capacity, Each	6 mgd	6 mgd
Total, Dynamic Head, Ft	60	60
Pump Station Building	CMU, 600 sq ft	CMU, 600 Sq Ft

A general arrangement of facilities is shown on Figure 16 for the precipitation alternative. Figure 17 shows the general arrangement for the electrocoagulation alternative.

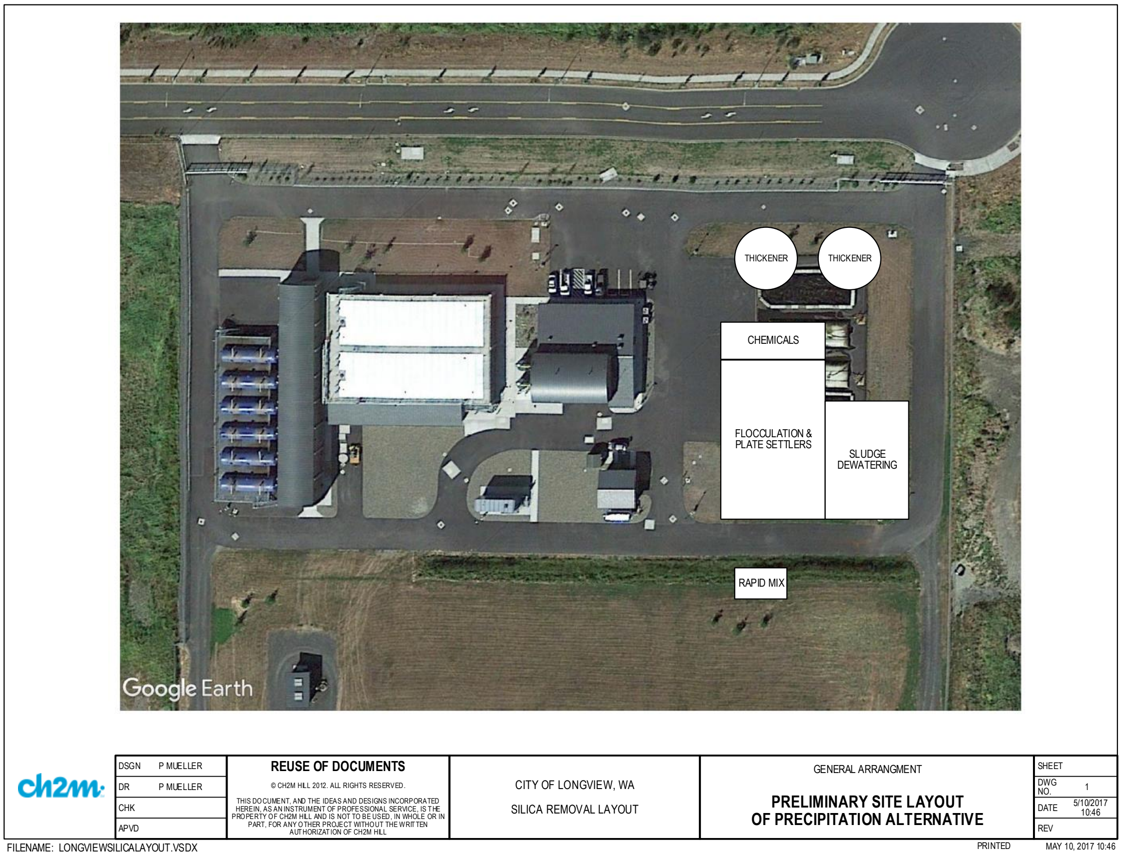


Figure 16 – Preliminary Layout of Silica Removal Facilities using Precipitation

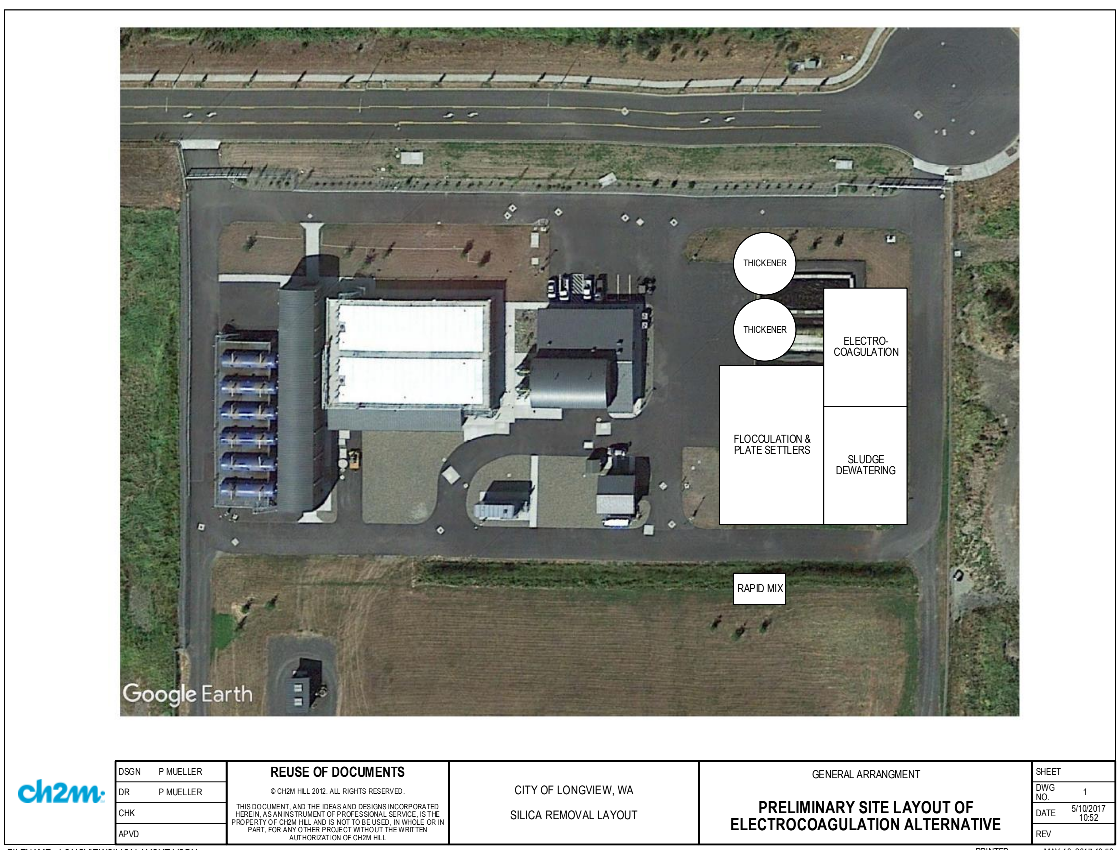


Figure 17 – Preliminary Layout of Silica Removal Facilities using Electrocoagulation

Recommendation

It is noted that the Electrocoagulation and Precipitation alternative treatment processes have weighted rankings and costs that are essentially similar. The Precipitation alternative has been used extensively by municipal systems to treat multiple types of water, and by many industries specifically for silica removal. The Precipitation alternative, however, requires more chemicals for treatment than does the Electrocoagulation option.

Electrocoagulation applications in municipal systems are very rare. The National Sanitation Foundation, which is the organization that certifies elements and chemicals used in drinking water treatment as safe, does not even have a category developed for Electrocoagulation. The Washington State Department of Health Drinking Water Program (WDOH) will require NSF or ANSI certification of all elements used in the water treatment plant that are in contact with drinking water. Obtaining ANSI or NSF certification is not viewed as a fatal flaw, because it is believed that certification could be obtained, although it would take time to acquire such status. Rather, the lack of certification demonstrates how relatively new, the Electrocoagulation technology is to the drinking water industry. Further, Electrocoagulation has not been used in the capacity needed for the Mint Farm system. If Electrocoagulation were chosen, this would be the largest application developed.

It is our recommendation that if the City and District wish to further evaluate Electrocoagulation treatment, that significant due diligence should be performed before proceeding with design of this alternative. Large scale industrial sites should be visited, a plan for ANSI/NSF certification should be developed by one or more potential equipment suppliers, as well as obtaining an understanding of how the equipment suppliers will scale up equipment from their traditional market. A pilot test would also be recommended for longer term demonstration of Electrocoagulation performance.

Precipitation could proceed directly to a project report for WDOH approval followed by design of the facility. Additional bench testing would be beneficial to identify a chemical feed system which can be optimized or if alternative pH adjustment approaches like carbon dioxide would be effective. Based on these considerations, precipitation is the recommended alternative for implementation of silica removal, especially if treatment is desired to be accomplished in the near term.

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