

APPENDIX H

Wellhead Treatment Evaluation (West Yost, November 2017)



TECHNICAL MEMORANDUM

DATE: November 15, 2017 Project No.: 418-02-14-36.133
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SUBJECT: Wellhead Treatment Evaluation

INTRODUCTION

The City of Modesto (City) has a number of wells with elevated levels of contaminants that either would require treatment if used to provide potable supply, or may require treatment in the future to meet regulatory maximum contaminant levels (MCLs). The particular groundwater contaminants of interest considered in this evaluation (as determined and provided to West Yost by City staff) include hexavalent chromium, nitrate, manganese, strontium, uranium and arsenic. The purpose of this memorandum is to evaluate the range of wellhead treatment options available for removal of these contaminants and recommend which processes would best suit wellhead treatment applications at the City's wells.

SUMMARY OF REGULATORY REQUIREMENTS

The regulatory requirements for the six contaminants of interest are summarized in Table 1 below. Five of the six contaminants have primary or secondary MCLs, one, strontium, does not. However, strontium has been identified by the United States Environmental Protection Agency (USEPA) for future regulatory action (USEPA, 2014a).

Table 1. Summary of Regulatory Requirements			
Hexavalent Chromium	0.010 mg/L		California MCL. There is no Federal MCL for hexavalent chromium.
Manganese		0.05 mg/L	SMCLs are binding in the state of California.
Nitrate	45 mg/L as NO ₃ ⁻		
Strontium			Identified by USEPA for future regulatory action.
Uranium	20 pCi/L		California MCL. The Federal MCL is 30 µg/L.
Arsenic	0.10 mg/L (10 µg/L)		Federal MCL is also 10 µg/L.
SMCL = secondary maximum contaminant limit			

Hexavalent Chromium

Chromium (Cr) is a metallic ion that occurs naturally with iron, though usually in much smaller concentrations. Chromium is typically in a reduced (cationic) state as either trivalent or hexavalent chromium. Cr(III) will complex with inorganic and organic compounds that usually have low solubility—chromium hydroxide (Cr(OH)₃) is a typical form. The trivalent form will quickly convert to the hexavalent form in the presence of oxygen; Cr(VI) occurs primarily as the anion chromate (CrO₄⁻²). Cr(III) is necessary in trace amounts for natural biological processes in the body and is considered a nutrient. Cr(VI) has been shown to cause cancer in animals and is considered a likely human carcinogen (NIH, 2010). The federal MCL for total Cr in drinking water is 0.1 mg/L. The new California MCL for Cr(VI) is 0.010 mg/L.

Manganese

Manganese (Mn) occurs naturally in many portions of the Central Valley groundwater basin. Manganese concentrations in individual wells are typically stable, although concentrations among different wells within an aquifer can vary greatly (Tobiason et al., 2008). Manganese is regulated with a secondary maximum contaminant limit (SMCL) to address issues of aesthetics. Elevated manganese can cause discoloration and staining. The California State Water Resources Control Board Division of Drinking Water (DDW, formerly in the California Department of Public Health) has also established a health-based drinking water notification level (NL) of 0.5 mg/L. While Federal SMCLs are guidelines at the Federal level, in California, SMCLs are enforceable. Utility experience indicates that adverse public reaction often begins to occur when Mn levels approach or exceed 0.02 mg/L (pp. 155; Tobiason et al., 2008).

Nitrate

The major sources of nitrates in drinking water are runoff from long-term fertilizer use, leakage from septic tanks, sewage, and erosion of natural deposits. In the historically agricultural Central Valley of California, contamination from agricultural sources is the largest contributor (Viers et al., 2012). The main concern from elevated nitrate exposure is “blue baby syndrome” in infants and fetuses—nitrate will interfere with oxygen uptake by hemoglobin, this can be life-threatening in young children. Long-term exposure to elevated levels can also cause rashes and other adverse health effects. The Federal and State MCL for nitrate is 45 mg/L as nitrate (NO_3^-), which is approximately equivalent to 10 mg/L as nitrogen (N).

Strontium

Naturally occurring strontium is released into fresh water from geologic weathering associated with sedimentary rocks such as gypsum, anhydrite, rock salt, limestone, and dolomite, as well as shales and sandstones (pp. 7, AWWA, 2014¹). Strontium exists in two cationic oxidation states, Sr^0 and Sr^{+2} and has 16 known isotopes. The predominant naturally occurring species of strontium are Sr-84, Sr-86, Sr-87, and Sr-88; these are not radioactive. Though it is currently not subject to any national or state primary drinking water regulation, strontium was listed on the Third Candidate Contaminant List (CCL3) by the USEPA. On October 10, 2014, USEPA announce a preliminary regulatory determination to regulate strontium (USEPA, 2014a²), so it will likely have an MCL in the next five to ten years.

While the radioisotope Sr-90 has been linked to bone cancers and leukemia, USEPA classifies non-radioactive strontium as “Cancer Class D” (not classifiable as to human carcinogenicity; USEPA, 2012). EPA’s current health reference level for non-radioactive strontium is 4.2 mg/L. There is no evidence that drinking water with trace amounts of naturally-occurring strontium is harmful. However, strontium is a molecular surrogate for calcium and can bond directly to hydroxyapatite (bone minerals) and interfere with crystalline growth in the human skeleton. Exposure to high levels of naturally-occurring strontium during the prime bone-development years of infancy and childhood can affect bone growth, causing rachitic, or Rickets-like softening and deformation, and dental changes (defective enamel formation, and deformation and misalignment of teeth). The USEPA reference dose (RfD) for strontium is 0.6 mg/kg/day based on the no observed adverse effect level (NOAEL) of 190 mg/kg/day to prevent rachitic bone growth. Conversely, there is some evidence that strontium increases bone density in adults (AWWA, 2014).

¹ AWWA. (2014). *The Potential Regulatory Implications of Strontium*. AWWA: Denver, CO.

² USEPA. (2014). Announcement of Preliminary Regulatory Determinations for Contaminants on the Third Drinking Water Contaminant Candidate List; Proposed Rule. *Federal Register*, 79(202):62716-627. 40 CFR Part 141.

Uranium

Uranium is a naturally-occurring element found at low levels in virtually all rock, soil, and water. Significant concentrations of uranium occur in some substances such as phosphate rock deposits, and minerals such as uraninite in uranium-rich ores. Naturally occurring uranium is released into fresh water from geologic weathering. There are three natural isotopes: U-234, U-235, and U-238, with U-238 greatly predominating (>99 percent). All three isotopes are radioactive—they decay over time and release alpha particles. Uranium has several valence states: U^{+3} , U^{+4} , and U^{+6} . In reducing (low oxygen) conditions, U^{+4} and its aqueous complexes predominate. At oxygenated and acidic conditions, uranium occurs predominantly in the U^{+4} oxidation state and it is present as the uranyl cation UO_2 (Shen and Schäfer, 2014). The Federal MCL for U is 30 $\mu\text{g/L}$. The California MCL is 20 $\mu\text{g/L}$. In the pH range of 6.5 to 7.6, typical for groundwater, uranium will be present as a divalent anion ($UO_2(CO_3)_2^{-2}$).

Arsenic

Arsenic is a naturally-occurring element found at low levels in rocks and soil, water, air, plants and animals. Volcanic activity, erosion of rocks and minerals, and forest fires are natural sources that can release arsenic into the environment. About 90 percent of arsenic used in the United States was used for wood preservation purposes, and in paints, drugs, dyes, soap, metals, and semi-conductors. Agricultural use, mining and smelting also contribute to arsenic releases. Arsenic can be released from geologic weathering associated with sedimentary rocks into groundwater supplies. Arsenic can be present as a trivalent ion [$As(III)$] and as a pentavalent ion [$As(V)$].

Arsenic tends to be found at higher concentrations in groundwater sources more frequently than in surface water sources. Arsenic is often found at higher concentrations in geographic “hot spots,” areas which have higher concentration levels than other groundwater in an area. The federal MCL for arsenic is 10 $\mu\text{g/L}$, and the California MCL is 0.010 mg/L (the same as 10 $\mu\text{g/L}$).

IDENTIFICATION OF BEST AVAILABLE TECHNOLOGIES

Table 2 summarizes the range of treatment technologies that have been demonstrated to effectively remove the various contaminants of interest. Most can be effectively removed by both ion exchange (IX) and reverse osmosis (RO), though in the case of IX, the removal efficiency for each contaminant varies by resin type. The efficacy of other technologies on contaminant removal varies significantly. In many cases, the appropriate choice is governed by other water quality parameters, including the co-occurrence of other contaminants. These treatment processes are described in the following sections.

Table 2. Summary of Treatment Options for Different Contaminants

Contaminant	Ion exchange	Technology ^(a)							
		(R/C/F)	(O/C/F)	Activated Alumina	(Oxidation)/ Sorption	Biological Treatment	EDR3	RO	Lime Softening
Nitrate	X					X	X	X	
Hexavalent Chromium	X	X ^(b)				X	X	X	
Strontium ^(c)	X					Unknown		X	X
Uranium	X	X		X		X ^(d)		X	X
Manganese					X	X		X	
Arsenic	X		X	X		X		X	X

(a) To be considered, technologies must have published data demonstrating their efficacy and have commercial treatment processes available.
 (b) The Cr(VI) is first reduced to Cr(III).
 (c) Little data has been collected on non-radioactive strontium treatment to-date (AWWA, 2014). EPA has designated BATs only for radioactive Sr.
 (d) Only demonstrated at bench-scale to date.
 (R)/C/F = Reduction/Coagulation/Filtration; some, but not all contaminants require reduction prior to coagulation and filtration
 (O)/C/F = Oxidation/Coagulation/Filtration; As(III) requires oxidation to As(V) prior to coagulation and filtration
 EDR = electrodialysis reversal
 [Blue shaded cell] = EPA-designated BATs (best available technologies).

Ion Exchange

Ion exchange (IX) is a physical/chemical process where an ion on the surface of the IX media is exchanged with a contaminant ion in the feed water. The media is typically selected to preferentially adsorb the target contaminant. Anion exchange is used for arsenic, hexavalent chromium, strontium, and nitrate removal. Cation exchange is needed for strontium removal. Mixed bed resins, for mixed contaminant removal, use SAC and SBA resins combined together.

In IX, feed water is continuously passed through a bed of ion exchange resin beads in a downflow or upflow mode until the resin is exhausted (i.e., the resin exchange sites have been filled by contaminant ions). IX media is regenerated using a concentrated solution of ions initially exchanged from the resin (e.g., sodium chloride). Strong-base ion exchange requires on-site regeneration. Weak-base IX is typically run to media exhaustion. The resin is then replaced, and the exhausted media is trucked off-site for regeneration.

IX efficiency is influenced by the feed water concentration of the target contaminant, the selectivity of the resin for the contaminant, the presence of competing ions (those which also have a strong affinity for the resin), and the empty bed contact time (EBCT). EBCT is the volume of the empty vessel (the portion that would be occupied by the IX resin) divided by the flow rate. I.e., it is a measure of how long the contaminated water is in contact with the media.

In pilot testing, EBCT is screened to determine the shortest EBCT that can be used without adversely impact removal capacity. In IX, EBCT is typically on the order of half a minute to a few minutes. EBCT is a key design parameter. The lower the EBCT, the smaller the vessels. Another key design parameter is bed volumes (BVs), which is a measure of how much water can be treated

before the media needs regeneration. The measure of BVs is important from an operational perspective, as it determines the frequency of resin regeneration. The number of BVs that can be treated before exhaustion varies with resin type and influent water quality. For example, a well-designed hexavalent chromium strong-base anion exchange (SBA) system can typically achieve 40,000 to over 100,000 BV, depending upon conditions (primarily co-occurring anions). Regeneration typically requires 1 to 5 BV of regenerant followed by 2 to 20 BV of rinse water (USEPA, 2000).

Competition from other ions for sites on the resin is a key consideration in IX. Water quality parameters such as pH, competing ions (particularly sulfate, nitrate, and chloride for anionic resins and calcium for cationic resins), alkalinity, TOC, and influent contaminant concentration affect process efficiency. If the water is high in organic matter, turbidity, hardness, total suspended solids, sand or iron and manganese above 0.1 mg/L, pretreatment (filtration, softening or pH adjustment) is often used to avoid resin fouling.

Spent regenerant waste management options depend on a variety of factors, including quantity, frequency of regeneration, and the concentration and leachability of hazardous materials (e.g., arsenic, hexavalent chromium, uranium). Treatment residuals from ion exchange for removal of heavy metals and/or radioactive materials are often hazardous and/or TENORM (technically enhanced naturally occurring radioactive material) wastes. These wastes cannot be disposed of in a Class III landfill. For example, strong base anion exchange (SBA) generates spent brine that contains high levels of Cr(VI) and total dissolved solids (TDS). This brine is typically further treated to reduce the volume prior to disposal as a hazardous waste. Weak-base anion exchange (WBA) is much less efficient, but does not create a hazardous brine as there is no on-site regeneration. It is generally preferred for applications where low-strength brine disposal is more cost effective than SBA brine management.

For treatment of compounds like hexavalent chromium, WBA and SBA generates spent resin that is usually a non-RCRA hazardous waste (i.e., hazardous in California) and if uranium is present may also be a TENORM or low level radioactive waste (LLRW). A good deal of research and product development has gone into improving brine reuse and minimization to reduce waste disposal costs. See the section Management of Contaminant Treatment Wastes below for more details.

[\(Reduction\)/Coagulation/Filtration](#)

Enhanced coagulation/filtration (C/F) is a BAT for uranium removal and reduction/coagulation/filtration (R/C/F) is a BAT for hexavalent chromium removal. Whereas traditional coagulation and filtration treatment is used to remove solids from drinking water supplies, in the case of hexavalent chromium or uranium removal, the coagulation process is used to convert some dissolved species into particles, which are then filtered out. A coagulant, typically an iron salt, sometimes with polymers, is added and mixed with the influent water. The larger particles formed by coagulation are then removed from the water by filtration (typically using sand, anthracite coal, or a combination of the two). When solids accumulate to the point of excessive headloss through the filter media, the media must be backwashed, so backwash water and solids handling systems are needed as well.

Uranium removal efficiency with R/C/F depends on water quality parameters, especially pH. While uranium removal is more efficient at a higher pH values, turbidity removal is not. At pH levels typically seen in potable water (approximately pH 6.5 to 7.5), removal efficiencies are generally between 50 and 80 percent. For systems that do not have existing filtration, the capital costs and advanced operator skill level required may make the process unattractive.

Hexavalent chromium removal requires that the Cr(VI) first be reduced to Cr(III). Ferrous sulfate is added to the raw water and the water then flows through reduction tank(s). Aeration or chlorination is then used to oxidize the residual ferrous iron. If granular media filtration is used, polymer is typically added to enhance coagulation.

In C/F processes, the primary residual is spent filter backwash water, which will contain the contaminant(s) removed and iron. Backwash water concentrations are affected by raw water contaminant level, the ferrous iron dosage, and the efficiency of the filtration process. In a well-performing system, backwash water will account for about 3-5% of the total flow. The spent water can be discharged to the sewer if the contaminant concentration is below the sewer permit limit. The backwash can also be treated (to settled out the solids) and recycled to the head of the plant; the dewatered solids would be disposed in an appropriate landfill. Build-up of contaminants on the filter media is not anticipated. See section Management of Contaminant Treatment Wastes below for more details.

For microcontaminant treatment, C/F and R/C/F are typically only used where sorptive processes are not viable due to water quality or brine disposal challenges.

[\(Oxidation\)/Coagulation/Filtration](#)

Oxidation/coagulation/filtration (O/C/F) is a BAT for arsenic removal. Whereas traditional coagulation and filtration treatment is used to remove solids from drinking water supplies, in the case of arsenic removal, the oxidation step is used to convert the arsenite (As(III)) ions to arsenate (As(V)) ions. An iron or aluminum salt coagulation process is used to convert the dissolved As(V) species into filterable FeAs particles, which are then filtered out. Sometimes polymers are also added and mixed with the influent water to help facilitate the coagulation process. The coagulated and flocculated particles are removed from the water by filtration (typically using sand, anthracite coal, or a combination of the two). When solids accumulate to the point of excessive headloss through the filter media, the media must be backwashed, so both backwash water supply and waste backwash water and waste solids management handling systems are needed as well. The waste solids will contain arsenic at concentrations that may require disposal as a hazardous waste.

[Oxidation/Sorption](#)

In removal by oxidation and sorption, the dissolved contaminant (e.g., manganese or arsenic) is first oxidized to a particulate form and then removed by precipitation and filtration onto an adsorptive media. Free chlorine and permanganate are the typical oxidizing chemicals used in drinking water treatment. Adsorptive media include greensand, activated alumina, and iron-coated filter media. Non-sorptive filters (e.g., conventional media or low-pressure membranes) can also be used.

Activated Alumina

Activated alumina (AA) is a BAT for manganese and uranium removal. Activated Alumina (AA) treatment is a physical/chemical process by which ions in the feed water, like arsenic, fluoride, uranium, selenium, silica and organic matter are filtered through oxidized alumina oxide media in packed beds, where they sorb onto the media surface. Feed water is continuously passed through a bed of activated alumina in a downflow or upflow mode until the media is exhausted (the sorption sites are mostly or completely used up). When the media is saturated, the bed must be regenerated on-site or off-site by rinsing with a strong base, flushing with water, and neutralizing with acid.

AA efficiency is influenced by the feed water pH, the oxidation state of the contaminant, the presence of competing ions, and the EBCT. With AA, EBCT is typically on the order of 3 to 10 minutes. The longer the required EBCT, the larger the system size for a given capacity. Problem levels for water quality interferences are summarized in Table 3 below. As with IX, the number of BVs that can be treated varies greatly as a function of both the water quality and the media type. Alumina-based media is sensitive to pH and to concentrations of competing ions, particularly silica and fluoride (see Table 3). These ions compete for sorption sites on the media. This reduces the number of bed volumes that can be treated before target contaminant breakthrough and hence increases the cost.

Table 3. Common Water Quality Interferences with Activated Alumina Adsorption	
Parameter	Problem Level, mg/L
Chloride	> 250
Fluoride	> 2
Silica	> 30
Iron	> 0.5
Manganese	> 0.05
Sulfate	> 720
Dissolved Organic Carbon	> 4
TDS	> 1,000

Source: Table 2-3; USEPA, 2003.

Greensand Filtration

Greensand, also referred to as manganese greensand, is manganese oxide-coated glauconite.³ This treatment gives the media a catalytic effect in the chemical oxidation-reduction reactions necessary for iron and manganese removal—it has a natural ion exchange capacity. Greensand has been used for reduction and precipitation of iron (Fe²⁺), manganese (Mn²⁺), and hydrogen sulfide (H₂S) since the 1950s.

³ An iron, potassium and alumino-silicate marine mineral found on the east coast of the United States.

In the greensand filtration process for manganese removal, dissolved manganese (Mn^{2+} in solution) is adsorbed onto the MnO_2 coating on the filter particles. The $MnO_2(s)$ exchanges electrons (oxidized) with the adsorbed Mn^{2+} , reducing it to an insoluble precipitate that is physically removed by both co-precipitation and by chemical adsorption onto the media. The pH is typically maintained within the range of 6.2 – 8.6 (New Mexico State University, 1999). Over time, as the surface charge is reduced through its interactions with manganese and other species in the water, the greensand's oxidizing capacity becomes exhausted. The filtered solids are periodically removed via backwashing. The greensand is regenerated (reoxidized) with potassium permanganate, free chlorine, or other oxidant. This can be done continuously or intermittently. Continuous regeneration (CR) is generally preferred when iron removal is the main target. Intermittent regeneration (IR) is generally preferred when manganese is the main treatment target. In CR, the oxidant is fed to the influent water prior to its contact with the greensand filter bed. In IR, the feed water is passed through the filter bed, where adsorption and oxidation occurs directly on the greensand media grains. When the adsorptive capacity is exhausted, the media is regenerated with an oxidant—e.g., downflow of dilute $KMnO_4$.

Typically, vessels are arranged in parallel, with an additional unit provided for redundancy. That way, the majority of the treatment units can be kept on-line while one “extra” unit is backwashed or held in standby. Greensand filters are often surface washed prior to backwashing to remove surface solids. Biofouling is typically not a significant issue, except for instances where the vessels have to be taken offline for extended periods of time.

If these filters are to be kept off-line for more than a few weeks, the vessels should be backwashed and drained. In intermittent use applications, if the greensand filters have been offline for more than two weeks, the media will need to be regenerated with free chlorine or permanganate prior to being put back into service. To regenerate the media, the vessels are first filled with high-chlorine water (e.g., 0.4 gallons of 12 percent hypochlorite solution per cubic foot) and left to sit for 24 hours to reactivate/recondition the media. The literature indicates that approximately 2.7 ounces by weight of hypochlorous acid ($HOCl$)/gallon should be sufficient for normal regeneration; further guidance may be suggested by the greensand supplier. Regeneration with potassium permanganate will shorten the regeneration time significantly. The minimum recommended contact time for potassium permanganate (four ounces by weight per gallon of water) is two to four hours. This is a four-fold decrease in regeneration time over free chlorine, although soaking for eight to 12 hours is recommended to ensure sufficient regeneration (only reducing the regeneration time by 12 hours, or half).

Other Sorptive Media

A number of alternative sorptive media (SM) types have also been developed. These media may be coated with iron, titanium, or synthetic materials. Besides greensand, iron-based media are the preferred choice for manganese removal. Iron-based media are sensitive to silica and vanadium. Unlike AA, SM systems are typically run in a once-through mode. I.e., these are typically not regenerated. Media exchange is often a service offered by the media supplier. When the SM media is exhausted, it is removed from the vessel and replaced with fresh media. Upstream filtration and occasional backwashing is used to remove sand and grit that may accumulate in the treatment process. This treatment alternative typically has the simplest maintenance and waste management requirements. With no regeneration, there is little maintenance required beyond periodic

backwashing. Given the simplicity of greensand regeneration, once-through SM is typically only preferred for small systems where both the water quality is amenable to treatment (i.e., there are not a lot of competing ions present in the water) and low operator labor is desired. It is also attractive for small systems that need manganese co-removal with arsenic. In that case, once-through treatment and removal would avoid the need to deal with arsenic-laden waste from regeneration.

Biological Treatment

Biological treatment is an effective means of reducing the concentration of organic constituents and other contaminants in water supplies. The process can be aerobic or anaerobic in nature. As a result, both the oxidation and reduction of contaminants and organic matter is possible.

Bacteria create energy by mediating a series of redox reactions, transferring electrons from donors (reduced compounds) to acceptors (oxidized compounds). These redox reactions can be exploited to remove contaminants from water. As compounds are reduced or oxidized they change form, often becoming innocuous byproducts of metabolism. Nitrate treatment is a classic example. Nitrate can be anaerobically biodegraded to nitrogen gas in the presence of a simple carbon food, like acetic acid or citric acid using indigenous bacteria. The byproducts of nitrate metabolism include nitrogen gas, carbon dioxide, and biomass.

Treatment vessels can take the form of fluidized bed reactors (a nitrate BAT), fixed bed reactors (approved for conditional acceptance by the DDW), membrane biofilm reactors, and dynamic suspended growth reactors. At the commercial level, fixed-bed (i.e., biofiltration) and fluidized bed reactors of granular activated carbon (GAC) on which biofilms of indigenous bacteria are grown, are the most common. A carbon source and nutrients (phosphate) are fed into the bioreactor. Biological treatment is characterized by higher capital costs and low operating costs relative to other microcontaminant technologies. In the case of nitrate and perchlorate treatment, the contaminants are degraded to non-hazardous molecules and so the waste biological sludge can be wasted to the sewer.

Evaluation of this treatment approach has been extended beyond nitrate and perchlorate treatment to include hexavalent chromium, arsenic and uranium removal. For example, indigenous microorganisms can reduce hexavalent chromium to non-hazardous trivalent chromium, which is removed from the water with the waste sludge. If the sludge is kept anoxic (to prevent Cr(III) from converting back to Cr(VI)), it will be non-hazardous and can be landfilled as municipal (Class III) sludge. As of February 2015, research was still on-going on proving this concept at full-scale. Other research on arsenic treatment is promising, but in a less-advanced stage.

Reverse Osmosis

Reverse osmosis (RO) is a physical-chemical treatment process that uses high pressure on the feed side of a semi-permeable membrane to overcome osmotic pressure and force water to diffuse through the membrane to the lower solute concentration (permeate) side. Almost all of the solutes present, including monovalent ions, cannot readily diffuse through the membrane and are therefore “rejected,” retained on the feed side of the membrane, and a concentrated waste solution (concentrate) is produced. Sometimes antiscalant chemicals are added to the feed solution to

reduce the rate of inorganic membrane fouling (precipitation on the membrane surface, hindering flow).

RO is an effective treatment process for removal of most contaminants of concern. However, RO has a number of significant drawbacks:

1. The operating (energy) costs are very high. The major energy requirement is for the initial pressurization of the feedwater. Operating pressures typically range from 250 to 400 psi, depending upon the concentration of solutes in the feedwater.
2. The product recovery rate for RO systems is typically on the order of 80 to 85 percent, meaning you have to waste 10 to 15 percent of your feed flow. Intermediate chemical softening between RO stages to remove supersaturates solutes like calcium, manganese and silica⁴, can boost recovery above 90 percent, but at the expense of producing significant volumes of additional waste sludge needing disposal.
3. The concentrate stream will be high in total dissolved solids (TDS), so disposal to the sanitary sewer is frequently not an option. Disposal is often prohibitively expensive where a brine line or deep injection well is not available. RO is typically selected only when multiple contaminant removal (including softening or TDS removal) is needed.

Silica, strontium and barium are strong foulants of RO and if present in elevated concentrations will preclude its use. Silica is the chief concern among these minerals. Silica is a sparingly soluble element. Silica chemistry is complex; deposits can be polymeric or crystalline form, and can also reach the membranes as colloidal particles. Further, conventional antiscalants are limited in their ability to inhibit silica fouling and the scale is not readily removed by chemical cleaning, and so has a strong negative impact on process performance. Rapid barium/strontium sulfate scaling can also be a problem if present in significant concentrations, necessitating an impractical level of membrane cleaning.

Although it is not a USEPA BAT for the contaminants under consideration here, nanofiltration (NF) would also be highly effective at microcontaminant removal depending upon the target contaminant. Like RO, NF is a high-pressure membrane process, but has a less selective membrane, so monovalent ions can pass through this membrane while they are retained by RO. NF systems can operate at lower transmembrane pressures, have modestly higher recoveries, and produce a lower-TDS concentrate. However, they are still very expensive and concentrate disposal is still challenging. But if RO were considered for microcontaminant treatment NF should be considered as well.

Electrodialysis Reversal

RO cannot be used to treat waters with high levels of silica (> 30 mg/L), barium or strontium. In those cases (and where NF is not the best choice), electrodialysis reversal (EDR) may be used. EDR uses a “stack” of semipermeable alternating anionic and cationic membranes to separate

⁴ See “Lime Softening” section below for more information.

solutes from water. An electric current is applied, and dissolved ions migrate through the stack. As the membrane becomes fouled with these solutes the direction of the current is periodically reversed to release these solutes from the membrane surfaces back into solution. This minimizes the effect of inorganic scaling. The water that permeates through the membrane stack is collected as permeate and the retained high-solute water is the concentrate, analogous to an RO system. Like RO and NF, EDR produces a high-TDS brine that poses a disposal problem in many locations.

Lime Softening

Lime softening is used to soften water by the addition of calcium hydroxide. Calcium hydroxide raises the pH, causing calcium and magnesium to settle out and form a solid sludge, which is removed by sedimentation and filtration. Like C/F, lime softening is generally used only when it is needed for additional treatment goals and when sorptive processes are precluded.

The presence of significant magnesium hydroxide precipitates is important for good uranium removal through softening. Lee et al. (1982, cited in Sorg, 1988) reported that addition of 50-250 mg/L of lime with magnesium carbonate could remove in excess of 90 percent of the uranium present. Lime softening without addition of magnesium carbonate resulted in only 30 percent removal.

Management of Contaminant Treatment Wastes

The disposal options for each type of waste stream depend on the type of waste, federal, state and local regulations, landfill and wastewater treatment plant requirements, and location of the wellhead treatment plant site in relation to disposal options. The various potential disposal options are summarized in Table 4.

Table 4. Potential Disposal Options for the Different Treatment Waste Streams (EPA, 2014b)						
Residuals	Possible Disposal Options					
	Direct Discharge to Surface Water	Discharge to POTW	Underground Injection	Class III Landfill ^(a)	Class I/II Landfill ^(b)	Low-Level Radioactive Waste Facility
Liquids	X	X	X			
Sludge		X	X	X	X	X
Aged Resins/Media					X	
Exhausted Resins/Media				X	X	X
Spent Membranes				X	X	X

^(a) California Class III landfills accept nonhazardous solid waste.
^(b) California Class I landfills accept hazardous waste. Class II landfills accept designated waste (wastes that threaten water quality).

Drinking water treatment plant residuals are categorized as filter media, IX resins, membranes, sludges, and liquids (USEPA, 2005). Liquid residuals include filter backwash water, rinse water, IX brines, RO and EDR concentrates, and neutralization solutions. The first concern associated with the disposal of treatment system wastes is whether it is either hazardous or radioactive (TENORM) waste, as defined in California.

Liquid Residuals Disposal

There are several options available for disposal of liquid wastes. These include discharge to a body of water, discharge to a wastewater treatment plant (WWTP) via a sewer connection or vehicle transport, and deep-well injection. The primary liquid waste disposal option available to the City is discharge to a WWTP (see additional discussion provided below). Direct discharge and deep-well injection are not available options for the City.

Discharge to Wastewater Treatment Plant

Generally speaking, liquid wastes that are mixed with domestic sewage and discharged to the sewer are not considered hazardous waste. The City of Modesto has the ability to restrict concentrations of certain constituents in discharges to the collection system through the enforcement of “local limits”. Under the Resource Conservation and Recovery Act’s (RCRA’s) “domestic sewage exclusion” (40 CFR 261.4(a)(1)), liquid wastes mixed with domestic sewage and discharged to a wastewater treatment plant are not necessarily regulated under RCRA, because they are subject to the Clean Water Act. Hazardous waste that is accumulated, managed, or transported (e.g., by truck) prior to introduction into the sewer system (e.g., hexavalent chromium-, arsenic-, or uranium-laden waste), however, would be subject to regulation as a hazardous waste.

Industrial users are required under 40 CFR 403.12 to notify the wastewater treatment agency, in this case the City, if discharging materials that could otherwise be considered hazardous wastes. In addition, discharges to the sewer may be required under a federally approved pretreatment program to meet technically based local limits (TBLL) established by the wastewater agency to ensure that the wastewater treatment plant can meet its NPDES (National Pollutant Discharge Elimination System) permit requirements without upsetting the treatment process—i.e., meet its effluent limits. To date, the City has not established specific TBLLs for the constituents of concern that would apply to individual industrial users.

The City of Modesto’s treated wastewater effluent objectives and current effluent concentrations are summarized in Table 5 below. While the City has capacity with respect to many of the constituents of concern reviewed here (chromium, manganese, arsenic, likely uranium), it does not have capacity with respect to TDS (total dissolved solids). In the case of IX, RO, and EDR, high-strength brines are produced that likely would not be eligible for sewer disposal due to concerns about the high level of TDS present, even if other contaminants, like Cr(VI), As, and U, were present in acceptable amounts. Any IX brines would very likely need to be treated and shipped off-site for disposal.

Table 5. Summary of Modesto Treated Effluent Concentrations for Constituents of Concern from Groundwater Well Water Treatment				
Constituent	Units	Water Quality Objective	Average Secondary Effluent Concentration (Jan. 2012-Apr. 2014)	Average Tertiary Effluent Concentration (Jan. 2012- Mar. 2014)
Chromium, Hexavalent	µg/L	10	Not evaluated ^(a)	< 5.0 ^(b)
Chromium, Total	µg/L	50	0.82	0.80
Manganese	µg/L	50	11	17
Nitrate (as N)	mg/L	10 ^(c)	6.6	2.4
Total Dissolved Solids	mg/L	450	664	522
Strontium	pCi/L	8 ^(d)	Not evaluated ^(a)	Not evaluated ^(a)
Uranium	pCi/L	20	Not evaluated ^(a)	Not evaluated ^(a)
Arsenic	µg/L	10	3.0	1.7 ^(e)

^(a) Hexavalent chromium, strontium, and radioactive compounds are not typically evaluated in wastewater effluent.
^(b) “<” signifies non-detect (ND) data with the Method Detection Limit (MDL) shown as the value.
^(c) Water quality objective shown is for “nitrate plus nitrite.” Nitrite, however, is generally non-detect or just above the MDL (typically 0.01 mg/L as N) in wastewater effluent.
^(d) Water quality objective shown is for Strontium-90, a radioactive isotope of strontium that is not commonly found in the environment.
^(e) Only one tertiary effluent arsenic result is available for January 2012 to March 2014. Average shown is based on this result and three additional results from August and October 2014.

There are no current federal regulations concerning disposal of radionuclides to the sewer, but in the case of uranium, there are strict conditions for disposal if a system has high enough concentrations to be considered radioactive source material. Then the system must ensure the waste is soluble and there are limits on the average and total amounts discharged (10 CFR 20). EPA has published guidelines based on the U.S. Nuclear Regulatory Commission (NRC) requirement that discharges with greater than 600 pCi/L of radium-226 and radium-228, and 3,000 pCi/L of uranium should not be sent to the sewer. (E.g., concentrated uranium ion exchange brines). There is also a requirement that the total be less than unity. In other words, the following equation should be true: $Ra_{226}/600 + Ra_{228}/600 + U/3,000 < 1$ (all in units of pCi/L). If a treatment technology generates enough source material to require a specific license from the NRC, there are strict conditions set for disposal into any sanitary sewer system (10 CFR 20.2003):

- The material must be readily soluble (or readily dispersed biological material) in water;
- The quantity of licensed or other radioactive material that is released into the sewer in one month divided by the average monthly volume of water released into the sewer cannot exceed the concentration listed in Table 3 of Appendix B in 10 CFR 20;
- The total quantity of licensed and other radioactive material released into the sanitary sewer in a year cannot exceed 5 curies of H-3, 1 curie of C-14, and 1 curie of all other radioactive materials combined; and
- Additional requirements apply if more than one radionuclide is released.

Non-liquid Residuals Disposal

Solid waste is generally sent to landfills. Figure 1 outlines the general classification decision tree for identifying the waste class (and hence disposal options) for a particular waste. Prior to landfill disposal, it must be determined whether the waste is hazardous (through process knowledge and/or analytical testing) and whether the waste contains any free liquids (using the Paint Filter Liquids Test), which landfills cannot accept. Generally, wastes with greater than 20 percent solids will not have free liquids. If the waste contains free liquids, dewatering must be used prior to landfill disposal.

Non-hazardous and California Hazardous Waste

To be disposed of in a Class III (non-hazardous) landfill, waste ion exchange resins, filtration media and backwashed sludge must be nontoxic, as characterized by the TCLP (Toxicity Characteristic Leaching Procedure) test and the California WET (Waste Extraction Test). These tests were designed to simulate leaching in a landfill environment; the CA WET is the more aggressive of the two. It is not uncommon for a contaminant treatment waste to be nonhazardous according to the Federal (TCLP) criterion but be a California hazardous waste according to the WET results.

Radioactive (TENORM) Waste

In general terms, TENORM waste is material containing radionuclides that are present naturally in rocks, soils, water, and minerals and that have become concentrated and/or exposed to the accessible environment as a result of human activities such as manufacturing, water treatment, or mining operations (pp. 3; USEPA, 2000). For wastes to be designated non-radioactive, they must not be a TENORM or LLRW. E.g., if the uranium concentration on a resin exceeds 0.05% by weight, the resin is classified as a LLRW, which can only be disposed of at three facilities in the U.S. The nearest is in Clive, Utah.

The TENORM limit is generally only a concern when radioactive material is the target for removal (uranium in this case). There have also been cases where anion exchange resins are used for hexavalent chromium or some other contaminant and uranium co-accumulated (e.g., Blute et al. 2012). In those cases, spent resins, filters and membranes generally contain elevated levels of radioactivity and must be sent to a facility licensed for disposal of radioactive waste.

ASSESSMENT OF BEST TECHNOLOGY OPTIONS BY CONTAMINANT TYPE IDENTIFICATION OF BEST AVAILABLE TECHNOLOGIES

The best technology for a given application is dependent upon both the basic characteristics of the technology type (cost, type and volume of waste stream produced, proven performance in the field, etc.) and the site-specific conditions, particularly water quality. The following section presents an evaluation of currently available water quality data for a range of the City's wells and subsequently presents recommendations for the best one to three technologies for treatment of each contaminant, taking both general technology characteristics and site-specific factors into account. For all the contaminants investigated, RO was a USEPA-designated BAT. EDR was likewise a BAT for many of the contaminants. However, due to its high cost and the difficulty of disposing of concentrate inland, RO is typically selected only when multiple contaminant removal (including softening or desalting) is needed. Likewise, EDR is usually selected only when RO is not feasible due to high levels of silica or other strong RO foulants. Therefore, neither RO nor EDR is a recommended technology for any of the contaminants of interest for the City of Modesto and so are not discussed in detail below. For similar reasons, NF was also not a best alternative contender.

Well Water Quality—An Evaluation of Contaminant Treatment Needs

Water quality data on nitrate, arsenic and uranium from a number of wells was provided by the City. An evaluation of this data, summarized in Table 6 below, indicates that there are wells that would need treatment for either nitrate, uranium, arsenic, or a combination of up to all three. Therefore, recommendations have been developed for removal of each of the contaminants of interest individually and co-removal of nitrate and uranium is also considered.

Hexavalent Chromium

The best alternatives for Cr(VI) treatment are anion exchange (strong-base and weak-base) and reduction/ coagulation/filtration⁵. Recent data demonstrating the efficacy of biofiltration indicates that this method is also viable and may have waste-reducing benefits. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 7 below.

⁵ R/C/F is only a BAT for systems with >500 service connections due to operational complexities.

Table 6. Summary of Significant Exceedances of Contaminant MCLs in Modesto Inactive Wells, 2000-2012 data

Well	Needs treatment? / Recent Trend			Comments
	Nitrate	Arsenic	Uranium	
MOD029	Yes/ > 50 mg/L	No	Maybe/High before 2003 and in 2012 near 20 -25 pCi/L	Likely need treatment for NO ₃ ⁻ and U.
MOD038	Probably/ Ranges ~ 45-55 mg/L	No	Maybe / High before 2009; recent trend 16 – 20 pCi/L	Likely need treatment for NO ₃ ⁻ if it cannot be blended. U was high but from 2008 to mid-2012 below the MCL at 16 – 20 pCi/L.
MOD049	No	Maybe / Before 2008 high; since 2008 has been <8 µg/L	No	
MOD050	No/ Just below the MCL	No	Yes/After 2006 RAA ^(a) periodically exceeds/ Varies from 10 to >35 pCi/L	Recent trend indicates U treatment is needed.
MOD066	No	Yes / Recent data is consistently >300 µg/L	Yes / Recent data is consistently >800 pCi/L	Arsenic and uranium far exceed the MCLs by over an order of magnitude. Treatment of both would be needed.
MOD100	Maybe / Consistently just below MCL	No	Not likely/High values in 2001, mostly near 10 from 2002-2008	May need treatment for NO ₃ ⁻ in the future if it cannot be blended. Data consistently just below the MCL.
MOD212	No	No	Maybe/Some more recent high values (34 – 40 pCi/L)	High values in 2008 – 2010, back down to half the MCL in late 2010 - 2012.
MOD223	Yes/Frequently >MCL	No	Yes/Consistently well above the MCL	Nitrate and U treatment needed.
MOD225	No	No	Yes/Data trend exceeds RAA	U treatment likely needed.
MOD247	No	No	Yes/Data trend exceeds RAA	U treatment likely needed.
MOD274	Yes	No	No	Nitrate treatment needed.
MOD292	No	No	Yes/Data trend exceeds RAA	U treatment likely needed.
MOD295	Yes	Maybe	No	Nitrate treatment needed. May need arsenic treatment based on variant historical trend.
MOD301	No	No	No	No treatment needed.
MOD304	No	No	Maybe/Data trend exceeds RAA	U treatment likely needed if blending is not available.
MOD306	Maybe	Maybe	No	NO ₃ ⁻ spiked above MCL in mid-2008 and was highly variable during the subsequent period tested. Arsenic was low in 2004, one very high arsenic datapoint collected in mid-2008.

^(a) RAA = Running annual average

Table 7. Pros and Cons of the BATs for Hexavalent Chromium Treatment			
Treatment Process	Critical parameters	Pros	Cons
Ion exchange (SBA type)	Water quality parameters <ul style="list-style-type: none"> • Cr(VI) • Sulfate • Chloride • Nitrate • Uranium • pH • Alkalinity • Conductivity 	<ul style="list-style-type: none"> • Demonstrated successful operation at multiple treatment sites • Significant advances in brine reuse and minimization technologies 	<ul style="list-style-type: none"> • SBA produces a high-salt brine • Requires pH control • Spent media is usually hazardous • Process efficiency strongly influenced by competing anions • Can concentrate other anions to problematic levels (nitrate, arsenic, uranium)
Biological Treatment	<ul style="list-style-type: none"> • Nutrients • Carbon source (acetic acid) 	<ul style="list-style-type: none"> • Reduces Cr(VI) to nonhazardous Cr(III) • Can remove multiple contaminants (nitrate, organic compounds) • “Green” waste stream • Low operating cost 	<ul style="list-style-type: none"> • In the pilot-testing phase of development • Larger footprint than IX • Higher capital cost than IX
Reduction/coagulation/filtration	<ul style="list-style-type: none"> • Feed Cr(VI) concentration • pH • Feed coagulant concentrations 	<ul style="list-style-type: none"> • Demonstrated successful operation at multiple treatment sites • Offers a solution where IX is not a practical option 	<ul style="list-style-type: none"> • Produces a high-Cr(VI) sludge that requires disposal • Operationally more complex than the other two alternatives

For applications where an elevated level of nitrate is not present, the recommended technology for hexavalent chromium removal is strong-base anion exchange (SBA). SBA has been the target of numerous research projects over the past decade, most sponsored all or in part by the Water Research Foundation, with two final studies on brine management currently on-going (#4556, and #4561). New advances in waste minimization have significantly reduced the volume of chromium-laden brine produced by this process. The best local example of this is the new 1-mgd wellhead treatment installation at Soquel Creek Water District. They use a proprietary process by Ionex SG that has greatly improved their brine recovery and reduced their waste production, significantly reducing their anticipated operating costs (Seidel et al., 2014; Gorman et al., 2014). This system has been operated at demonstration-scale for a year and is now permitted for regular operation. Similar systems are now being planned for installation at multiple Central Valley sites by the California Water Service Company. These systems have a small footprint and are largely automated. Data published to date (as of February 2015) supports this technology as the most cost-effective proven alternative on the market for most water qualities tested.

There are many different ion exchange resins on the market. If significant arsenic or uranium is present, this fact should be kept in mind when selecting the proper SBA resin, as some resins will have a stronger affinity for these contaminants than others and so should be avoided, particularly with respect to uranium, as that can inadvertently create a TENORM waste. Accumulation of copper and vanadium has also been seen (Blute et al., 2012).

When nitrate is present at concentrations near to above the MCL, it is recommended that biological treatment also be seriously considered. All strong base anion exchange resins will strongly remove nitrate, which will usually breakthrough first (i.e., start to bleed back off the resin into the water). Sulfate is another strong adsorber to SBA resins. If they co-occur, these two contaminants can greatly reduce resin capacity for Cr(VI). A key aspect of the Ionics brine minimization process is an ability to “bleed off” the accumulated sulfate and nitrate on the resin before hexavalent chromium starts to desorb, so more Cr(VI) can be removed before the brine is regenerated. However, if the feed water nitrate level is near or above the MCL, blending this excess nitrate back into the product stream is not an option and reduction of the waste brine becomes much more complex and expensive.

One biological treatment technology, BIOTTTA™ (AdEdge Water Technologies), has conditional approval for treatment of nitrate and is pursuing DDW conditional approval for hexavalent chromium treatment in 2015 (pilot testing is planned for Spring 2015). The footprint and capital cost for this biological treatment system is larger than an ion exchange system would be, but like IX it is also largely automated. Biological treatment also has the benefit of being a “green” technology—nitrate is reduced to N₂ and Cr(VI) is reduced to Cr(III). If brine minimization is anticipated to be difficult due to the presence of high levels of nitrate, it is anticipated that biological treatment may present a more cost-effective alternative, provided that the chromium treatment and waste handling is proven out. Removal of uranium is under investigation. Waste management is still being evaluated with respect to disposal requirements.

There are other commercial biological treatment processes on the market for nitrate treatment in California, including Envirogen’s fluidized bed reactor and AroNite—APT Water’s membrane biofilm reactor, and one under demonstration-testing by Evoqua. But their abilities to remove co-contaminants are unknown at this time. While none of these technologies are yet conditionally approved for Cr(VI) removal by the DDW as of February 2015, much research is on-going. New, more detailed performance and waste management data will likely be available to allow better assessment as to its appropriateness as compared to SBA.

Manganese

The best alternative for manganese treatment is oxidation/filtration with sorptive media. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 8 below. For applications where manganese, or manganese and iron are the target contaminants, the recommended media/technology is greensand filtration. Greensand is a simple, well-proven technology that does not produce a hazardous waste stream and is often the lowest-cost alternative. The ability to dispose of significant volumes of backwash water on a regular basis is needed. Sewer disposal is typical. Other adsorptive filter media are also sometimes used. Sometimes these alternatives are preferred if costs for the specific application would be cheaper, or co-removal of another contaminant is desired.

Table 8. Pros and Cons of the BATs for Manganese Treatment

Treatment Process	Critical parameters	Pros	Cons
Greensand filtration	<ul style="list-style-type: none"> • Feed Mn concentration • pH • Co-contaminants (Fe, H₂S, As) 	<ul style="list-style-type: none"> • Simple to operate • Long service life • Moderate capital cost and low operating cost 	<ul style="list-style-type: none"> • Must add an oxidant • Regeneration takes at least 4 - 24 hours after extended dormancy
Oxidation/ adsorption on MnO ₂ -coated filter media (typically GAC)	<ul style="list-style-type: none"> • Feed Mn concentration • pH • EBCT • Co-contaminants (Fe, H₂S, As) • Oxidation state of coating (higher oxidation state results in greater removal efficiency) 	<ul style="list-style-type: none"> • Simple to operate • Long service life • Can be cheaper than greensand 	<ul style="list-style-type: none"> • More sensitive to pH • Must add an oxidant • Regeneration takes at least 4 - 24 hours after extended dormancy

Nitrate

The best alternatives for nitrate treatment are biological treatment and ion exchange. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 9 below.

Table 9. Pros and Cons of the BATs for Nitrate Treatment			
Treatment Process	Critical Parameters	Pros	Cons
Biological treatment	<ul style="list-style-type: none"> • Feed concentration of carbon source (e.g., citric acid) and nutrients (PO₄) 	<ul style="list-style-type: none"> • No high-TDS, high-nitrate waste stream • Robust response to changes in nitrate concentration • Low O&M cost 	<ul style="list-style-type: none"> • Comparatively new technology • Capital cost is likely higher
Ion exchange	Water quality parameters <ul style="list-style-type: none"> • Cr(VI) • Sulfate • Chloride • Nitrate • Uranium • pH • Alkalinity • Conductivity 	<ul style="list-style-type: none"> • Proven technology with long track record • Moderate capital cost 	<ul style="list-style-type: none"> • Produces a high-TDS waste • Co-contaminants compete for sorption sites

Given the problematic issue of brine disposal from IX processes and California’s conditional acceptance of biological treatment processes, where nitrate alone is the target contaminant, the recommended technology is biological filtration. As discussed in the previous section on hexavalent chromium treatment, a number of biological filtration technologies have earned conditional approval in the state of California and are either installed (West Valley Water District) or in the process of being installed (City of Delano) for full-scale treatment. The City of Rialto uses biofiltration for co-treatment of perchlorate and nitrate. Biofiltration’s waste is “green.” The nitrate is converted to nitrogen gas and the only byproduct is biomass that must periodically be wasted from the filter beds. This is typically sent to the sewer. This avoids the problem of disposing of a high-TDS brine waste that IX processes feature. As biofiltration is a very efficient, stable process (nearly complete removal of nitrate), sidestream treatment with blending to reduce system costs should be considered.

While biological filtration is recommended, SBA is also a well-tested, proven alternative. SBA is very efficient at nitrate removal and would require frequent regeneration. The high waste brine will typically be 1.5% of your process flow stream. This high-TDS waste stream would likely need to be trucked off site for disposal at East Bay Municipal Water District or other high-TDS waste receiving agency. The City of Modesto’s Sutter Wastewater Treatment Plan discharges to the San Joaquin River and uses a sidestream of recycled water to irrigate fodder crops. The Sutter Plant denitrifies, so the accumulated nitrate would not be a concern, but it does already have trouble meeting its TDS and chloride TMDL, and all plants have irrigation TDS limits.

Where nitrate co-occurs with uranium, it is recommended that treatment with biofiltration and SBA in series be investigated. This will be discussed in more detail in the subsequent section on uranium treatment.

U

The best alternatives for uranium treatment are ion exchange and coagulation/filtration. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 10 below.

Treatment Process	Critical Parameters	Pros	Cons
Ion exchange	Water quality parameters <ul style="list-style-type: none"> • Uranium • Sulfate • Chloride • Nitrate • pH • Alkalinity • Conductivity 	<ul style="list-style-type: none"> • Proven technology with long track record • Moderate capital cost 	<ul style="list-style-type: none"> • Can produce a high-TDS waste that is difficult to dispose of • Resins are TENORM wastes • Co-contaminants compete for sorption sites
C/F	<ul style="list-style-type: none"> • pH • Feed coagulant concentrations 	<ul style="list-style-type: none"> • Demonstrated successful operation at multiple treatment sites • Offers a solution where IX is not a practical option 	<ul style="list-style-type: none"> • Produces a hazardous sludge that requires disposal • Operationally more complex than IX

Like hexavalent chromium, uranium is very well removed by anion exchange. If uranium is the only constituent, anion exchange with off-site regeneration is recommended. Groundwater uranium treatment systems are relatively common in Southern California and Nevada. These systems are typically operated to resin exhaustion, and then the resin supplier returns to change out the spent resin, or it is sent back to the vendor by the utility. The exhausted resin is then regenerated off site and the associated TENORM waste is contracted out to be dealt with by others. The replacement frequency at these sites can extend to one to two years, depending upon water quality.

The downside of anion exchange for uranium removal is the resin’s strong affinity for nitrate. Given the orders-of-magnitude difference in their concentrations, the resin will become exhausted relative to nitrate long before it would relative to uranium. (It also has a strong affinity for sulfate, but sulfate breakthrough is much less problematic from a regulatory compliance standpoint.) If the concentration of nitrate is low, this is not problematic, but for applications where nitrate will be a significant competitor for sorption sites, which would likely include a number of the City’s wells, it is recommended that biofiltration be considered for use upstream of the ion exchange process to remove the nitrate and sulfate from the feed water.

The practicality of adding an upstream process can be determined relatively easily by working with a biofiltration manufacturer and an ion exchange resin vendor or two to size systems based

on the water quality with and without biological pretreatment—system sizes, costs, and waste management pros and cons (particularly the feasibility of offsite regeneration) can be quickly assessed. It is unknown whether uranium accumulation in the biological treatment sludge would be a concern. That would need to be investigated. There is some initial anecdotal data indicating that some biological technologies may remove uranium as well, but there is no peer-reviewed data on that application to date.

Sr

USEPA BATs for Sr-90 are ion exchange and RO. No BATs have been established for non-radioactive strontium, though both IX and RO should be effective. The literature suggests that best alternatives for strontium treatment are ion exchange and lime softening. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 11 below.

Table 11. Pros and Cons of the BATs for Strontium Treatment			
Treatment Process	Critical Parameters	Pros	Cons
Ion exchange	Water quality parameters <ul style="list-style-type: none"> • Strontium • Calcium • Radium • Other cation hardness • pH • Alkalinity • Conductivity 	<ul style="list-style-type: none"> • Proven technology in mining waste treatment • Moderate capital cost 	<ul style="list-style-type: none"> • Produces a high-TDS waste • Co-contaminants compete for sorption sites
Lime Softening	<ul style="list-style-type: none"> • Calcium concentration • pH 	<ul style="list-style-type: none"> • No high-TDS waste stream. • Simple technology 	<ul style="list-style-type: none"> • Small dataset on efficacy • Produces a sludge that needs disposal • Significantly larger footprint

Given its non-regulated status, limited drinking water treatment information is available for strontium. It is unclear at this time what the best technology for strontium removal is for the City of Modesto’s application. After the Fukushima Daiichi nuclear accident in early 2011, several new articles were published with innovated treatment solutions for Sr-90, but focused on removing strontium from the environment, not from water. But given the USEPA’s recent positive decision to regulate strontium, it is expected that research will advance relatively quickly over the next five years or so. The Water Research Foundation (WaterRF) and the American Water Works Association have jointly funded an initial study to characterize the state of the science, “Critical Review of Treatment Options and Considerations for Strontium Removal from Water.” A second project is expected to be solicited by WaterRF in late spring, “Evaluation of Treatment Options for Removal of Strontium from Water,” to evaluate IX, lime softening and other, non-conventional approaches at bench-scale.

Better information will become available as the implementation process moves forward. However, some basic conclusions can be drawn. Depending upon the ultimate Federal MCL relative to the City's strontium levels, lime softening or lime softening followed by cation exchange are likely the best alternatives for strontium removal based on currently available information. While most of the other contaminants of interest above can be removed by anion exchange, strontium occurs in groundwater as a cation. But while cation exchange is very effective at strontium removal, there are a number of strongly competing ions, particularly calcium, which make operation expensive. Any co-occurring radium would also likely co-accumulate on the resin and so would need to be considered. Like high nitrate in anion exchange uranium treatment applications, calcium has a strong affinity to cationic resins and so will exhaust the resin and breakthrough very quickly compared to strontium. This may increase the regeneration cycle by orders of magnitude. This suggests that lime softening or even an NF process to reduce the calcium level prior to treatment would be needed. This fact might shift the choice for best treatment option to lime softening.

There is limited data indicating that the softening process alone may provide sufficient treatment. A study conducted in 1954 compared strontium removal by chemical treatment used at treatment plants (Alexander et al. 1954). The study determined that lime softening removed, on average, 73% of the strontium while a plant solely practicing alum or ferrous sulfate coagulation would only see a 12% reduction. These removals are dependent on higher calcium content. So, if the needed strontium removal were relatively modest, a simple lime softening process may be adequate.

Arsenic

The best alternatives for As(III) and As(VI) treatment are anion exchange (strong-base and weak-base), activated alumina, and oxidation/coagulation/filtration. The key water quality parameters affecting performance and the pros and cons of these technologies are summarized in Table 12 below.

Table 12. Pros and Cons of the BATs for Arsenic Treatment			
Treatment Process	Critical parameters	Pros	Cons
Ion exchange (SBA type)	Water quality parameters <ul style="list-style-type: none"> • Oxidize As(III) to As(V) • Iron • NO₃⁻² • SO₄⁻² 	<ul style="list-style-type: none"> • Proven technology 	<ul style="list-style-type: none"> • Requires pH control • Must oxidize As(III) to As(V) • Pre-filter may be needed ahead of resin vessels • Treated water pH may be lowered by HCO₃⁻ to CO₃⁻² exchange on resin
Activated Alumina	<ul style="list-style-type: none"> • pH less than 5.5 	<ul style="list-style-type: none"> • Proven technology • Removes both As(III) and As(V) doesn't require oxidation of As(III) to As(V) 	<ul style="list-style-type: none"> • Requires reducing pH to optimize treatment. • Requires increasing pH to neutral range after treatment for corrosion control • Use of acid and base to adjust pH during and after treatment will increase TDS
Oxidation/ coagulation/ filtration	<ul style="list-style-type: none"> • Feed As(III) concentration • pH • H₂S • Fe:As ratio • Feed coagulant concentrations 	<ul style="list-style-type: none"> • Proven technology • Co-precipitates with Fe⁺³ • Optimal strategy if [Fe⁺³] >0.3 mg/L and Fe:As >20 	<ul style="list-style-type: none"> • Produces a high-As(V) sludge that requires disposal • Phosphate, silicate, and NOM, interfere with iron adsorption

SUMMARY & CONCLUSIONS

The best technology for wellhead treatment depends upon both the target contaminant and the ambient water quality of the well water. The technologies considered included ion exchange, (reduction)/coagulation/filtration, sorptive processes, biological treatment, RO, NF, EDR and lime softening. A series of recommended treatment approaches were developed based on the published literature, conversations with vendors, and the available water quality data. Some contaminants had different recommendations based upon the feed water quality. These conclusions are summarized in Table 13 below.

Table 13. Summary of Wellhead Treatment Recommendations by Contaminant Type			
Contaminant	Recommended Process(es)	Rationale	Additional Notes
Hexavalent chromium/low nitrate	Strong-base anion exchange	Advances in brine minimization have greatly reduced waste management costs for at least one technology	If SBA or biological treatment cannot be used alone, biofiltration followed by SBA may be warranted to minimize expensive IX brine disposal requirements.
Hexavalent chromium/high nitrate	Biological treatment (if proven), anion exchange if not	Biological treatment is proven at bench-scale, pilot testing in progress	
Manganese	Greensand filtration	Simple to operate, low-cost alternative	Permanganate is a more effective oxidant but use of free chlorine may be simpler as it can also serve as a disinfectant residual post-treatment.
Nitrate	Biological filtration	Lowest-cost, simple operation, eco-friendly	A comparatively new technology but conditionally approved by DDW and does not produce a brine waste.
Uranium	Anion exchange with off-site regeneration	Long operating life if the nitrate concentration is low, no TENORM waste production on-site	If nitrate is relatively high (so violation of the MCL is likely at breakthrough), pretreatment with biofiltration should be considered.
Strontium	Cation exchange and/or lime softening	Both proven efficacious	Dataset is limited. Cations like calcium can be a big problem for strontium removal with IX so pretreatment may be warranted.
Arsenic	Oxidation, coagulation, and filtration	Simple to operate, low-cost alternative	Chlorine (hypochlorite) can be used as both an oxidant and as a post-treatment residual disinfectant.

As the City moves forward with treatment at one or more of its wells, site-specific details like water quality, available footprint, and access to waste disposal options may shift the preferred technology choice. Also, as technologies develop new (and/or better proven) options may become available that warrant serious consideration. Those have been highlighted in the text where developing information was available.

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**Figure 1. Waste Classifications and Disposal Options for Solid Waste Disposal
(reproduced from pp. 10; Marchack, 1989)**

