Appendix B

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MEMORANDUM

Chino Basin Watermaster
Treatment Technologies Technical Memorandum
Metropolitan Dry-Year Yield Program Expansion Project
PRELIMINARY

B&V Project 160374
September 29, 2008

1.0 PURPOSE

This Technical Memorandum (TM) identifies the six groundwater contaminants of concern in the Chino Basin (Basin) and describes eight technologies to treat them. The list of treatment technologies is narrowed down to a recommended set for each combination of contaminants. These recommendations will later be used in developing the Dry Year Yield (DYY) Program Expansion Facilities outlined in the DYY Program Expansion Preliminary Design Report.

2.0 BACKGROUND

Currently, groundwater quality is impaired in many portions of the Chino Basin due to irrigation return flows from agriculture, dairy waste, municipal waste discharge, and groundwater pumping patterns.

2.1 Project Overview

Groundwater treatment is envisioned as part of the Chino Basin Storage and Recovery Program, which in turn, is part of the Chino Basin Optimum Basin Management Program (OBMP) Program Elements 8 and 9—Groundwater Storage Management and Conjunctive Use Programs. The Inland Empire Utilities Agency (IEUA), on behalf of Metropolitan Water District of Southern California (MWD), has authorized Black & Veatch to conduct a preliminary design for a 150,000 acre-foot (acre-ft) DYY Program Expansion. This expanded program builds off of the original 100,000 acre-ft DYY Program developed in 2003.

The DYY Program Expansion will involve a combination of increased groundwater pumping or increased imported water purchases from MWD in-lieu of normal groundwater production or imported water usage. During a “put” year, or periods of plentiful imported supply, Chino Basin appropriators will reduce groundwater production and increase imported water purchases. Likewise, during a “take” year, or during periods of limited imported supply, the appropriators will increase groundwater production and reduce imported water purchases, from MWD.

2.2 Abbreviations and Acronyms

The following abbreviations/acronyms are used in this report:

acre-ft	acre-feet
afy	acre-feet per year
AOPs	advanced oxidation processes
As	arsenic
AWWARF	American Water Works Association Research Foundation
B&V	Black & Veatch
Basin	Chino Basin
BATs	best available technologies
CDPH	California Department of Public Health
CEQA	California Environmental Quality Act
Cl^-	chloride
ClO_4^-	perchlorate
CMP	Comprehensive Monitoring Program
Cr	chromium
Cr(VI)	chrome six or hexavalent chromium
CVWD	Cucamonga Valley Water District
DBCP	Dibromochloropropane
DC	direct current
DYY	Dry-year yield
EBCT	empty bed contact time
EDR	electrodialysis reversal
FOC	Findings of Consistency
FWC	Fontana Water Company
GAC	granular activated carbon
gpm	gallons per minute
HCO_3	bicarbonate
IBM	iron-based media
ICF	iron coagulation followed by filtration
IEUA	Inland Empire Utilities Agency
IX	Ion Exchange
JCSD	Jurupa Community Services District
MCL	maximum contaminant level
mg	milligrams
mgd	million gallons per day
mg/L	milligrams per liter
MIEX	Magnetic ion exchange
µg/L	micrograms per liter
MWD	Metropolitan Water District of Southern California
MVWD	Monte Vista Water District

ND	non-detect
NO_3^-	nitrate
NOM	natural organic matter
O&M	operation and maintenance
OBMP	Optimum Basin Management Program
OCSD	Orange County Sanitation District
PCE	tetrachloroethylene
ppb	parts per billion
PTA	packed tower aeration
RO	reverse osmosis
SBA	strong-base anion
SO_4	sulfate
TCE	trichloroethylene
TDS	total dissolved solids
USEPA	United States Environmental Protection Agency
UV	ultraviolet
VOCs	volatile organic compounds
Watermaster	Chino Basin Watermaster
WBA	weak-base anion
WEI	Wildermuth Environmental, Inc.

2.3 Nature and Location of Contamination

The OBMP has included many evaluations of groundwater quality and possible impacts on groundwater management for the Basin. An inventory of available groundwater production and imported water treatment facilities was recently conducted for each of the major Chino Basin appropriators. This inventory also included an investigation of any groundwater contaminants commonly found at each of the wells. The five most common constituents found include nitrate (NO_3^-), arsenic (As), perchlorate (ClO_4^-), volatile organic compounds (VOCs), and dibromochloropropane (DBCP). In addition, hexavalent chromium (Cr(VI)), an emerging contaminant, has been identified as a potential contaminant of concern in the Basin. Treatment may potentially be required where contamination is a concern for both new and existing wells if detected levels exceed California Department of Public Health (CDPH) maximum contaminant levels (MCLs) or Action Levels.

2.3.1 Inorganic Contaminants of Concern, Their Speciation, and Treatment Technologies

Inorganic contaminants may occur in groundwaters due to natural mineral weathering and leaching reactions in soil, sediment, and rock formations; and through industrial, municipal, agricultural, and surface runoff effluents that either percolate or are injected into the subsurface. Inorganic contaminants typically occur in ionic form in aqueous solution, and may be associated with suspended and colloidal solids or be present as dissolved species. Positively and negatively charged ions are termed cations and anions, respectively. There are currently National Primary Drinking Water Standards for 16 inorganic elements and compounds including arsenic, chromium, and nitrate, which are of particular concern in Chino Basin groundwaters. Perchlorate is under consideration for regulation by the United States Environmental Protection Agency (USEPA), and CDPH has set an action level for perchlorate. Regulatory standards for arsenic, chromium, nitrate, and perchlorate in drinking water established by CDPH are listed in Table 2-1.

Table 2-1
Groundwater Contaminants of Concern

Contaminant	Source	Range in Concentrations	Max. Contaminant Level
Nitrate (as NO_3^-)	Dairy waste disposal areas	ND – 122.0 mg/L	45 mg/L
Perchlorate	Rocket Fuel	ND – 17.0 µg/L	6.0 µg/L
Arsenic	Naturally occurring	ND – 110 µg/L	10.0 µg/L
Volatile Organic Compounds	TCE & PCE widely used industrial solvents for degreasing	ND – 12 µg/L	5 to 6 µg/L
Dibromochloropropane	Soil fumigant in orchards	ND – 1.27 µg/L	0.2 µg/L
Chrome VI	Still under investigation	ND – 81 µg/L	<50 µg/L

Soluble arsenic in natural waters primarily occurs as variably charged oxyanion species, with either +3 or +5 valance (As(III) or As(V)). The charge of arsenic species depends on pH and oxidation-reduction potential, with neutrally charged $H_3AsO_3^0$ (As(III)) dominant in waters from reducing environments and negatively charged $HAsO_4^{2-}$ and $H_2AsO_4^-$ (As(V)) species predominant in waters from oxidizing environments. Because $H_3AsO_3^0$ does not adsorb strongly to positively charged metal oxide surfaces, removal of arsenic from groundwater usually requires chemical pre-oxidation of the neutrally charged As(III) species to negatively charged As(V) species to promote effective adsorption.

Chromium most often occurs in natural waters in cationic forms with Cr(III) and Cr(VI) valance states. Cr(III) is very insoluble in the neutral to alkaline pH range, forming precipitated $Cr(OH)_{3,S}$ particles that may be removed from drinking water by various filtration methods. Coagulation is often applied to enhance the removal efficiency of $Cr(OH)_{3,S}$ particles. In contrast, Cr(VI) species (predominantly CrO_4^{2-} and $Cr_2O_7^{2-}$) are highly soluble in natural waters and may occur at concentrations well above the 0.1 mg/L MCL for chromium. Anion exchange resins have a high affinity for Cr(VI) species, as do positively charged preformed and precipitated iron surfaces. Cr(VI) species are also effectively removed by membrane processes such as RO and EDR.

Nitrate and perchlorate ions are both non-volatile and adsorb only very weakly to either organic or inorganic surfaces. Therefore, they are typically removed from drinking water by processes that retain or reject charged species such as ion exchange, reverse osmosis, or electrodialysis reversal. Both nitrate and perchlorate may also be biologically reduced to nitrogen gas and chloride, respectively. However, biological reduction is more appropriate to treatment of waste and residual stream, and is therefore not considered here as a primary means of nitrate or perchlorate removal from drinking water.

2.3.2 Organic Contaminants of Concern, Their Speciation, and Treatment Technologies

The term "VOCs" is used here to include four volatile organics which have similar characteristics when considering available removal technologies: 1,1-dichloroethylene, 1,1-dichloroethane, trichloroethylene (TCE), and tetrachloroethylene (PCE). Because these contaminants are relatively low molecular-weight neutrally-charged compounds, they are not amenable to removal by IX, RO, EDR, or iron adsorption processes. Aeration, activated carbon adsorption, and advanced oxidation are candidate technologies for VOC removal from Basin groundwaters.

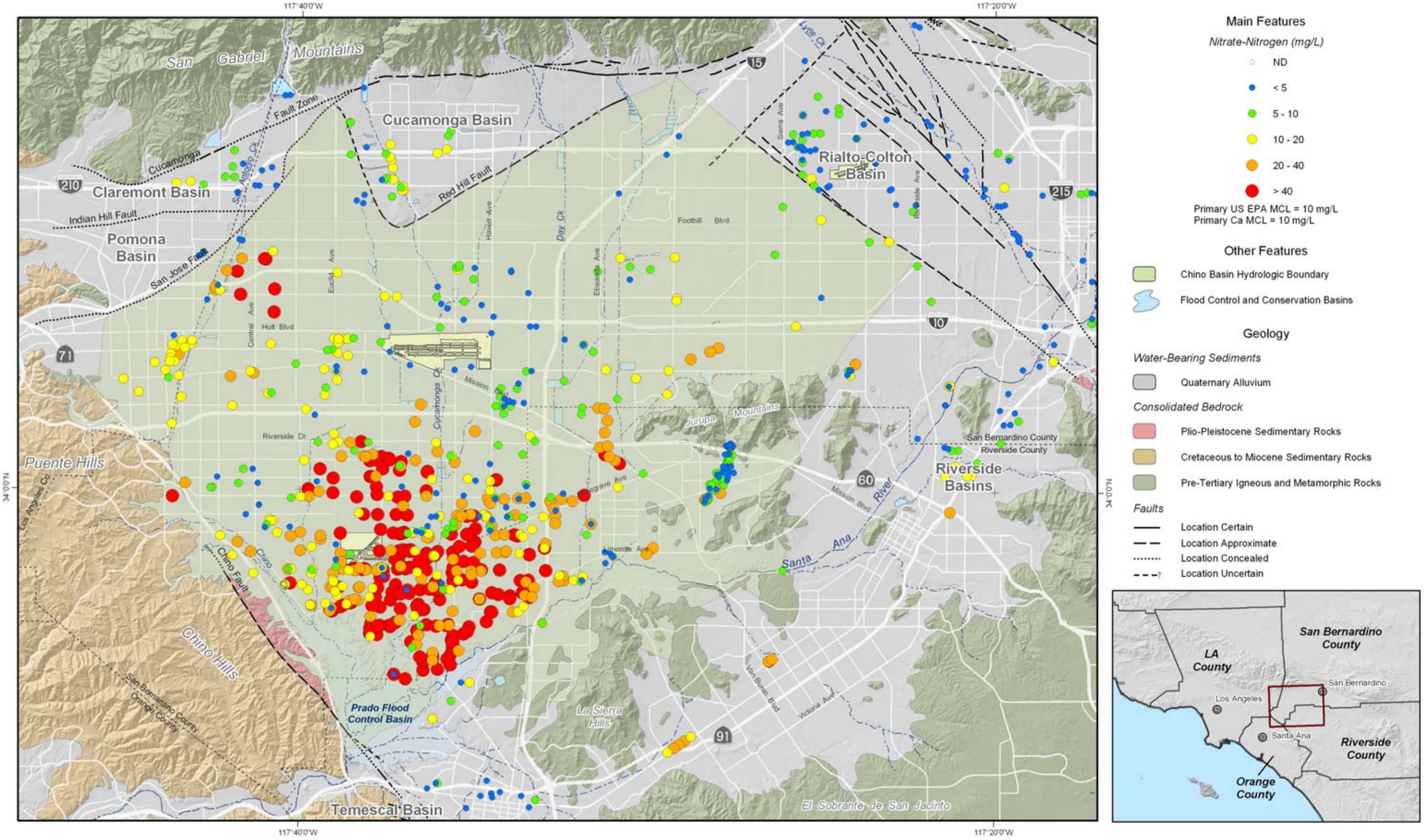
DBCP is slightly less volatile and slightly more polar compared with the VOCs considered here, and, certain RO membrane materials may effectively reject DBCP. Thus RO is also considered a potential candidate technology for DBCP removal from Basin groundwaters.

2.3.3 Distribution of Contaminants in Groundwater Across the Chino Basin

As part of the OBMP Program Element No. 1, the Chino Basin Watermaster (Watermaster) completed the initial round of a Comprehensive Monitoring Program (CMP). The CMP consisted of water quality sampling of over 600 private wells in the Chino Basin and collection of water quality data from other municipal and regulatory agencies. Wildermuth Environmental, Inc. (WEI), has developed a database of this water quality information, which was used to develop maps illustrating the distribution of various contaminants across the Chino Basin. Table 2-2 presents a summary of the concentrations found in the Basin for each of the six constituents, where the contaminants come from, and their corresponding MCLs. The range in concentrations shown for each contaminant was developed from this database for nine major appropriators in the Chino Basin.

The contaminants occur in clusters, but the locations of the clusters depend on the type of contaminant. Figure 2-1 shows nitrate-contaminated wells to cluster in the south part of the Basin near the Prado Flood Control basin. Figure 2-2 shows perchlorate contamination clustered near the cities of Jurupa and Pomona. Figure 2-3 shows arsenic contamination clustered in the southwest portion of the Basin. VOC contamination (represented by TCE) is clustered in the south near the Prado Flood Control Basin and to the west near Pomona. Maps showing the TCE concentration, location of DBCP contamination, and Cr(VI) concentration in the Basin are shown in Figures 2-4, 2-5, and 2-6, respectively.

In order to implement the Chino Basin DYY Program Expansion, treatment systems will be needed for both existing and new wells located in the areas where contamination is a concern. These treatment systems will be in addition to the appropriators' existing systems and any treatment that was constructed under the original DYY program.



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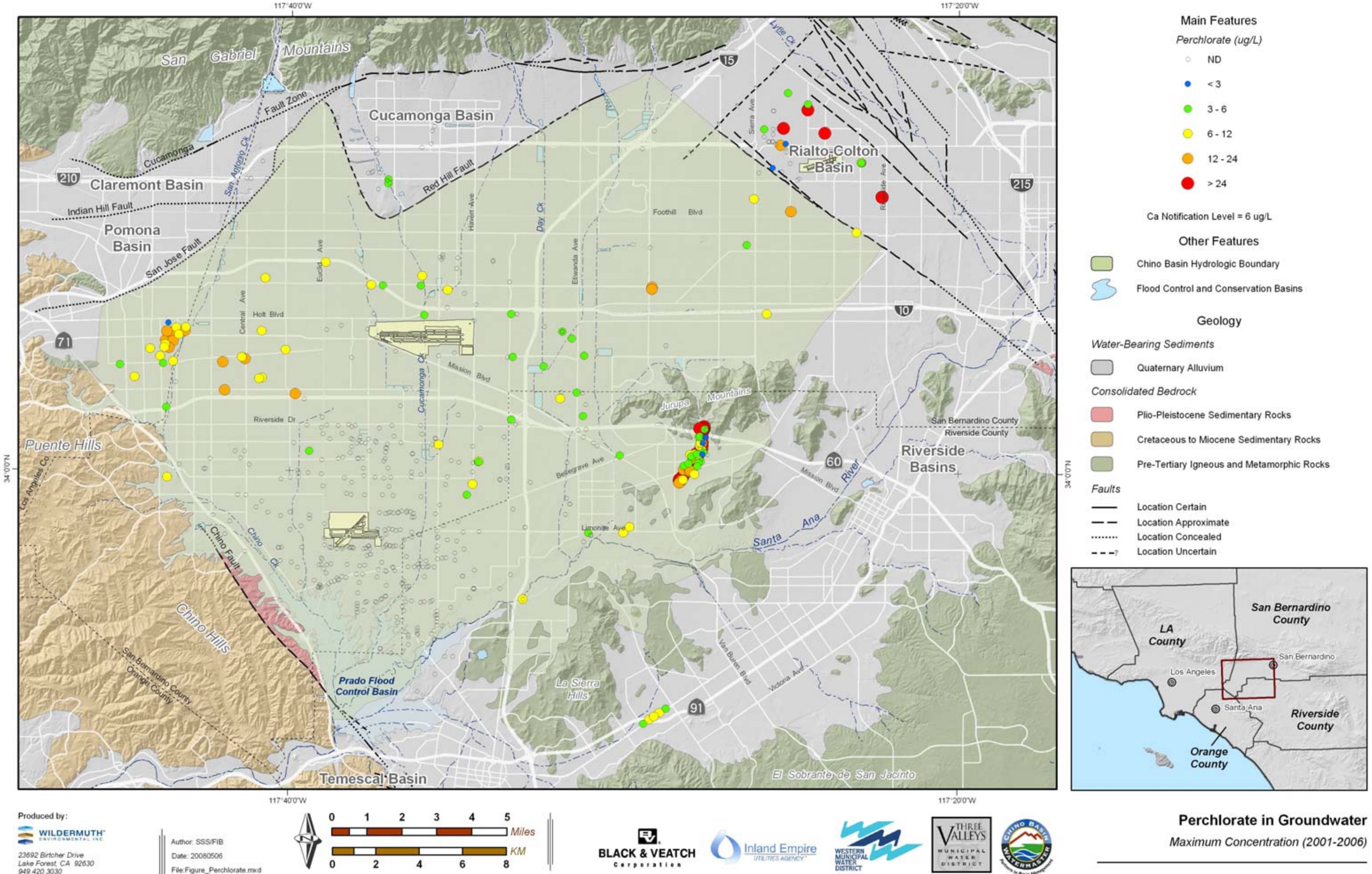
Nitrate as Nitrogen in Groundwater

Maximum Concentration (2001-2006)

Figure 2-1



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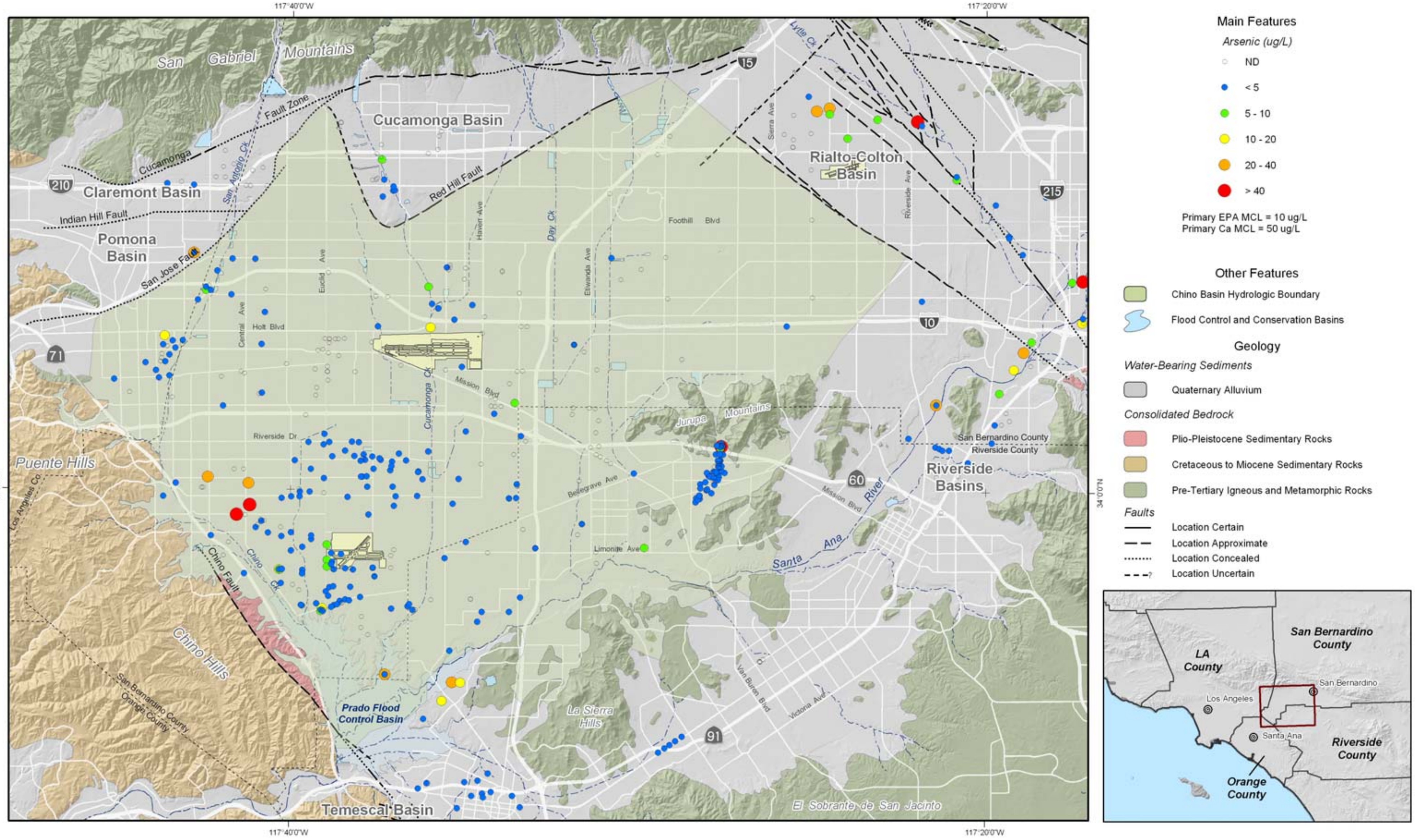
Perchlorate in Groundwater

Maximum Concentration (2001-2006)

Figure 2-2



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THREE VALLEYS MUNICIPAL WATER DISTRICT

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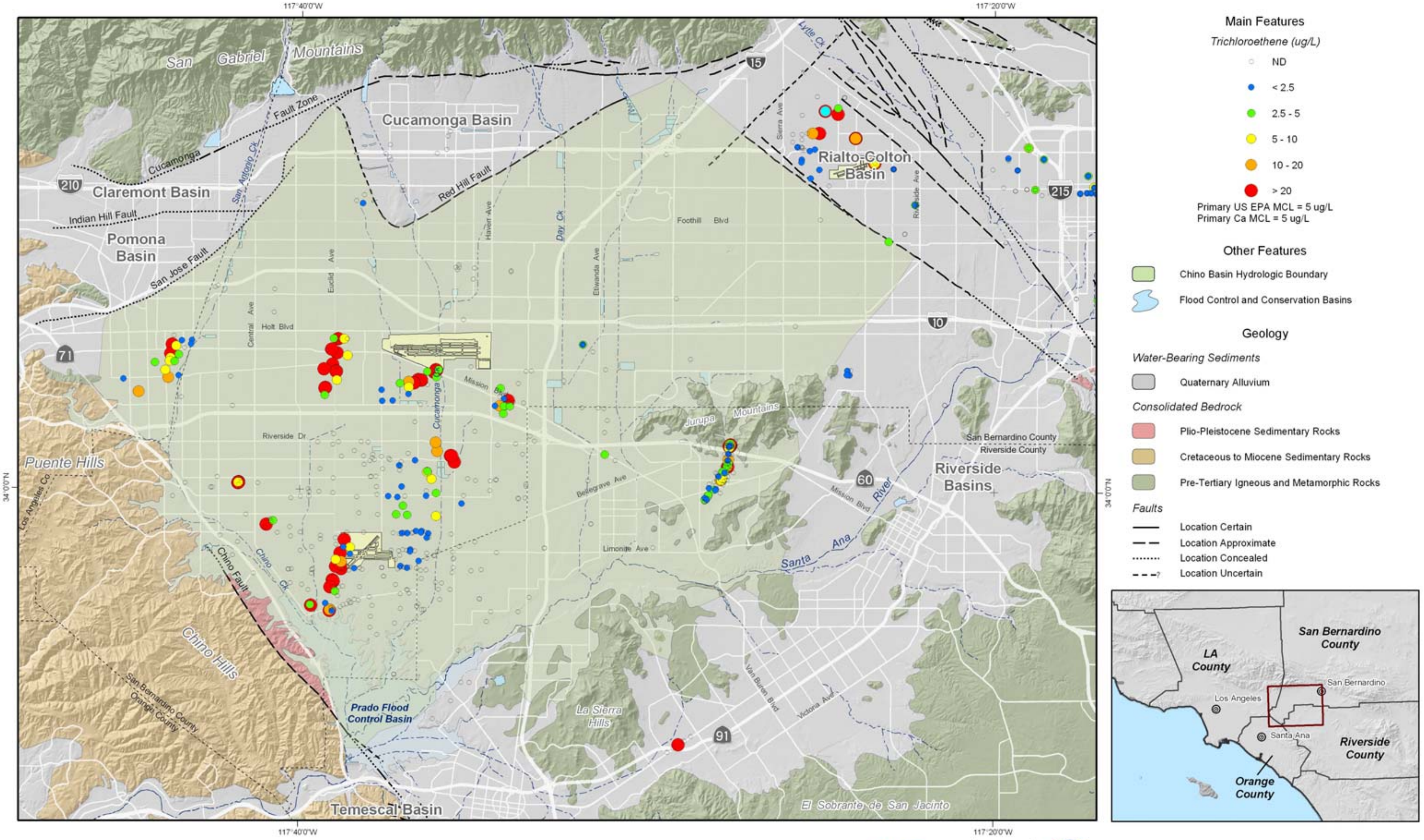
Arsenic in Groundwater

Maximum Concentration (2001-2006)

Figure 2-3



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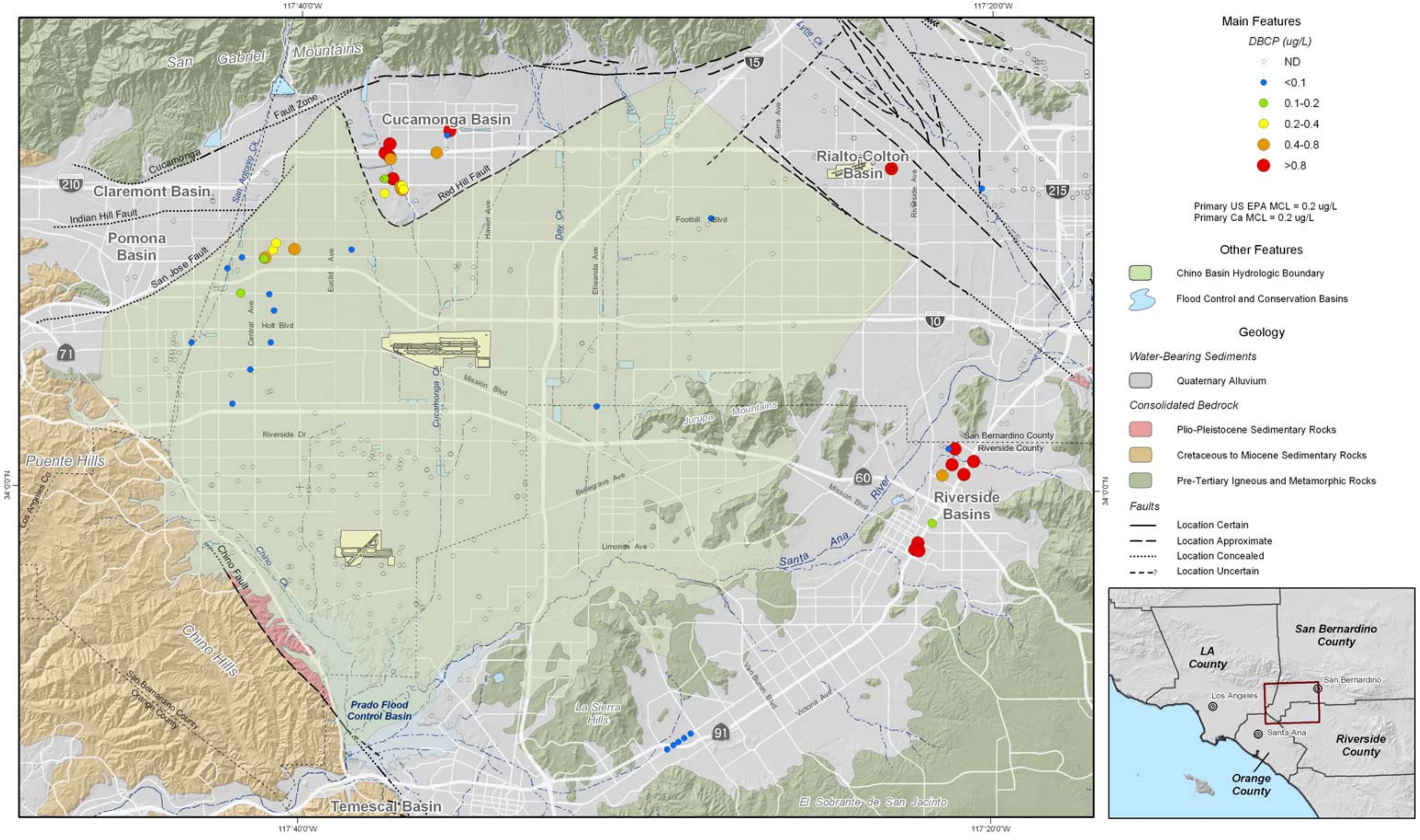
Trichloroethene in Groundwater

Maximum Concentration (2001-2006)

Figure 2-4



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0 1 2 3 4 5 Miles
0 2 4 6 8 KM

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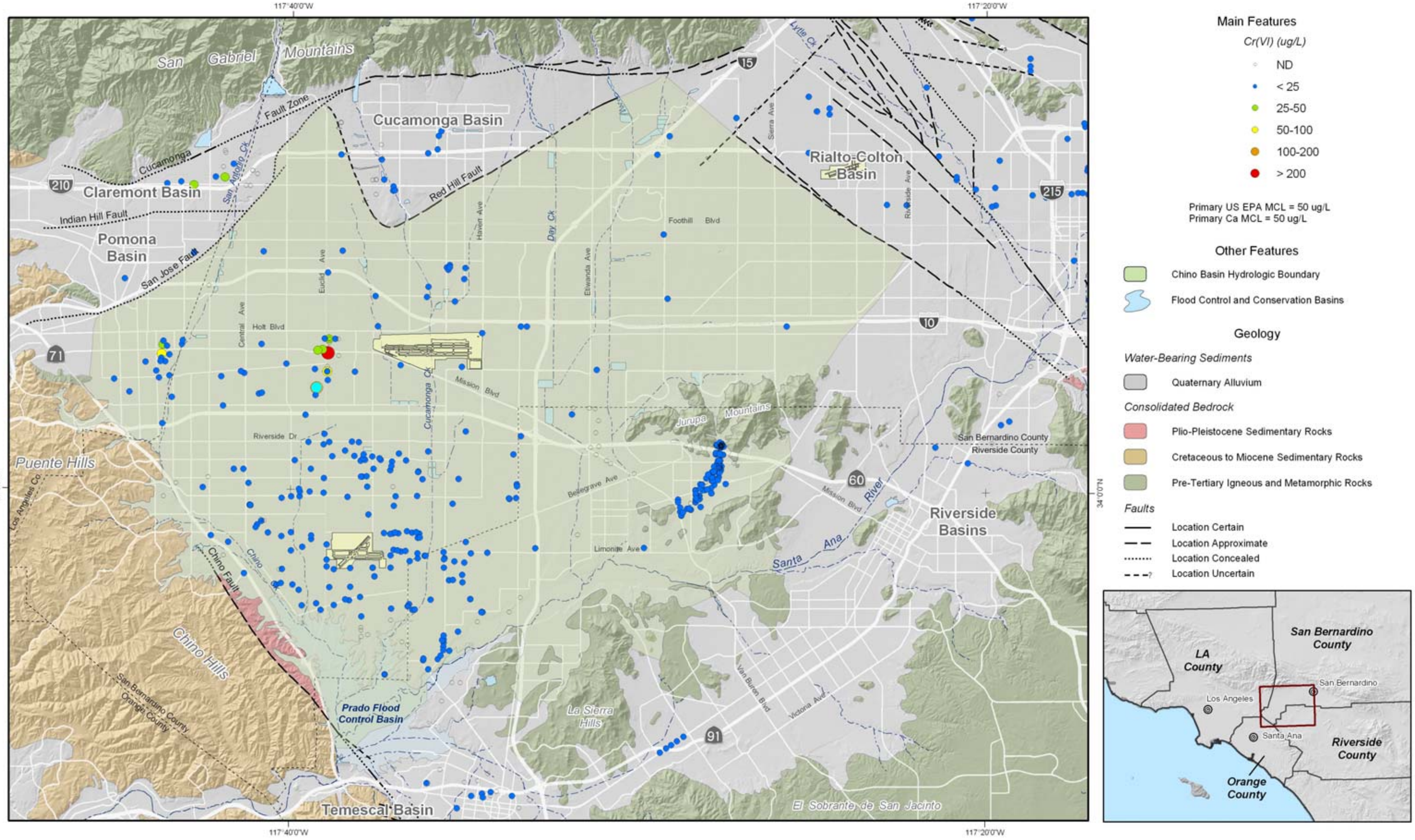
DBCP in Groundwater

Maximum Concentration (2001-2006)

Figure 2-5



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0 1 2 3 4 5 Miles
0 2 4 6 8 KM

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Chromium(VI) in Groundwater

Maximum Concentration (2001-2006)

Figure 2-6

3.0 PROCESS REVIEW

This section presents common treatment technologies for mitigation of the five most prevalent contaminants in the Basin. Because there are numerous proprietary and emerging technologies, this memorandum presents only the most well-known treatment processes. These processes include ion exchange (IX), reverse osmosis (RO), electrodialysis reversal (EDR), granular activated carbon (GAC), air stripping via packed tower aeration (PTA), advanced oxidation processes (AOP), iron coagulation followed by filtration (ICF), and adsorption onto iron-based media (IBM). Table 3-1 summarizes which contaminants can be treated using these eight technologies. Subsections 3.1 through 3.8 describe the technologies in more detail. A process overview, discussion of treatment for the specific contaminant, and preliminary information on capital and operation and maintenance (O&M) costs are provided.

Table 3-1
Available Treatment Technologies for Basin Contaminants

Contaminant	**Available Treatment Technologies**							
	IX	**RO**	**EDR**	**GAC**	**PTA**	**AOP**	**ICF**	**IBM**
NO_3^-	X	X	X					
ClO_4^-	X	X	X					
As	X	X	X				X	X
VOCs		X(1)		X	X	X		
DBCP		X		X	X(2)	X		
Cr	X(3)	X					X(4)	X(3)

Notes:
(1) Some RO membranes can remove limited amounts of VOCs.
(2) PTA designed for VOC removals can also remove limited amounts of DBCP.
(3) Anion exchange of Cr(VI) or adsorption of Cr(VI)
(4) Co-precipitation of Cr(III) in colloidal or particulate form.

3.1 Ion Exchange

IX is used extensively for softening municipal water supplies and for demineralization of water for industrial uses, such as production of semiconductor rinse water in the electronics industry and high-pressure boiler feedwater in the electric utility industry. Nitrate removal using IX for potable water use is a "Best Available Technology" (BAT) currently in use by Pomona and Upland in the Basin.

3.1.1 Process Overview

IX is a process where pre-saturant ions adsorbed on the surfaces of synthetic resin beads, the adsorbent, are exchanged for unwanted contaminant ions of similar charge in solution. Source water is continually passed through a packed-bed of IX resin until the target contaminant in the resin-bed effluent reaches an unacceptable concentration, at which point the IX vessel is taken out of service and the resin is either regenerated or replaced. IX can be a relatively simple and cost effective method for removing inorganic contaminants from drinking water, but can produce relatively large volumes of liquid or solid residuals that may be classified as hazardous or radiologically controlled material. Residuals disposal should be thoroughly studied when IX is considered for inorganic contaminant removal, especially when well-head treatment is contemplated at a relatively large number of widely spaced locations.

Strong base anion (SBA) exchange resins are typically used for ion exchange treatment of perchlorate, chromate, arsenic, and nitrate contaminated drinking waters because of high resin capacity, simplicity, and cost-effectiveness. SBA resin in the chloride (Cl^-) form is currently the preferred packed-bed media for removal of anionic contaminants. SBA resins have varying affinity for anionic contaminants, and preferentially exchange Cl^- for anions with higher affinity compared to those with lower affinity, as listed in Table 3-2. Non-target ions may compete for exchange sites on SBA resin and reduce the effectiveness of target contaminant ion removal. This is particularly the case when SBA exchange is used to remove arsenate or nitrate from source waters high in sulfate (SO_4^{2-}), which has a higher affinity for SBA resins. Also of note is the very high affinity of SBA resin for the uranyl carbonate ion: even when waters with very low uranium concentrations are treated, elevated uranium concentrations may be present in spent resin and/or regenerant solution and result in these residuals being classified as radiologically controlled materials.

Table 3-2
SBA Ion Exchange Resin(1) Affinity for Anions

Anion	α^{I}_{Cl-} (2)
$UO_2(CO_3)_3^{4-}$	3,200
ClO_4^{-}	150
CrO_4^{2-}	100
SeO_4^{2-}	17
SO_4^{2-}	9.1
$HAsO_4^{2-}$	4.5
HSO_4^{-}	4.1
NO_3^{-}	3.2
Br^{-}	2.3
SeO_3^{2-}	1.3
HSO_3^{-}	1.2
NO_2^{-}	1.1
Cl^{-}	1.0
BrO_3^{-}	0.9
HCO^{-}	0.27
CH_3COO^{-}	0.14
F^{-}	0.07

Notes:
(1) SBA resin in the chloride form.
(2) Binary separation factor is a measure of the preference of a resin for one ion over another during ion exchange. Values listed above are SBA resin preference for anions relative to Cl^{-}.

Exhausted chloride-form SBA resin may be regenerated using a concentrated brine solution (NaCl – table salt), which reverses the ion exchange process. Using nitrate removal as an example, high chloride concentration in the brine solution displaces the nitrate ion from resin active sites. The brine regeneration is followed by a slow rinse using softened water, also in the counter-current mode. Regeneration requires storage tanks for brine solution and softened water, waste regenerate receiving tanks, brine and softened water production units, and associated pumps and valves. Alternatively, exhausted IX resin may be replaced rather than regenerated on-site if source water contaminant levels are comparatively low (µg/L) and their affinity for SBA resins is comparatively high. Uranium and perchlorate removal from drinking water is often consistent with these criteria for resin replacement. A spare IX vessel is typically included to allow for continuous operation while one of the vessels is removed from service for resin regeneration or replacement.

Because IX processes are capable of removing contaminant ions to concentrations well below regulatory limits, a portion of the total production may sometimes bypass IX treatment. In split-stream bypass mode, treated water is blended with raw water to meet the desired finished water quality and reduce overall water treatment costs. Finished water may need to be pH-adjusted prior to distribution, depending on source water pH.

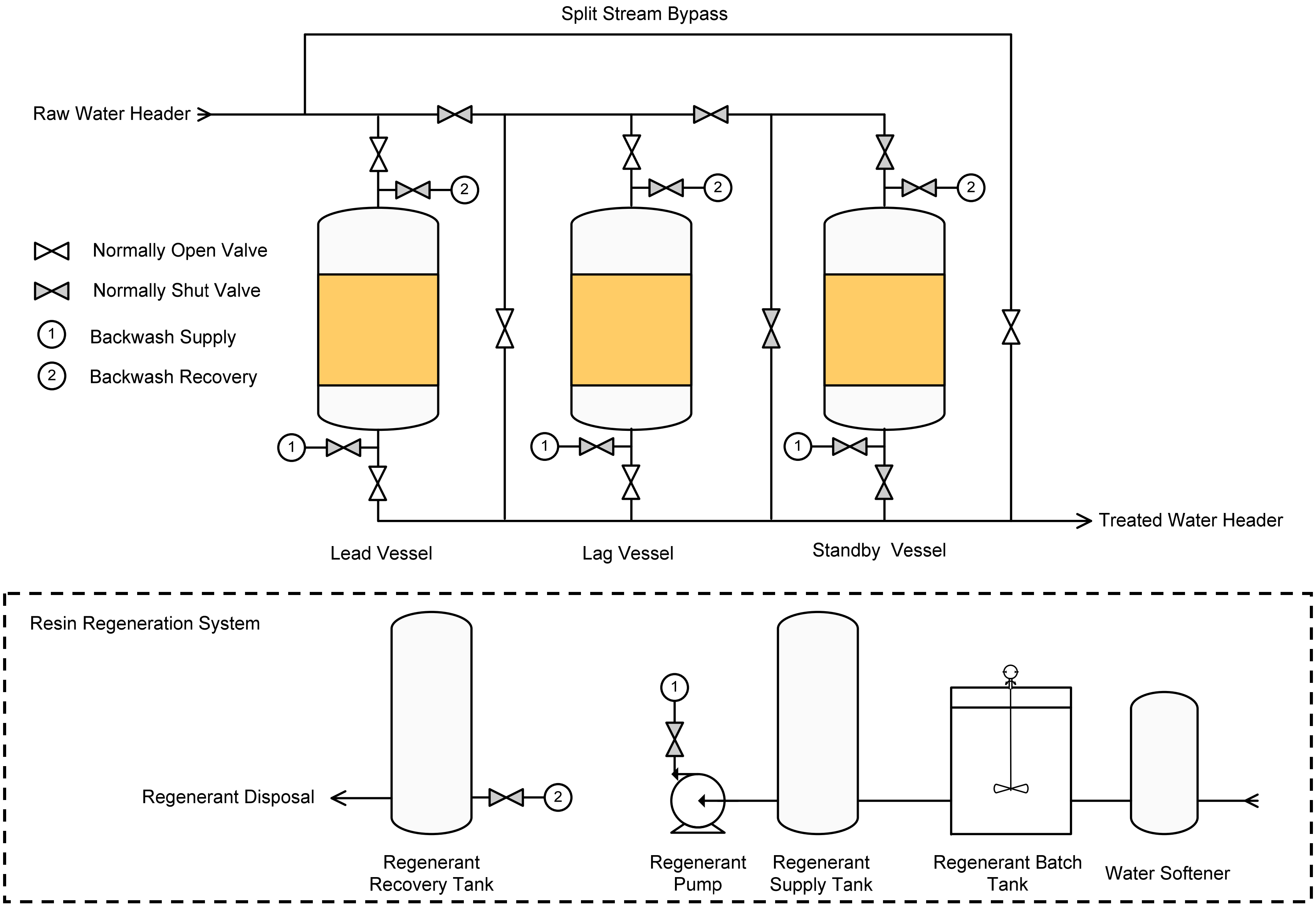
The process flow schematic for a typical split-stream IX process with counter-current regeneration is shown on Figure 3-1. Water to be treated flows downward; however, during regeneration, the brine solution is introduced in the upflow direction. This direction is purposely counter-current to the treatment flow during normal operation so that nitrate leakage can be minimized. Brine regeneration is followed by a slow rinse using softened water, also in the upflow mode. The final step is a fast rinse in the downflow mode with feed water.

3.1.2 Treatment of Specific Contaminants

Depending on the specifics of IX system design and regeneration level used, nitrate removal through IX treatment may vary between 75 and 98 percent. Average nitrate leakage through IX vessels is approximately four percent. Full-scale treatment facilities have also demonstrated arsenate removals of 95 to 99 percent. Similar removal of the reduced arsenite form can be achieved if provisions for oxidation to arsenate are included prior to the IX process. Bench-scale tests have shown that IX can decrease perchlorate concentrations to below detection levels. The main factors determining which IX process to choose for perchlorate removal will depend on the background concentrations of sulfate and nitrate in the water. Calgon Corporation has developed a proprietary method for perchlorate removal from drinking water. The patented ISEP continuous IX system can effectively remove perchlorate and the ISEP+ catalytic destruction system destroys the perchlorate in the resulting IX regeneration brine solution, simplifying waste disposal. In February of 2000, Calgon Carbon received CDPH approval of its ISEP system for the treatment of perchlorate in drinking water. The process is currently installed in La Puente, California, a 2.9 million gallon per day (mgd) facility. The City of Chino also has a Calgon ISEP facility operating in nitrate removal mode. The 5,000 gallons per minute (gpm) plant was constructed in 2005.

3.1.3 Costs

Construction costs for conventional IX facilities, as outlined in Figure 3-1, are approximately $1.00 per gallon per day (gpd) of IX treatment capacity, and O&M costs are approximately $70.00 per acre-ft of IX product water ($0.21 per 1000 gallons). Blending strategies can reduce the production costs by reducing the required size of the treatment units. Projected capital cost for the proprietary ISEP process is approximately $3.63 per gpd treatment capacity with O&M costs ranging from $0.28 to $0.34 per 1,000 gallons of product water. Site economic parameters, such as availability of brine disposal would be considered to determine if the higher cost of this proprietary system is justified.



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Ion Exchange Treatment Process Schematic

Figure 3-1

3.2 Reverse Osmosis

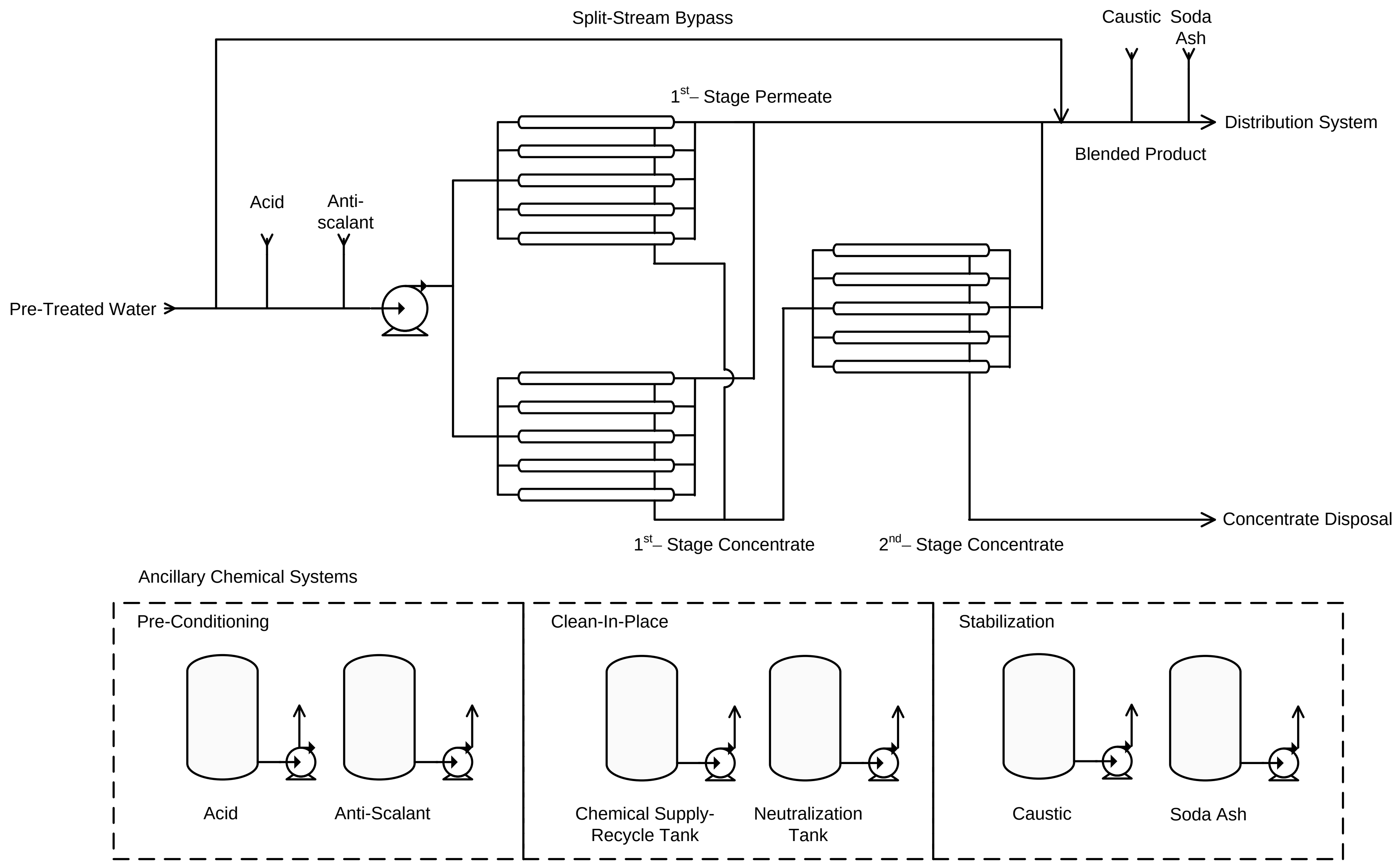
Reverse osmosis is a pressure-driven membrane separation process primarily used for the removal of dissolved organic and inorganic substances from water, including salts, disinfection by-products, and synthetic organic compounds. RO is currently used in the Basin for removal of total dissolved solids (TDS), a process known as desalting.

3.2.1 Process Overview

Reverse osmosis treatment is based on driving water under pressure through a semi-permeable membrane that rejects dissolved constituents based on their charge, polarity, and size. Membrane material and pore size determine the extent to which various dissolved ions and molecules including inorganic salts and metals, natural organic matter, and synthetic organic compounds are rejected from drinking water. However, as a practical matter, no membrane system can provide complete separation of dissolved constituents from water using a finite driving force. Consequently, RO results in two liquid streams: a treated product stream, referred to as *permeate*, which has a low dissolved matter concentration, and a waste byproduct stream, referred to as *concentrate*, which contains the dissolved constituents that were removed from membrane feed to produce the permeate stream.

Performance is described in terms of recovery of product water, rejection of contaminants, operating pressure, and flux rate at the operating pressure. Recovery is the ratio of product water to influent feed water, and is limited by the concentration of sparingly soluble salts on the upstream face of the membrane. Recovery from RO treatment of freshwaters typically ranges between 75 to 90 percent; however, may be substantially lower from brackish and saline source waters. Rejection measures the fraction of any given contaminant removed and varies among different membranes. Solute rejection by RO membranes is a function of molecular weight, shape, and charge. Membranes with greater than 99 percent rejection of many dissolved contaminants are currently available. Operating pressures are on the order of 100 psi or higher, depending on salinity. Flux rate measures the flow per unit area of membrane surface at a given pressure, and varies by membrane type and by the particular water chemistry. Membrane fouling directly reduces the flux rate, hence decreases the overall treatment capacity if the problem is not mitigated either by pretreatment, membrane cleaning, or both.

The RO process is schematically represented in Figure 3-2. Pretreatment is usually required to prevent irreversible fouling, improve performance, and extend membrane life. Pretreatment may include turbidity reduction by various forms coagulant addition and particulate filtration, pH reduction, and addition of scale inhibitors. The type and extent of pretreatment will depend on the type of membrane used, composition of feed water, and desired flux and recovery of the system. Scale inhibitor addition is a common chemical pretreatment step that inhibits precipitation of sparingly soluble salts that can foul membrane surfaces.



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Two-Stage Reverse Osmosis Membrane Treatment Process Schematic

Figure 3-2

Pretreated water is pumped through vessels containing several RO membrane elements connected in series. Several RO configurations such as single-pass or multi-pass arrangements can be applied for water treatment. In a single-pass system, part of the feed stream passes through the membrane (product water or permeate) while the remaining part exits the membrane as brine (concentrate or reject). In a multi-pass system, concentrate from one stage passes through another membrane as its feed water or if it is the last stage in the design, it could be discharged. The second and consecutive stages would treat water with higher TDS and hence would produce a permeate water slightly lower in quality compared to the first stage. However, blending the permeates from the various stages results in water that still meets or exceeds overall project water quality goals.

Reverse osmosis permeate is somewhat corrosive because it is depleted in calcium and alkalinity and may have a relatively low pH. Post treatment operations for corrosion control for RO product water include releasing carbon dioxide in a degassifier; adding caustic, sodium bicarbonate, or sodium carbonate to increase bicarbonate alkalinity and pH; and adding lime to increase both calcium ion and alkalinity concentrations and pH. Permeate is often blended with source water to produce the targeted design concentrations of the finished water, reducing overall water treatment costs.

3.2.2 Treatment of Specific Contaminants

RO has the potential to remove three inorganic contaminants of concern. The typical removal of nitrate by RO is greater than 95 percent. Removal of perchlorate by RO membranes is currently under extensive study by several researchers. Based on the results currently available, RO membrane rejection of perchlorate is expected to be greater than 85 percent and possibly as high as that of nitrate. However, the effect of perchlorate on membrane life is yet to be fully quantified. A high concentration of this oxidant could yield some membrane degradation. Removal of arsenic is possible with RO; however, the level of arsenic rejection by RO depends on the oxidation state. For example, removals greater than 95 percent are possible for As(V), whereas removal of As (III) is significantly lower (60 to 85 percent) depending on the type of membrane used and water quality. Since RO membranes do not remove dissolved gases, these membranes provide relatively poor removal of VOCs. However, VOCs could be removed after RO via the degassifier used to remove carbon dioxide from the permeate. If VOCs are present in the feed water, it is likely that the degassifier design could be optimized for the removal of VOCs, while still obtaining carbon dioxide removal. Rejection of DBCP by Dow FilmTec® RO membranes has been reported by the manufacturer to be 79 percent; however, substantially lower DBCP rejection has been reported for other membrane types.

3.2.3 Costs

Construction costs for RO facilities are approximately $1.00 to $1.50 per gpd RO product water capacity and O&M costs range between approximately $0.30 and $0.50 per 1,000 gallons of RO permeate, depending on source water quality and local electricity costs. These O&M costs assume that concentrate disposal by sewer or ocean discharge is available.

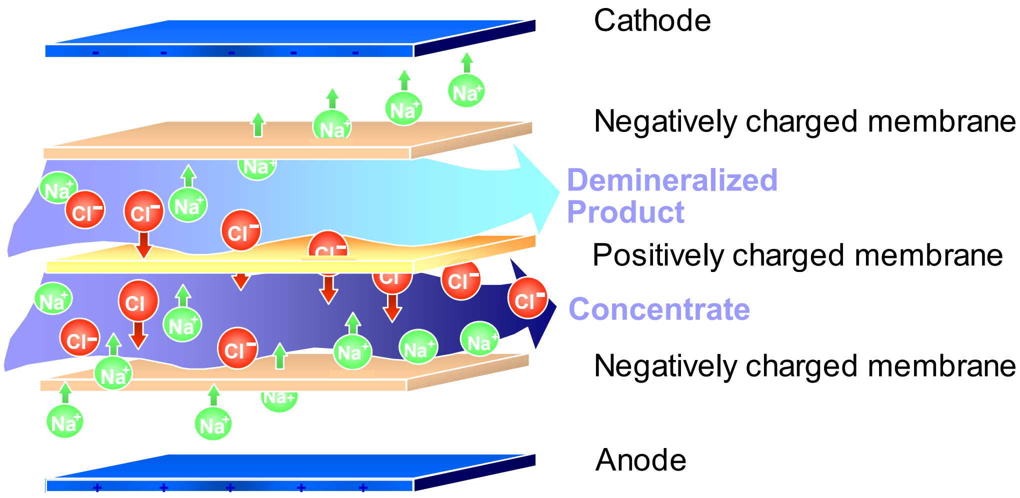
3.3 Electrodialysis Reversal

Electrodialysis reversal (EDR) is a membrane-based electrochemical separation process for the removal of ionic contaminants from a water supply. EDR uses ion-selective exchange membranes that allow passage of either anions (anion-transfer membranes) or cations (cation-transfer membranes).

3.3.1 *Process Overview*

The basic electrodialysis cell configuration consists of parallel flow channels created by stacking flat-sheet anion-transfer and cation-transfer membranes separated by flow spacers. The membrane stack is placed between electrodes, and an imposed voltage causes a direct current (DC) to flow: positively charged cations move toward the negatively charged electrode (cathode) and negatively charged ions move toward the positively charge electrode (anode). A single membrane cell pair is shown on the adjacent diagram. Because of the alternating arrangement of cation-exchange and anion-exchange membranes, as ions move toward the cell electrodes they become trapped in alternating flow channels, resulting in demineralized water and concentrate streams. Uncharged substances such as silica and many synthetic organic compounds (SOCs) are not removed by EDR, nor are particulate matter or pathogens.

There is a limit to the current carried per unit membrane area (current density) based on transport of electrolyte ions under the applied electrode voltage. As cations and anions are removed from the demineralized stream, ion concentrations at the membrane surfaces become progressively depleted. Polarization occurs when too few electrolyte ions are present to allow proper current flow and the resulting high electrical resistance causes water molecules to dissociate into protons (H^+) and hydroxide ions (OH^-). Excessive flow of OH^- ions across the anion-selective membranes into the concentrate channels can lead to increased pH and Calcium carbonate precipitation. In EDR, the polarity of the electrodes is reversed periodically to reverse the direction of ion flow and flush scale forming ions from the membrane surfaces.



A treatment process schematic of the EDR process is shown on Figure 3-3. The performance of EDR depends on feed water quality. As in RO, scaling of sparingly soluble salts limits the overall recovery of product water. The use of chemicals, such as antiscalants, is required to control the formation of inorganic scale. The presence of natural organic matter may also affect the EDR process performance. To achieve high recovery and high rejection, multi-stage systems are required; typical multi-stage EDR facility includes three stages. Recoveries in the range of 70 to greater than 90 percent are possible depending on the water quality. It should be noted that only one manufacturer supplies EDR equipment in North America, thus eliminating a competitive bidding environment.

3.3.2 Treatment of Specific Contaminants

EDR has the potential to remove three contaminants of concern: nitrate, arsenic, and perchlorate. Removal of nitrate by EDR facilities is fairly high; however, the specific value depends on various factors, including the mixture of ions present in the water and the number of stages used in the EDR system. Nitrate rejection values ranging from 80 percent to greater than 90 percent have been reported. The manufacturer of EDR equipment is currently investigating the rejection of arsenic ions. It is expected that As(V) rejection would be higher than that of As(III) and that EDR rejection of arsenic ions would be similar to, or possibly lower than, those exhibited by RO. Perchlorate removal by EDR is currently under investigation and its removal is expected to be in the range of 70 to 80 percent.

3.3.3 Costs

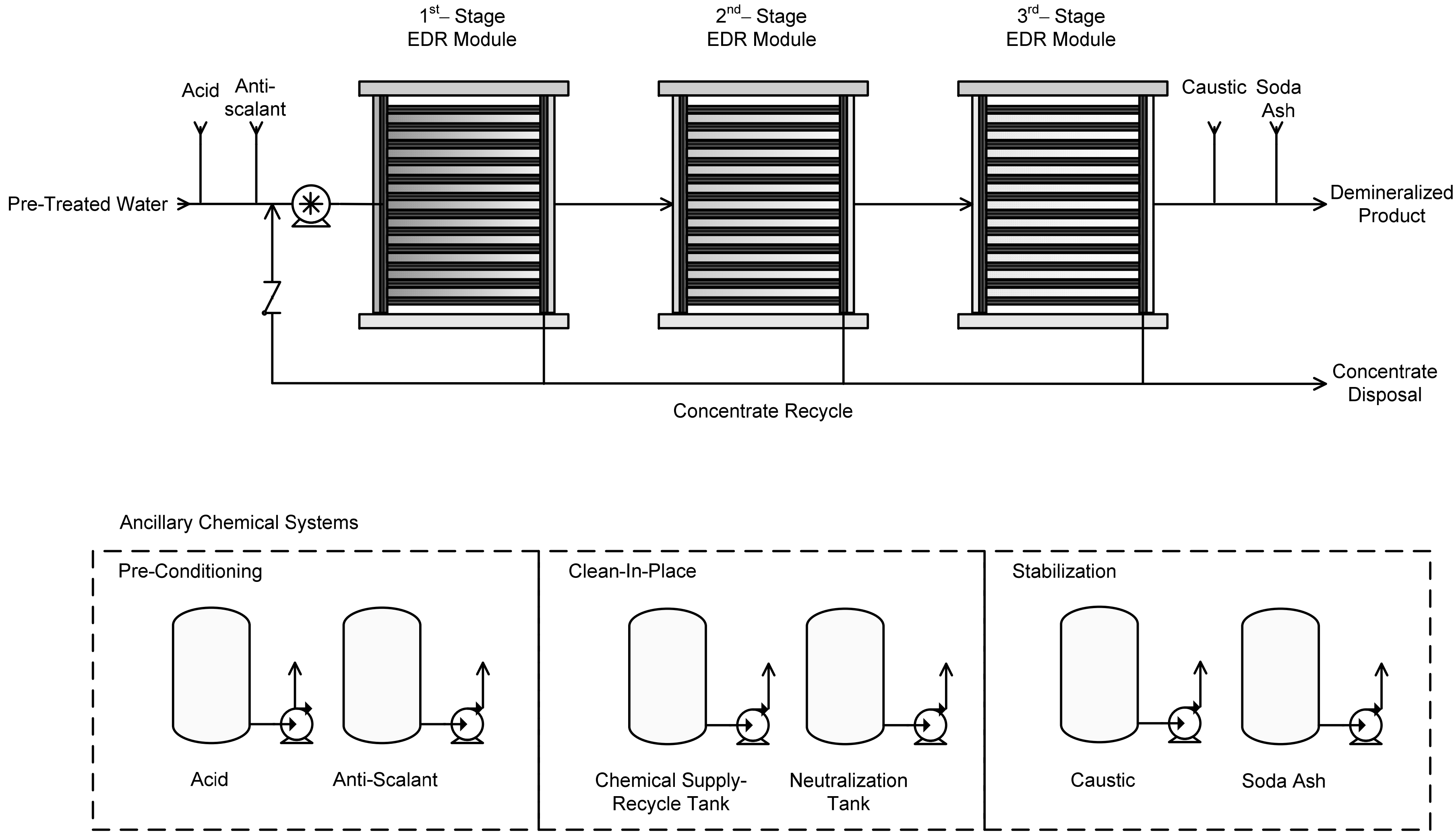
Construction costs for EDR facilities are approximately $1.00 per gpd of EDR treatment capacity and O&M costs are approximately $0.60 per 1,000 gallons of EDR product water. These O&M costs assume that concentrate disposal by sewer or ocean discharge is available.

3.4 Granular Activated Carbon

GAC is an established treatment technology for the removal of organic compounds from drinking water. GAC systems are generally relatively easy to implement because of the simplicity of the equipment.

3.4.1 Process Overview

GAC removes contaminants from water by adsorption from the liquid phase to the GAC surface. GAC is created by grinding, burning, and then activating carbon materials, such as peat, coal, and wood. The most common raw material for GAC in water treatment is coal. This procedure develops a porous media with a high surface area for improved adsorption. When the adsorptive capacity is exhausted, the GAC is replaced or regenerated. Figure 3-4 presents a typical GAC facility arrangement.



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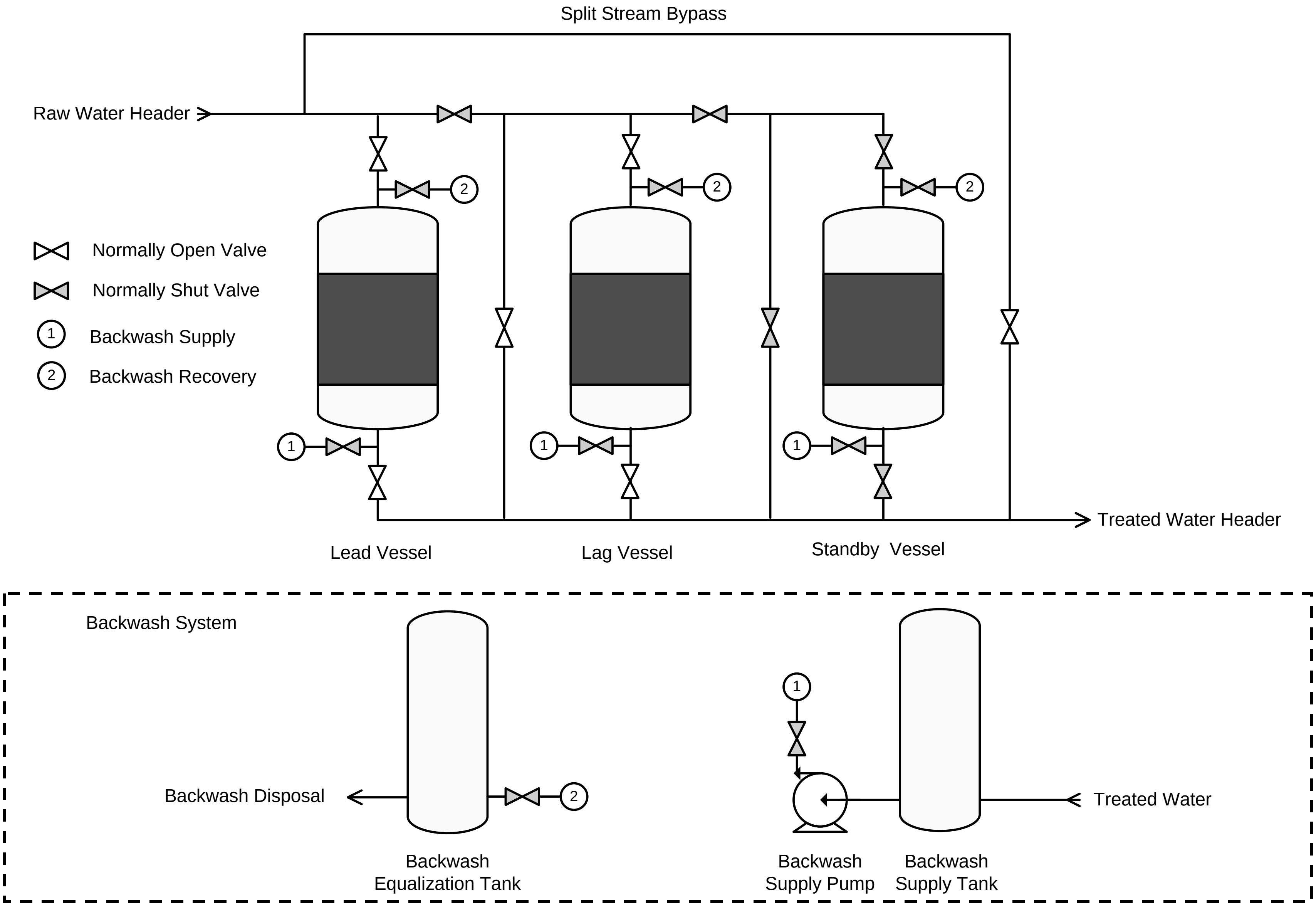
3-Stage Electrodialysis Reversal Membrane Treatment Process Schematic

Figure 3-3



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Granular Activated Carbon Adsorption Treatment Process Schematic

**Figure
3-4**

The effectiveness of GAC for removing contaminants is described by its adsorptive capacity. Adsorptive capacity is measured in terms of the weight of contaminant removed from the water per unit weight of GAC. A higher adsorptive capacity translates to less frequent GAC media replacement, hence lower operating cost. Each contaminant has a theoretical adsorptive capacity. However, the extent to which a GAC system can attain its theoretical capacity depends on several factors: the required treated water concentration, the empty bed contact time (EBCT), and the concentration of interfering compounds, such as natural organic matter (NOM). A lower desired treated water concentration results in a lower attainable adsorptive capacity. A lower EBCT (i.e. smaller GAC contactor) results in a lower attainable adsorptive capacity. EBCT for conventional GAC treatment for organics removal is on the order of 5 to 15 minutes, depending on the contaminant to be removed and water quality. A higher concentration of interfering compounds results in a lower attainable adsorptive capacity. Where there is a mix of contaminants to be removed, one of them will govern the system design and will determine the attainable adsorptive capacity for the others.

3.4.2 Treatment of Specific Contaminants

GAC is the BAT for the removal of DBCP and can be used for removing VOCs. The carbon usage rate is estimated at 0.068 mg DBCP per gram carbon at a DBCP influent concentration of 0.6 µg/L. Therefore, 73.6 pounds of GAC for every million gallons of treated water will be consumed. VOCs are generally removed through packed tower aeration (PTA), which is more cost effective. However, if off-gas treatment is required, liquid phase adsorption by GAC can become cost effective.

Perchlorate removal by GAC occurs but by a process of ion exchange rather than adsorption. In an American Water Works Association Research Foundation (AWWARF) study, it was found that virgin GAC removed perchlorate for only two weeks before regeneration or replacement of the carbon. The adsorptive capacity of GAC was also determined during this study and was determined to be approximately 0.172 milligrams (mg) perchlorate per gram GAC. Assuming this capacity for reducing 19 µg/L to the action limit of 4 µg/L requires approximately 10 times as much GAC per million gallons than was required for DBCP. This translates to more frequent regeneration or replacement of activated carbon, which increases the treatment cost. GAC impregnated with iron, copper, zinc, oxalic acids, or aluminum can assist with perchlorate removal, but still functions primarily as a media on which ion exchange and not adsorption occurs. Because of the high GAC replacement frequency, GAC is not a good candidate for perchlorate removal.

Nitrate removal on GAC by biological degradation under anoxic conditions has been studied. Likewise, perchlorate removal under anaerobic conditions was studied. However, results indicate that significantly longer than conventional contact times would be required. Further development is needed for biological GAC to be considered for nitrate or perchlorate removal.

GAC can also adsorb arsenate and adsorption increases with decreased pH. Recent pilot studies conducted at the City of Scottsdale, Arizona, showed that bituminous and lignite GAC (EBCT = 15 minutes, pH approximately 7.7) removed as much as 8 parts per billion (ppb) from a surface water containing about 20 ppb arsenate. Some arsenite was also adsorbed, but limited data were collected. Further field studies would be needed before GAC can be considered for arsenic removal.

3.4.3 Costs

Conventional GAC facilities for DBCP removal and possibly VOC removal are approximately \$0.50 to \$1.00 per gpd treatment capacity and O&M costs are approximately \$0.10 to \$0.20 per 1,000 gallons treated. However, the expected O&M costs associated with GAC contactors is very much a function of scale and regeneration frequency.

3.5 Packed Tower Aeration

PTA is the most widespread treatment technology for VOC removal available today.

3.5.1 Process Overview

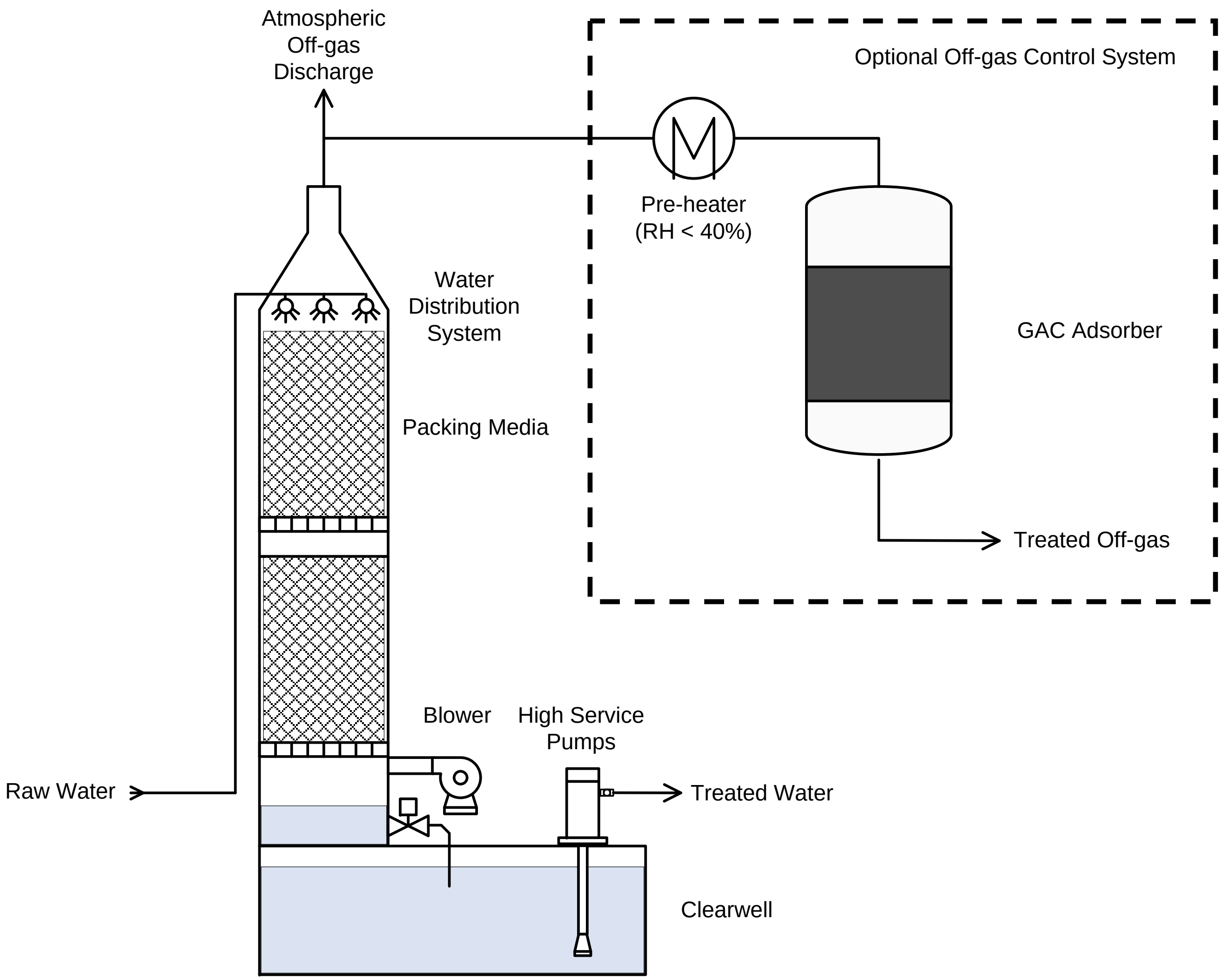
The PTA process uses media-filled towers to transfer volatile contaminants from water to air. Figure 3-5 presents a typical air stripping process schematic. Contaminated water is pumped to the top of the tower and distributed, then percolates downward through the media. A blower discharges to the bottom of the column providing counter-current air flow up through the tower. Packed media provides the needed surface area for gas transfer to occur. After the packed tower removes volatile contaminants from water, the contaminated air (off-gas) may need GAC treatment to prevent discharge of the contaminant to the atmosphere, depending on local air quality regulations.

Henry's Constant measures the tendency for a given contaminant to move from water into the air. A higher Henry's Constant means a greater tendency to move from the water to the air and results in a shorter tower. Although the Henry's Constant increases with higher temperature, heating raw water is typically too costly to be practical for most drinking water applications. Henry's Constant for a given contaminant determines the required dimensions of the tower (i.e., the amount of packing required) for a given percent removal.

3.5.2 Treatment of Specific Contaminants

Chemicals with Henry's Constant values greater than 0.001 ($1\text{x}10^{-3}$ atm-m^3/mole) are considered volatile and amenable to air stripping. The four VOCs of concern here have relatively high Henry's Constants, making them amenable to removal by air stripping. When more than one volatile chemical is found in a water supply, the system is designed to treat the least volatile to a target level below the regulatory level. There is no competition between the volatile constituents as the partial pressure of each chemical provides the driving force for volatilization.

DBCP has a relatively low Henry's Constant ($1.47 \text{ x } 10^{-4}$ atm-m^3/mole). Although DBCP can be removed by PTA, a Henry's Constant below $3.6 \text{ x } 10^{-4}$ atm-m^3/mole suggests that adsorption on granular activated carbon may be a more practical method. If removal of DBCP is to be attempted with PTA, pilot tests should be performed.



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Packed Tower Aeration Treatment Process Schematic

Figure 3-5

3.5.3 Costs

Construction costs for VOC removal using PTA facilities with GAC off-gas treatment are approximately $0.25 per gpd treatment capacity and O&M costs are approximately $0.10 per 1,000 gallons treated.

3.6 Advanced Oxidation Processes

Advanced oxidation includes processes that produce highly reactive hydroxyl radicals (OH^-). Target contaminants are primarily organics; although, reduced nuisance metals such as iron and manganese as well as reduced sulfur may also be oxidized.

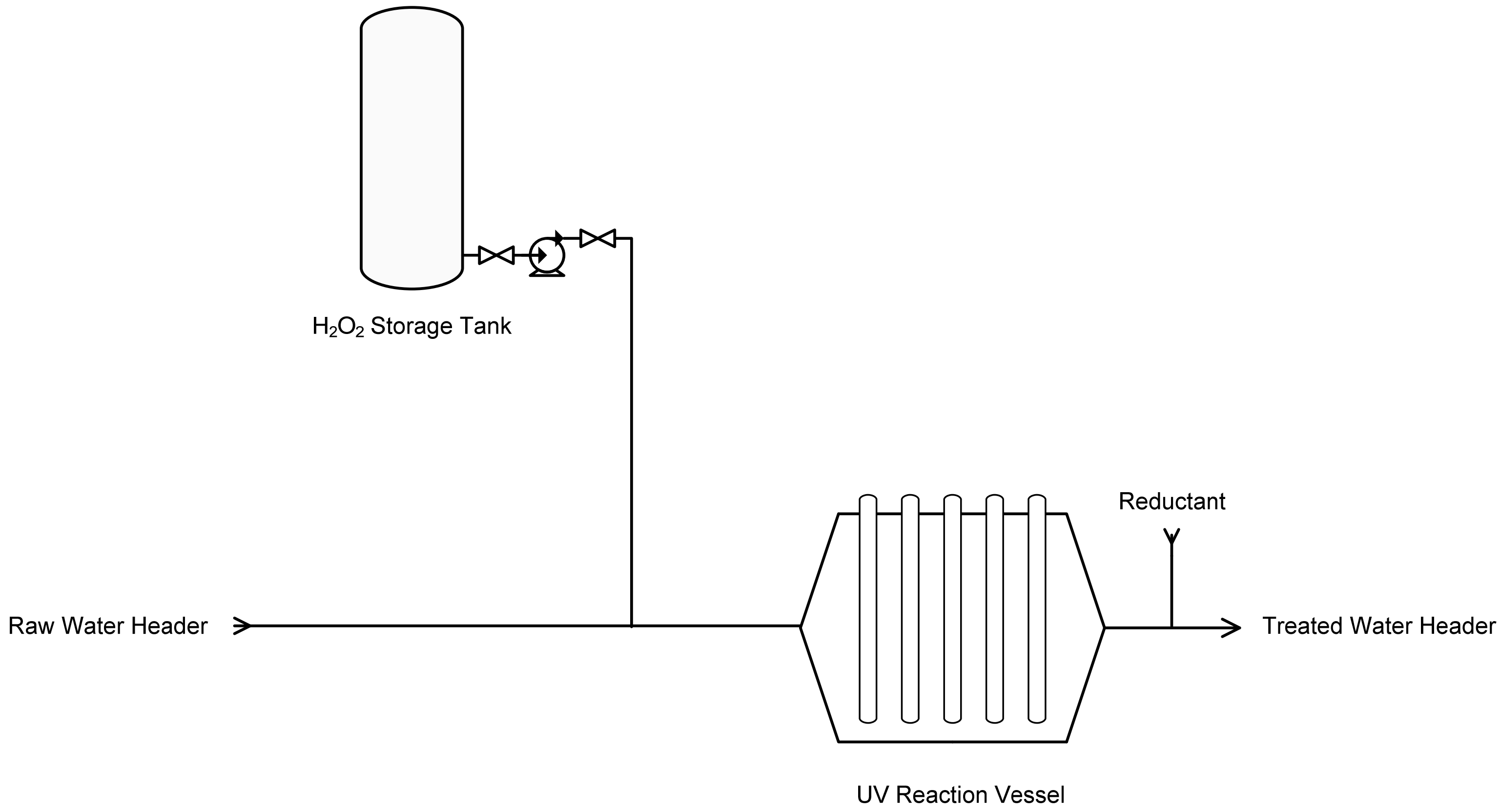
3.6.1 Process Overview

Advanced oxidation processes (AOPs) that generate highly reactive hydroxyl radicals (+OH) at ambient temperatures have become more widely used in recent years. Unlike conventional oxidants such as free chlorine, which exhibit very selective reactivity with organic compounds, hydroxyl radicals produced by AOPs are capable of completely oxidizing organic compounds to carbon dioxide and mineral acids. AOPs have several inherent advantages over other organic micropollutant control measures such as air-stripping or GAC adsorption including:

- Contaminants can be completely destroyed
- Contaminants that are not volatile or adsorbable can be destroyed
- Processes such as air-stripping and GAC adsorption merely transfer contaminates to another phase, generating a residual that may require further treatment or disposal

Several methods of hydroxyl radical formation for AOP use in drinking water treatment are possible including ozone contact at alkaline pH, ozone contact with hydrogen peroxide addition (O_3/H_2O_2), ozone contact with ultraviolet (UV) irradiation (O_3/UV), and hydrogen peroxide contact with UV irradiation (H_2O_2/UV). AOPs tend to have high operating costs due to the energy requirements for ozone production and UV irradiation. AOPs also tend to be more operationally complex than other organic micropollutant control methods such as air stripping or GAC adsorption. Figure 3-6 presents a typical AOP process utilizing hydrogen peroxide addition with UV light.

Influent water quality has a direct impact on advanced oxidation organic contaminant removal efficiency. Because hydroxyl radical oxidation is a non-selective process, non-target compounds also exert an oxidant demand. These side reactions may also prevent complete oxidation of the target contaminant, resulting in byproducts other than carbon dioxide and water. In some instances, incomplete oxidation of target contaminants can lead to formation of byproducts that are also regulated. Examples of how water quality can affect AOP processes are as follows:



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UV – Hydrogen Peroxide Advanced Oxidation Treatment Process Schematic

Figure 3-6

- Total organic carbon (organic matter) exerts oxidant demand.
- Other oxidizable species (As (III), reduced forms of iron, manganese, etc.) exert oxidant demand, especially if they are more easily oxidizable than the target organics. Some can form scale in the presence of UV light.
- Alkalinity scavenges hydroxyl free radicals and may require pH reduction to minimize the scavenging effect.
- Nitrate absorbs UV light and is converted to nitrite, which exerts an oxidant demand.
- Bromide, if present in sufficient concentrations, can be converted by ozone to bromate (which has an MCL).
- Turbidity (not generally a problem with groundwater) lowers transmittance of UV light.

3.6.2 Treatment of Specific Contaminants

Advanced oxidation can be considered for removal of VOCs and DBCP from Chino Basin groundwater. AOP has been demonstrated to be effective at removing two of the VOCs, TCE and PCE, and is likely to be effective for the other VOCs. Because water quality conditions have such a significant effect on the process, pilot testing would be required to set the proper dosing for each water source.

3.6.3 Costs

Costs for an AOP system can vary widely dependent on the water quality and finished water requirements. Capital costs range from $0.60 to $1.00 per gpd treatment capacity. O&M costs range from $0.30 to $0.90 per 1,000 gallons treated.

3.7 Iron Coagulation and Filtration

Iron-salt coagulants can be used for arsenic and chromium removal. Such a system would require first a coagulation step to trap the contaminant in a floc particle (co-precipitation) and then a filtration step to remove the floc particles from the water.

3.7.1 Process Overview

The oxidized As(V) form of arsenic is more easily removed by this process because it typically occurs as the negatively charged $HAsO_4^{2-}$ or $H_2AsO_4^{-}$ arsenate species in groundwaters. Co-precipitation occurs when the negatively charged arsenate is attracted to the positively charged floc composed of iron hydrolysis products. Co-precipitation, hence, arsenate removal is more effective between pH 5.5 and 7.5 where iron floc particles are more positively charged. Co-precipitation removal of arsenic is subject to interference by compounds such as phosphate, sulfate, and silica, if they are present in the water being treated.

A process schematic for ICF is shown on Figure 3-7. In drinking water treatment, coagulation must be followed by filtration to remove the turbidity that results from floc formation. If traditional media filters are used, adequate floc development is needed upstream of filtration. Floc development would include adequate rapid mixing followed by tapered flocculation. In some instances, a sedimentation (or clarification) process is added upstream of the filters to lessen the solids loading and headloss buildup on the filters.

If membrane filtration is used, less floc development is needed because the co-precipitation reaction with arsenic is rapid. The mixing of ferric-coagulant into the process stream is very important because adsorption occurs within the first few seconds of contact. This process was successfully pilot-tested in Scottsdale, Arizona. The Scottsdale pilot study showed excellent results for arsenic removal by iron coagulation followed by membrane filtration (either ultrafiltration or microfiltration). Coagulation using 25 mg/L as ferric sulfate lowered the arsenic concentration from approximately 50 ug/L to less than 7 ug/L.

3.7.2 Treatment of Specific Contaminants

ICF application for arsenic or chromium removal from Chino Basin water supplies would probably utilize membrane filtration rather than media filtration. This is because membrane filtration is more automated, less subject to water quality disturbances, and requires a smaller footprint.

The backwash stream from this process will be approximately 10 percent of the feed water flow. This stream will contain concentrated arsenic and iron, which will require disposal. Disposal options include discharge to a sewer or secondary treatment to reduce the flow prior to discharge to the sewer. A backwash water recovery system could be included to reduce liquid residual disposal.

3.7.3 Costs

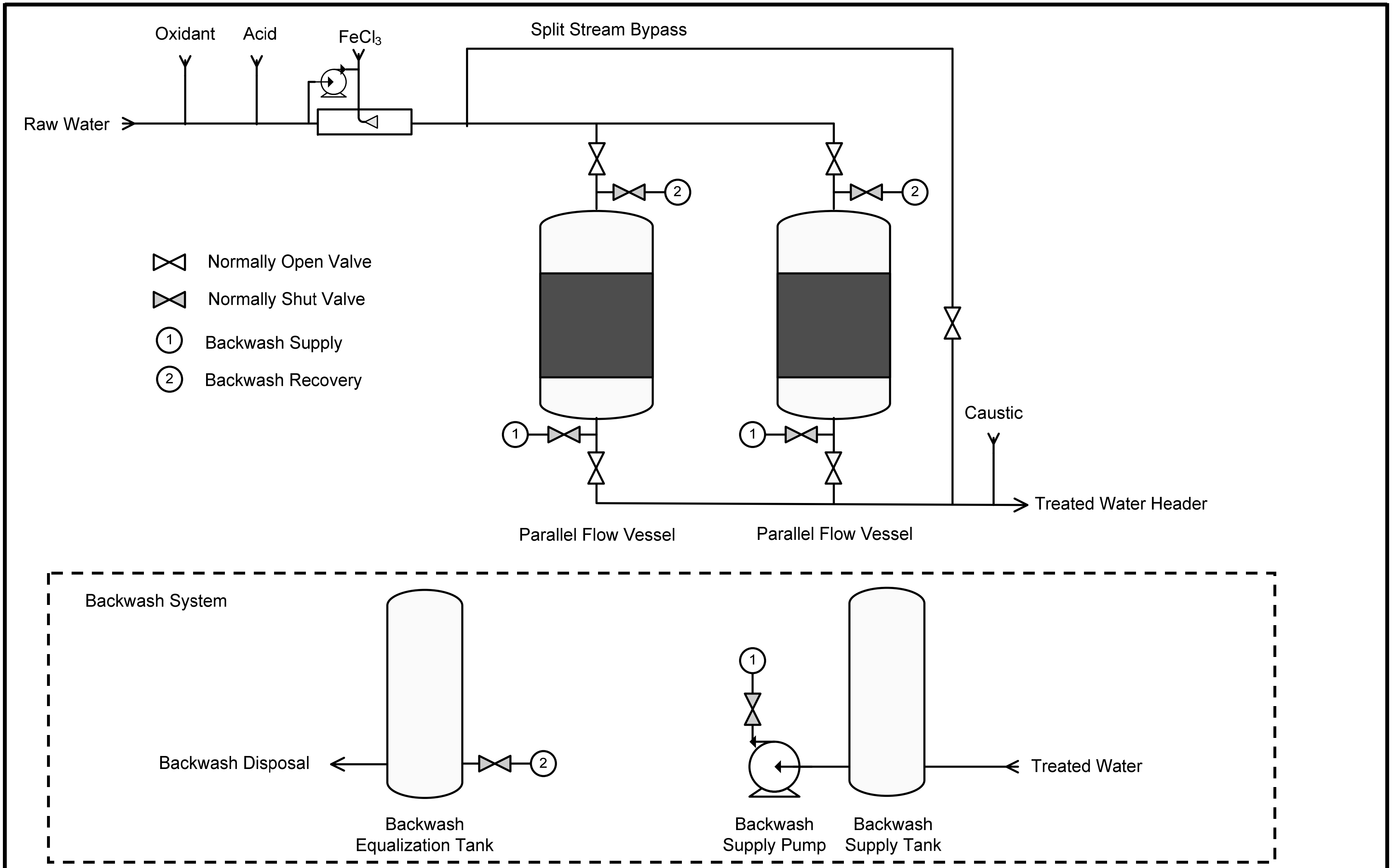
A budgetary capital cost estimate for this system is $1.20 per gpd treatment capacity. O&M costs range between $0.10 and $0.20 per 1000 gallons treated. These O&M costs assume solid residuals disposal by sewer or sanitary landfill is possible.

3.8 Iron Based Media Adsorption

Iron based media adsorption has been found to effectively remove arsenic and chromium from drinking water.

3.8.1 Process Overview

As discussed in Section 3.7, arsenate exists as negatively charged compounds that are adsorbed by positively charged surfaces. Iron-based media has positively charged surfaces and have been shown to be effective for arsenic and chromium (as Cr(VI) species) removal. This process is, however, subject to some interfering compounds and should be field-tested prior to any full-scale installation.



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Coagulation-Assisted Direct Filtration Treatment Process Schematic

Figure 3-7

Feed water is passed through a bed of iron media at a rate to achieve an empty bed contact time of three to four minutes. The depth of the bed depends on the stability of the media. Gravity or pressure filtration can be used; however, there is a maximum pressure that the media can withstand (as specified by the manufacturer). Media may be fairly fragile, and the beds are backwashed only when needed. For this reason, it is important to remove as many solids from the feed water as possible before applying it to the iron based media bed.

3.8.2 Treatment of Specific Contaminants

A process schematic for IBM is shown on Figure 3-8. IBM can be used to remove arsenic and other negatively charged metal ions including Cr(VI) species. The bed-life, however, can be limited by the presence of interfering ions such as nitrate, silica, sulfate, and sometimes phosphate. Therefore, the presence of nitrate contamination can complicate design of an IBM system for arsenic or chromium. Heavy metals (not found in OBMP wells) can also be removed and can hinder arsenic removal if in sufficient concentrations. Pilot testing is advisable if potentially interfering ions are present at significant concentrations.

The pH of the feed water significantly affects the performance of iron-based media for arsenic and Cr(VI) removal. Iron-based media have an increasing affinity for As(V) and Cr(VI) species as pH is lowered below 8. A pH adjustment system upstream of the iron-based media system may be needed for cost effective use of the iron-based media bed.

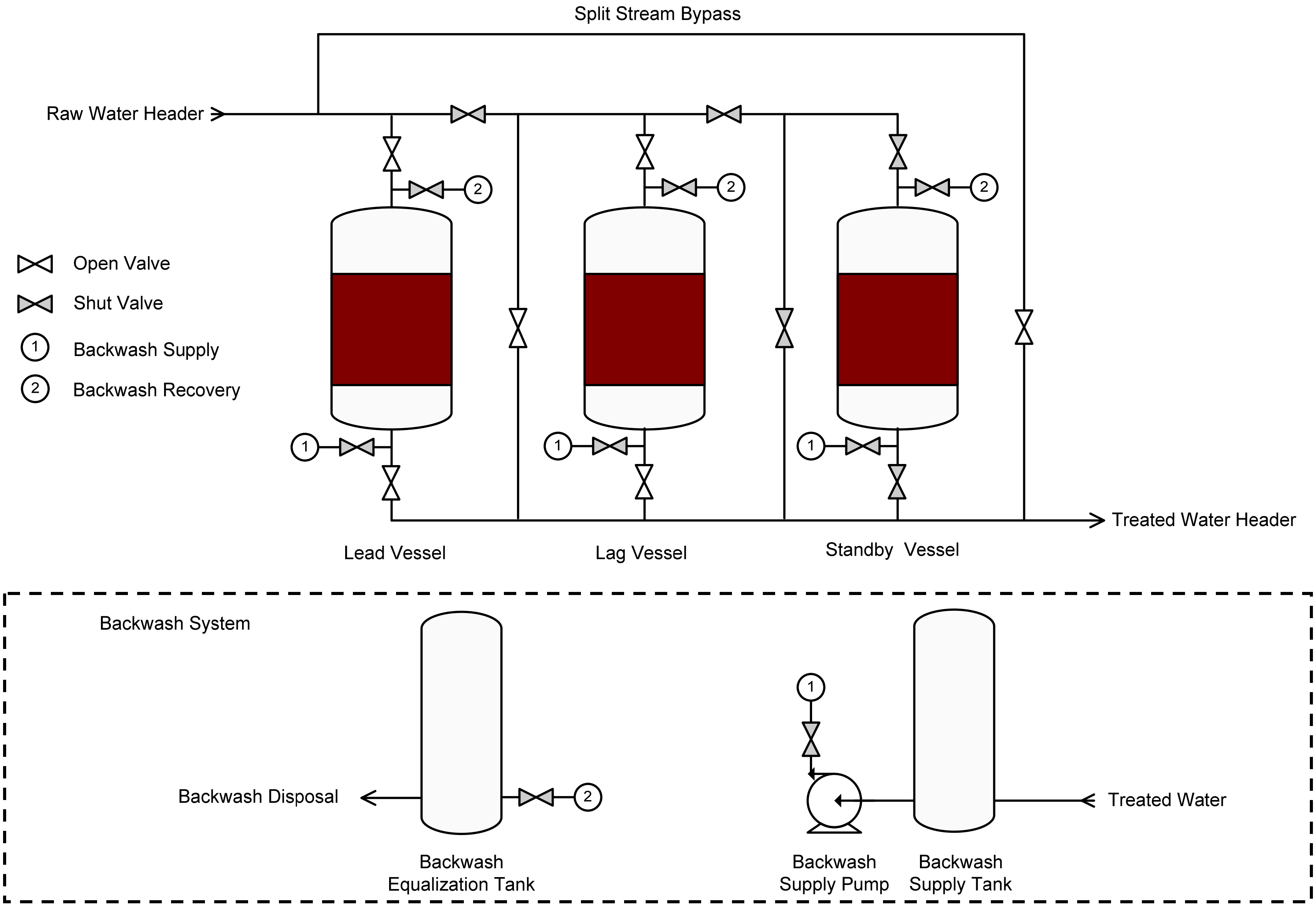
Backwash water is the only liquid waste stream from the iron-based media systems. The volume and frequency of backwashing will depend on the feed water quality. The spent, or exhausted, media will require disposal. As of January 2002, CDPH had not specified any disposal requirements for spent media, but indicated that disposal requirements are likely to be media and site-specific.

3.8.3 Costs

Capital cost is approximately $0.80 to $1.10 per gpd treatment capacity. Operating cost for this system is approximately $0.10 to $0.15 per 1,000 gallons, based on a 12 month bed-life for the media.

4.0 COMPARISONS

Table 4-1 summarizes the comparison among individual treatment processes. The primary selection criterion is removing the most contaminants for the lowest cost. Type of consumable supplies, type of residuals, and production losses are secondary criteria. Consumable supplies refer to the water treatment chemicals (other than disinfectant) or replacement media that would be required. The perceived safety risk from reactive chemicals would be a disadvantage. The type and quantity of residual determines residual disposal requirements. Liquid brine residuals require a non-reclaimable waste disposal pipeline, which is available in some parts of the Chino Basin. A smaller residuals flow reduces the connection and use fees required for non-reclaimable waste disposal. Larger liquid residual flows contribute to water production loss.



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Granular Iron-Based Media Adsorption Treatment Process Schematic

Figure 3-8

Table 4-1
Treatment Process Comparison

Treatment Process	Type of Contaminants Effectively Removed	Capital Cost ($/gpd capacity)	O&M Cost ($/1,000 gal)	Consumable Supplies Needed (other than disinfectant)	Residuals	Residual Quantity (% of Untreated Flow)	Other
Ion Exchange (IX)	NO3, ClO4, As, Cr(VI)	$1.00	$0.20 to $0.25	Salt(1) IX media(2)	Spent brine(1) IX media(2)	1% to 2%	
Reverse Osmosis (RO)	NO3, ClO4, As, Cr(III/VI), DBCP	$1.00 to $1.50	$0.30 to $0.50	Sulfuric acid, scale inhibitors	Brine (reject flow)	10% to 20%	
Electrodialysis Reversal (EDR)	NO3, As, Cr(VI)	$1.00	$0.60	Scale inhibitors	Brine (reject flow)	10% to 20%	Single supplier only.
Granular Activated Carbon (GAC)	VOC, DBCP	$0.50 to $1.00	$0.10 to $0.20	GAC media	Spent GAC media	Minimal	
Packed Tower Aeration (w/GAC offgas treatment)	VOC, DBCP	$0.25	$0.10	GAC media	Spent GAC media	Minimal	
Advanced Oxidation Processes	VOC, BDCP	$0.60 to $1.00	$0.30 to $0.90	Hydrogen peroxide, liquid oxygen(3)	None	Minimal	
Iron Coagulation and Filtration (ICF)	As, Cr(III/VI)	$1.20	$0.10 to $0.20	Ferric chloride or related iron-based coagulant	Filter backwash (due to coagulation)	10%	
Iron-Based Media Adsorption (IBM)	As, Cr(III/VI)	$0.80 to $1.00	$0.10 to $0.20	IBM media	Spent IBM media	Minimal	

Notes:
(1) Salt required if media is regenerated.
(2) Media replacement required in non-regenerable type used.
(3) Only if ozone is used.

For inorganic contaminants, IX has the best combination of lower costs (both capital and O&M) and largest number of contaminants effectively removed. IX also does not have the relatively large reject stream that both RO and EDR have. In addition, the reject streams of 10 to 20 percent for both RO and EDR will add to the groundwater production loss. In contrast, the spent brine regenerant stream from IX is a much smaller percentage of the overall treated water flow and thus has a much smaller impact on net groundwater production. The potential need to store sulfuric acid for pH adjustment also makes RO and EDR less attractive.

For the organic contaminants, PTA with off-gas treatment has the best combination of lower cost and largest number of contaminants removed if there is no DBCP. If DBCP is present, then GAC is more likely the best option because aeration designed for DBCP removal is likely to be less cost-effective than GAC. The higher and less certain costs of AOP make it a less favorable choice. Also, its requirement to store highly reactive chemicals (other than disinfectant) at each treatment site makes it a less favorable choice.

5.0 RECOMMENDATIONS

The type of treatment appropriate to a particular well is dependent on the type and number of contaminants present in the water. There are many possible contamination scenarios. The recommended treatment process for each individual contaminant is listed in Table 5-1. No more than two treatment processes should be needed for any one of the possible contaminant scenarios: one process for inorganic contaminants and one process for organic contaminants. If NO_3^-, ClO_4^-, or Cr(VI) are the target contaminant of greatest concern, then IX is the preferred treatment alternative. Iron-based technologies are preferred if arsenic or Cr(III) are present alone or in combination. For organic contaminants, the presence of DBCP immediately requires GAC, even when VOCs are also present. Otherwise, PTA with off-gas treatment is recommended for VOCs. The ISEP process may be considered where IX is recommended; however, its higher costs will need to be justified by specific site requirements, such as a need for perchlorate or nitrate destruction due to unavailability of a non-reclaimable waste pipeline nearby. Arsenic speciation should be examined for water at each of the water supplies designated for arsenic removal. This will determine if oxidation is necessary prior to iron-based technologies.

Table 5-1
Recommended Treatment Processes

Scenario	Contaminants	Recommended Treatment Process(es)
1	Any or all of NO3, ClO4, Cr(VI)	IX
2	Arsenic	IBM
3	Cr(III)	IBM
4	VOCs	PTA
5	DBCP	GAC
6	DBCP and VOCs	GAC