

APPENDIX H

**Groundwater Contaminants and Treatment Alternatives TM 1.4 by
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City of Fresno

**Groundwater Contaminants and
Treatment Alternatives
Technical Memorandum 1.4**

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CITY OF FRESNO

Groundwater Contaminants and Treatment Alternatives

**TECHNICAL MEMORANDUM
NO.1.4**

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Groundwater Contaminants and Treatment Alternatives

1.0 INTRODUCTION

1.1 Overview

The City of Fresno (City) has approximately 250 water production wells throughout the City's 115 square-mile area. According to the total production data from 2004, the annual average production from the groundwater is approximately 102,000 gpm. Based on more recent, one day production data (August 2, 2005), the total daily groundwater production peak ranged from 115,000 to 247,000 gpm. Due to various groundwater contamination issues, however, a number of wells have been shut down. As a result, the City has lost significant amount of groundwater production capacity over the years. The purpose of this Technical Memorandum (TM) is to evaluate the extent of groundwater contamination due to historical and emerging contaminants and summarize treatment alternatives.

1.2 Objectives

The main goals of this TM include the following.

- Identify and summarize the current and emerging groundwater contaminants in the City
- Evaluate the treatment alternatives for the major contaminants of concern
- Present general capital and O&M costs for each major contaminant identified by the City

The assumptions made for each subject are summarized in the following sections.

2.0 SUMMARY OF CONTAMINANTS OF CONCERN

In order to identify the major contaminants of concern (COC), a number of documents were reviewed. Table 1 lists the name, format, source, and date for each document reviewed and used for this TM.

Table 1 Documents reviewed to Identify Major Contaminants of Concern			
Document Name	Format	Source	Date
Fresno Metropolitan, Water Resources Management Plan	Phase 1 Report	CH2M Hill	January 1992
City of Fresno Plume Locations	PDF Map	City of Fresno	early 1990's
Fresno Source Water Screened	Excel Spreadsheet	City of Fresno	May 2005
WQ Reports	Excel spreadsheet	City of Fresno	April 2006
Water Quality Annual Report 2001	Report	City of Fresno	2001
Water Quality Annual Report 2002	Report	City of Fresno	2002
Water Quality Annual Report 2003	Report	City of Fresno	2003
Water Quality Annual Report 2004	Report	City of Fresno	2004

2.1 Known Plumes in the Area

There are a total of ten plumes located in the City, and Figure 1 shows eight of them without two new plumes. The size of these plumes range from 15 to 1,200 acres. The contaminants in the plumes include: trichloroethylene (TCE), tetrachloroethylene (PCE), total dissolved solids (TDS), chloride, salinity, VOCs, pesticides, iron, manganese, chromium, and nitrate. Table 2 shows the name, contaminants, size, and general location of each plume. The major COCs in these plumes are organics, pesticides, and inorganics as outlined in Table 2.

Table 2 Known Plumes in the City of Fresno				
Plume Name	Contaminant	Estimated Size (acre)	Cross Streets	
			West- East	North- South
TCE Plume (Pinedale, Vandoe North)	TCE, chromium, 1,1, DCE, 1,1, DCA, PCE	1,020	West - Palm	Alluvial - Barstow
Salt Plume	TDS, chloride, salinity	1,200	Blythe - Hughes	Dakota - Olive
THAN Plume	VOCs and pesticides	500	Fowler - Locan	McKinley - Belmont
FMC Plume	VOCs, pesticides, and chromium	50	East - Orange	Church - Jensen
Purity Oil Plume	VOCs, Fe, Mn	105	Cedar - Chestnut	Annadale - Muscat
VOC Plume (Old Hammer Filed Plume)	TCE, PCE	510	Peach - Clovis	Clinton - Olive
Fresno Landfill	TDS, chloride, nitrate	185	Hughes - West	Jensen - North
Weir Floway / Vandoe Plume	Pesticides	15	East - Orange	Church - Jensen
Former Dow Plume	TCE	NA	NA	PS201-203
Unibar USA Plume	TCE	NA	NA	NA

Data Source: City of Fresno Plume Location Map

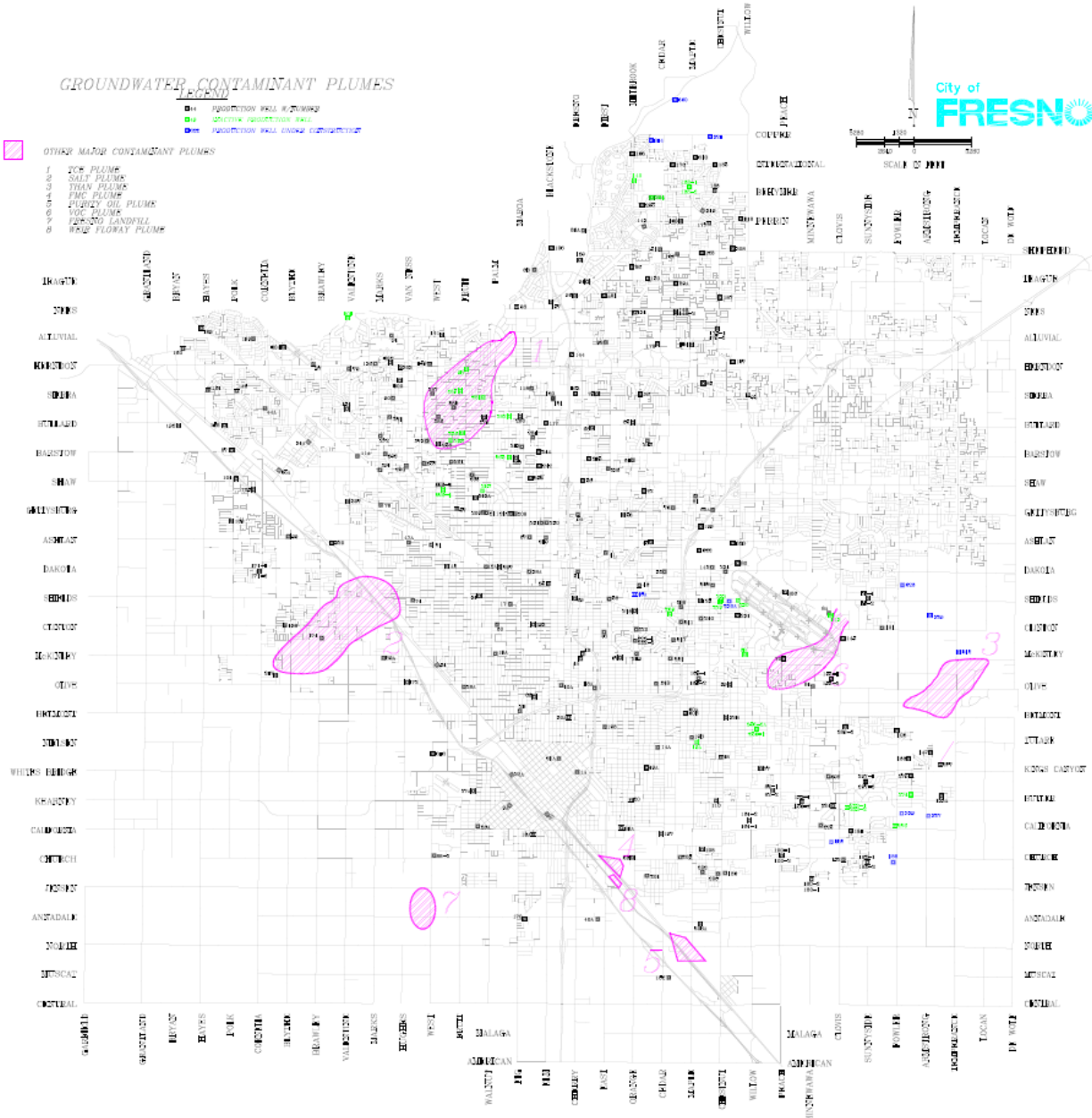


Figure 1. Known Plumes in the City of Fresno

2.2 Summary of Contaminants of Concern

2.2.1 Active Wells

Based on the City's most recent Annual Water Quality Report and the water quality database, typical ranges and average concentrations of the major COCs are summarized as shown in Table 3. The values taken from the 2004 Annual report is a summary of limited number of active wells requiring sampling that year, whereas the values listed based on the City's water quality database covers more comprehensive sampling data.

Table 3 Contaminants of Concern and Range				
Contaminant of Concern	Range	Average MCL/NL¹		Reference
1,1 DCE (ug/L)	ND-16	0.24	6	2004 Annual WQ Report ²
1,2 DCP (ug/L)	NA	NA	5	2004 Annual WQ Report
1,2,3-TCP (ug/L)	0.005-0.67	0.24	0.005	Fresno WQ database ³
cis 1,2-DCE (ug/L)	ND-5	0.11	6	2004 Annual WQ Report
DBCP (ng/L)	ND-380	30	200	2004 Annual WQ Report
EDB (ng/L)	ND-40	0.1	50	2004 Annual WQ Report
PCE (ug/L)	ND-7	0.18	5	2004 Annual WQ Report
TCE (ug/L)	ND-4	0.11	5	2004 Annual WQ Report
Arsenic (ug/L)	10-23	1.5	10 ⁴	Fresno WQ database
Chromium (ug/L)	ND-15	0.5	50	2004 Annual WQ Report
Nitrate (mg/L)	41-98	48	45	Fresno WQ database
Hydrogen Sulfide	NA	NA	NA	NA
Iron (ug/L)	310-5,300	950	300	Fresno WQ database
Manganese (ug/L)	60-1,100	120	50	Fresno WQ database ²
Radon (pCi/L)	1-2,708	611	NA	2004 Annual WQ Report ¹

Notes:

1. MCL: Maximum Contaminant Level, NL: Notification Level
2. 2004 Annual report summarize a limited number of wells requiring sampling that year
3. Fresno WQ database includes all wells
4. New federal arsenic regulation of 10 ug/L was put into effect in January 2006, but the Department of Health Services (DHS) has not yet set the limit

2.2.2 Inactive Wells

Currently, there are approximately 31 wells off line due to various contamination throughout the City. The main contaminants that resulted in shutdown include nitrate (14 wells, 9,270 gpm), TCE/PCE (8 wells, 8,660), 1,2-Dibromo-3-Chloropropane (DBCP) (3 wells, 3,570 gpm), arsenic (2 wells, 950 gpm), 1,2,3-Trichloropropane (1,2,3 TCP) (1 well, 950 gpm), and cis-1,2-dichloroethylene (cis 1,2-DCE) (1 well, 630 gpm) as summarized in Table 4. In addition, sand problems caused shut down of 2 wells with production capacity of 1,050 gpm.

Table 4 Inactive Wells, Contaminants, and Capacity Lost				
Well	Shut down	Contaminants	Capacity (gpm)	Notes
63	03/15/05	1,2,3 TCP	950	
Production Lost due to 1,2,3-TCP			950	
215	04/08/02	cis-1,2-DCE	630	Status unknown
Production Lost due to cis-1,2-DCE			630	
36	10/28/04	DBCP	1,800	GAC is planned by FMC/ERM Hovering around MCL (may be exceeding) shut down for > 10 years
102	na	DBCP	1,470	
168-2	na	DBCP	300	
Production Lost due to DBCP			3,570	
2B	09/06/05	PCE	2,500	Boyle designing a GAC system
93	na	TCE	1,800	
255	na	TCE	836	
256	na	TCE	830	
265	10/29/03	TCE	588	BSK identifying a treatment plant site
281	na	TCE	700	The well may have been sold
282	na	TCE	595	Capacity from 1986 PGE pump test
285	na	TCE	808	Capacity from 1986 PGE pump test
Production Lost due to TCE/PCE			8,657	
135A-2	na	Arsenic	500	Development project - treatment planned
168-1	na	Arsenic	450	Filtronics: not working. down for >10 years
Production Lost due to Arsenic			950	
113	na	Nitrate	660	DBCP treatment, planned for destruction replacement well acquired from the County
140	10/29/03	Nitrate	800	
155-2	na	Nitrate	600	
185	na	Nitrate	2,000	
201	08/12/04	Nitrate	480	
223-1	na	Nitrate	280	
226-2	01/05/06	Nitrate	540	

Table 4 Inactive Wells, Contaminants, and Capacity Lost				
226-1	na	Nitrate	531	"
249	na	Nitrate	850	
253-1	na	Nitrate	540	
253-2A	na	Nitrate	800	
274	10/29/03	Nitrate	400	Blend plan, no sewer
276	11/10/00	Nitrate	450	Developing a line to blend, no sewer
294	na	Nitrate	340	
Production Lost due to Nitrate			9,271	
110	na	Sand	250	
297-1	na	Sand	800	
Production Lost due to Sand			1,050	
TOTAL PRODUCTION LOST			25,078	

2.2.3 Organic Contaminants in the City of Fresno

1,1 DCE, 1,2 DCP, cis 1,2-DCE

There have been detections of 1,1-Dichloroethylene (1,1 DCE), 1,2-Dichloropropane (1,2 DCP), and cis 1,2-DCE in the past. 1,1-DCE is used in the production of polyvinylidene chloride copolymers used in flexible packaging materials (e.g., food wrapper); as flame retardant coatings for fiber, carpet backing, and piping; as coating for steel pipes; and in adhesive applications. 1,2-DCP, on the other hand, is created as one of by-products during the manufacture of pesticides ethylene dibromide (EDB) and DBCP. cis 1,2-DCE may be released to the environment in air emissions and wastewater during its production and use. In addition, under anaerobic conditions that may exist in landfills, aquifers, or sediment, it is likely to find cis 1,2-DCE that are formed as breakdown products of TCE and PCE. Currently, cis-1,2-DCE is the only contaminant that resulted in well shut down (Well 215) among these contaminants.

1,2,3-TCP

1,2,3-TCP is also created as one of the by-products produced during the manufacture of pesticides EDB and DBCP. There is no enforceable standard for 1,2,3 TCP, but DHS has set a notification level (NL) of 0.005 ug/L. Source water data show that concentrations meet or exceed this NL at 213 wells. The average concentration of these 213 wells is about 0.25 ug/L, well above the NL. There is currently one well shut down due to 1,2,3 TCP as noted in Table 4. The maximum concentration reading from Well 63 was 0.67 ug/L taken on September 27, 2000 based on the City's water quality database.

DBCP

DBCP is one of the active ingredients in pesticide (soil fumigant) preparations. According to the City Staff (Buche, 2006), there are 35 granular activated carbon (GAC) facilities throughout the City to remove DBCP. The City is currently working with FMC and its consultant (ERM) on a GAC facility for treatment of Well 36. In addition, water from Well 102 has concentrations of DBCP near the MCL, and Well 168-2 has been shut down for more than 10 years due to high DBCP concentration.

EDB

EDB is also one of the active ingredients in pesticide (soil fumigant) preparations. Although the exact source is not known according to Water Resources Management Plan Existing Water Supply System Assessment Report (WRMP) (CH2M Hill, 1992), pesticide applications to agricultural lands may have contributed to the detection of EDB throughout the City. According to the 2002 Annual Report, PS 275 has a treatment using GAC for the removal of DBCP and EDB. There have been detections of EDB slightly exceeding the MCL, but the more recent 2004 Annual report shows the concentrations below the MCL.

TCE/PCE

TCE and PCE are common industrial solvents and have been historically one of the major contaminants in the City's groundwater. Well 2B currently has PCE concentrations greater than the MCL. The City is working with Boyle to design and construct a treatment system for this well. Water from Wells 93, 255, 256, 265, 279, 281, 282, and 285 contains TCE concentrations greater than the MCL and thus currently shut down. Well 265 is located in the Vandoe Plume, and BSK Associates is working on identifying a plant site to treat water from this well.

2.2.4 Inorganic and Radionuclide Contaminants

Arsenic

Arsenic occurs naturally in deep groundwater and has a federal MCL of 10 ug/L as of January 23, 2006. The State of California, however, has not yet adopted a drinking water standard for arsenic. The DHS standard will be at least as stringent as the federal MCL. Arsenic has been detected in Well 310 at concentrations ranging from 10 to 23 ug/L. The most recent concentration reading from this well was 10 ug/L on January 3, 2003. A treatment system is planned for Well 135 as part of a new development.

Chromium

Chromium has a number of industrial use and manufacturing of alloys. Chromium detection is relatively low based on the monitoring data (up to 15 ug/L). However, both Vandoe North Plume (a.k.a., Pinedale or TCE Plume) and FMC Plume contain chromium that may impact City's wells in the future.

Hydrogen sulfide

Hydrogen sulfide is formed by sulfur bacteria that may occur naturally in water. These bacteria use the sulfur in decaying plants, rocks, or soil as their food or energy source and as a by-product produce hydrogen sulfide. There is limited occurrence data on hydrogen sulfide.

Iron

Iron occurs naturally and has a secondary MCL (SMCL) of 300 ug/L. It has been detected at concentrations greater than the SMCL in thirteen wells. The highest concentration recorded was 5,300 ug/L, which occurred in Well 297-3 on May 30, 2002. The average concentration from all wells is about 111 ug/L.

Manganese

Manganese also occurs naturally and has a SMCL of 50 ug/L. DHS recently established a NL of 500 ug/L based on the health effects. Concentrations above the SMCL were detected in nine wells. The maximum concentration reading was 1,100ug/L, which occurred in Well 083A on May 24, 2000. However, the average concentration from all wells is relatively low at about 17 ug/L.

Nitrate

Nitrate is the most common contaminant in groundwater and originates primarily from fertilizers, septic systems, and manure storage or spreading operations. Nitrate concentrations have exceeded 40 mg/L in 27 wells throughout the City. The maximum concentration detected was 95 mg/L on June 12, 2003 from Well 155-2. The average concentration for all 27 wells is 50 mg/L. Water from wells 140, 201, 226-2, 249, 253, 274, and 276 have concentrations greater than the MCL for Nitrate. Wells 226-1 and 226-2 have been abandoned due to nitrate contamination. The City is planning to acquire one or two replacement wells from the County's shallow wells. There is a blending plan set up for water from Well 274 and a similar plan for Well 276 is planned in the future. For a nitrate blending plan, DHS requires compliance of 80% of the MCL or 36 mg/L as the standard.

Radon

Radon occurs naturally in soil and thus in groundwater. The highest level of radon detected according to 2004 Annual report is about 2,700 pCi/L. The EPA proposed the Radon Rule in November 1999. The proposed rule would apply to all community water systems that use groundwater or mixed ground and surface water. The rule proposes an MCLG, an MCL, an alternative maximum contaminant level (AMCL), and requirements for multimedia mitigation (MMM) program plans to address radon in indoor air. The proposed MCLG for radon in drinking water is zero. The proposed regulation provides two options for the MCL. The proposed MCL is 300 pCi/L and the proposed AMCL is 4,000 pCi/L. The drinking water standard that would apply for a system depends on whether or not the state or community water system develops a MMM

program. If an MMM program plan is developed by either the state or the community water system, the maximum level of radon allowed would be 4,000 pCi/L. If an MMM program plan is not developed, then the MCL of 300 pCi/L would apply.

3.0 TREATMENT ALTERNATIVES FOR THE CONTAMINANTS OF CONCERN

A summary of treatment alternatives for each contaminant is shown in Table 5. The alternatives listed are the ones that are typically evaluated options and may not be suitable for certain applications depending on other conditions. More detailed discussion for specific type of contaminants is followed.

Table 5 Summary of Contaminants and Treatment Alternatives								
Contaminants	AS	GAC	AOP	IX	RO	CF/OF	Media	Bio
1,1 DCE	•	•	•					
1,2 DCP	•	•	•					
1,2,3-TCP	•	•	•					
cis 1,2-DCE	•	•	•					
DBCP		•	•					
EDB		•	•					
PCE	•	•	•					
TCE	•	•	•					
Arsenic				•	•	•	•	
Chromium				•	•	•	•	
Nitrate				•	•			•
Hydrogen Sulfide	•	•						
Iron					•	•		
Manganese					•	•		
Radon	•	•						

Notes: AS: Air Stripping, GAC: Granular Activated Carbon, AOP: Advanced Oxidation, IX: Ion Exchange, RO: Reverse Osmosis, CF: Coagulation Filtration, OF: Oxidation Filtration, Media: Single-use media, Bio: Biological Reduction (anaerobic)

3.1 Organic Contaminants

Organic contaminants can either be treated by air stripping or GAC. These are the most common treatment systems, and the City also has a number of GAC and air stripping systems to treat organic contaminants. Volatile organics such as PCE/TCE can be easily removed by air stripping as well as GAC. Air stripping process often requires treatment of off-gas using dry phase GAC, so the liquid phase GAC is sometimes preferred to minimize the process train. Pesticides such as, DBCP and EDB, cannot be effectively stripped, so only GAC can be used for those applications. Another emerging treatment option is advanced oxidation process (AOP) using either UV light or ozone with hydrogen peroxide. These are used where the contaminant cannot either be adsorbed to GAC or removed by air stripper.

3.1.1 Air Stripping-Packed Tower Aeration (PTA)

Air stripping or packed tower aeration (PTA) is one of the most widespread treatment technologies for VOC removal and is listed as a best available technology (BAT) by EPA. Air stripping is a technology in which VOCs are separated from water by greatly increasing the surface area of the contaminated water exposed to air. Types of aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration. The Henry's constant of a given contaminant determines the required air-to-water ratio for a given percent removal. The higher the Henry's constant, the lower the required ratio. Although increasing the temperature of the contaminated water increases the Henry's constant, such approach is impractical for most drinking water applications.

Off-gas treatment is typically required as part of the air-stripping process when the stripped off-gas from the process contains unacceptable levels of contaminants classified as air toxics. Gas-phase GAC adsorption or other carbonaceous adsorbent resins can be used to treat off-gas to comply with potential San Joaquin Valley Unified Air Pollution Control District (SJVUAPCD) regulations. When the gas phase GAC is saturated, the bed is replaced with new GAC.

3.1.2 Liquid Phase GAC

Liquid Phase GAC is another frequently used treatment for removal of organic compounds from water, and it is also listed as a BAT for a number of contaminants by EPA. GAC systems are efficient and relatively simple to operate if properly designed. GAC removes contaminants from water by the adsorption process in three consecutive steps. First, the contaminant molecule is transferred from the liquid phase to the exterior surface of the carbon. Second, the contaminant molecule is transport from the exterior of the carbon through the pores to an adsorption site. Finally, at some point in this transport process, the molecule is actually adsorbed and held to the pore surface.

The effectiveness of the GAC for removal of a particular contaminant is measured by its adsorptive capacity or isotherm. The higher the adsorptive capacity of a GAC, the less regeneration or change out it requires (i.e., longer period for the service cycle). The adsorptive capacity can be affected by the contaminant concentration, the empty bed contact time (EBCT)

and the concentration of any interfering compounds such as natural organic matter (NOM). The adsorption isotherms are compound and water specific, so modeling or testing is required to assess the effectiveness of GAC for each contaminant. In the presence of multiple or competing compounds, the overall capacity is decreased.

3.1.3 Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) generate hydroxyl radicals that break down organic compounds. Among several options, ozone with hydrogen peroxide or UV with hydrogen peroxide are the most commonly used alternatives.

An AOP promotes formation of free hydroxyl radicals that accelerate oxidation of organics and other compounds. The hydroxyl radical is a strong oxidant, which can breakdown contaminants from water by chemically transforming them through oxidation. If bromide is present in sufficient concentrations, bromate may be formed as a by-product during ozone process, and thus in such case, use of ozone should be avoided. UV process also provides photolysis that can also attack certain organics such as NDMA in addition to generating hydroxyl radicals. Thus UV may provide a better approach over ozone depending on the target compounds.

Effective removal of organics can be achieved with hydrogen peroxide and UV under optimal consideration. The applied UV dose required for oxidation will vary depending on influent water quality (UV absorbance of background water and presence of radical scavengers). Advantages of UV over ozone include low profile units, small space requirements, capability of intermittent operation, and operator friendliness. However, removal of VOCs with UV is characterized with high costs due to high energy requirements. Other possible concerns and limitations for UV include: breaking of lamps and mercury leakage, interference due to turbidity, iron, and nitrate, fouling of lamps due to presence of iron and other precipitants. TOC and alkalinity directly interferes with UV light or reaction with hydroxyl radicals as free radical scavengers.

3.1.4 Summary of Organics Treatment

Table 6 summarizes the advantages and disadvantages of air stripping, GAC, and AOPs for the removal of organics. Because AOP is more energy intensive and labor intensive than the other two processes, air stripping and GAC are more common treatment options.

Table 6 Advantages and Disadvantages of Organics and Pesticides Treatment		
Process	Advantages	Disadvantages
Air Stripping	<ul style="list-style-type: none"> • Established and proven technology 	<ul style="list-style-type: none"> • Phase change, not destruction • Often requires off-gas treatment
GAC	<ul style="list-style-type: none"> • Removes multi contaminants • Established and proven technology • Simple operation • Familiarity (currently used by Fresno) 	<ul style="list-style-type: none"> • Phase change, not destruction • Regeneration or replacement of GAC required
AOPs	<ul style="list-style-type: none"> • Destruction of organics • Compact footprint • Capable of intermittent operation 	<ul style="list-style-type: none"> • High-energy cost • Breaking of UV lamps and potential mercury leakage • Interferences cause by various water quality parameters (TOC, Alk, NO₃) • Formation of by-products (e.g., bromate for ozone)

3.2 Inorganic and Radionuclide Contaminants

There are a number of technologies available to treat inorganic and radionuclide contaminants. These COCs in the City's groundwater can be grouped into three categories based on their similar chemical characteristics. First group is inorganic anions, such as nitrate, arsenic, and chromium (chromium(VI)). The second category is iron and manganese, and the third one is radon and hydrogen sulfide. Since they share similar chemical properties, the treatment alternatives and thus discussion will be similar as shown below. Some of these processes generate either liquid or solid waste (or both), and the selection of a preferred treatment option may depend on the residual handling. Detailed discussions are given in the following sections.

3.2.1 Air Stripping-Packed Tower Aeration (PTA)

Similar to organics removal, air stripping or PTA is used to remove radon and hydrogen sulfide gas from water. As discussed previously for organics, air stripping packed towers, diffused aeration, tray aeration, and spray aeration can be used to remove radon and hydrogen sulfide from water. For hydrogen sulfide, the pH needs to be below 7 to convert hydrogen sulfide in the gaseous form.

3.2.2 Liquid Phase GAC

Again, similar to organics removal, GAC can be used to remove both radon and hydrogen sulfide. Once the GAC capacity is used up, the spent GAC is replaced with new GAC as

discussed for organics application. GAC also has small capacity for nitrate, and depending on the operational condition, nitrate may slough from the carbon bed. The same phenomenon can also occur when GAC is used for organics removal. In fact, such sloughing has been observed for the City's GAC plants.

3.2.3 Ion Exchange (Anion Exchange)

The regenerable ion exchange process involves exchange of soluble ionic species with chloride ions on the surface of resins. Ion exchange is currently the most demonstrated and implemented technology for treatment of nitrate in drinking water, and it has been used for arsenic and chromium. Most resins are NSF certified, and a number of commercial systems accepted by DHS have been implemented in several locations throughout California. The common resins used are strong-base anion exchange resins in the chloride form, specifically either polyacrylic or polystyrene resins. As mentioned, the chloride ion (Cl⁻) on the surface of the resin is exchanged for other anions present in the water (thus called anion exchange). Thus the process is impacted by the background concentrations of other anions including sulfate, alkalinity, uranium, etc.

After a certain service cycle, resins are typically loaded with nitrate or other anions and regenerated on-site with a salt solution (NaCl). In order for the chloride ion to substitute the nitrate ion loaded on the resin, a high concentration typically in the range of a several percent of chloride is required in the regenerant solution. Therefore, the spent brine solution can range from 6 percent salt (about 60,000 mg/L of NaCl) to as high as 20 percent salt (about 200,000 mg/L as NaCl) under special cases. Once the resin is reloaded with chloride, it is used again and the ion-exchange cycle is repeated. The spent brine solution produced during regeneration need to be disposed of appropriately or reused for further regeneration following treatment. Depending on the local discharge regulation, discharge of high TDS spent regenerant solution is a challenge. For a small treatment system, spent brine can also be hauled off-site.

3.2.4 Reverse Osmosis

Reverse osmosis (RO) can remove the soluble forms of nitrate, arsenic, chromium, as well as iron and manganese. The true benefit of the high-pressure membrane treatment process is its ability to remove co-occurring dissolved contaminants at the same time. High capital and operating costs and concentrate stream disposal issues typically make it economically unfeasible to apply RO for a single contaminant only. In addition, iron and manganese foul RO membranes and typically, these constituents are reduced to low concentrations prior to RO treatment to prevent such fouling.

The presence of elevated levels of sulfate, iron, barium, magnesium, calcium, silica, and strontium may also affect the operation of RO. Scaling and fouling of membranes will decrease membrane performance. The presence of elevated levels of silica can significantly limit the recovery of high-pressure membranes. The EDR process uses an electric field to separate ions rather than using pressure, so EDR process may be used if silica is a concern. Although the concentration of TDS in the RO reject stream is much less than the brine from ion exchange

process, significantly more volume need to be discharged compared with that for the spent brine.

3.2.5 Coagulation or Oxidation Filtration

Coagulation and oxidation filtration are different in that different types of chemicals are added. However, the common goal is to produce insoluble species that can be removed by the media filter downstream of either a coagulation or an oxidation step.

Arsenic and chromium can be removed by addition of ferric coagulant and forming insoluble flocs prior to a filtration step. After the filters are loaded with insoluble species, the filters need to be backwashed (typically once or twice daily), and the backwash water is discharged to sewer. Most of the backwash water may be recovered after the spent wash water is settled. Depending on the operation, the sludge from the backwash water may contain elevated levels of arsenic or chromium, which then requires special handling. If the contaminant level is high in the sludge, various discharge and disposal regulations apply. California regulations include total threshold limit concentration (TTLIC), soluble threshold limit concentration (STLC), etc. The backwash frequency and efficiency of the process depends on the coagulant dose, water quality (pH, speciation of contaminants), and finished water goal.

Oxidation followed by filtration is the most commonly used process for iron and manganese removal. Under reducing conditions, iron and manganese are stable as soluble forms (ferrous (Fe^{2+}) and manganous (Mn^{2+})). When they are oxidized by chlorine or permanganate, they become insoluble ferric (Fe^{3+}) and manganic hydroxide (Mn^{3+}) species, and these can be physically removed with a filtration process. Chlorine and potassium permanganate are common oxidants applied in commercial packaged systems. It has been reported that soluble (Mn^{2+}) was rapidly oxidized by potassium permanganate, chlorine dioxide, and ozone in low DOC waters. When chlorine is used as an oxidant, however, it can react with naturally organic matter (NOM) in the raw water to form trihalomethanes (THMs) and haloacetic acids (HAAs), which are regulated contaminants under the Stage 2 Disinfectants / Disinfection By-products (DBPs) Rule (D/DBPR). Therefore, if halogenated DBPs are an issue, other oxidants may offer benefits compared to chlorine, such as potassium permanganate, and chlorine dioxide. Testing may be required to confirm DBP formation potential with various oxidants.

3.2.6 Single-use media

Single-use media treatment technology relies on phase transfer methods to remove arsenic and chromium from water. Typically, there is limited generation of liquid waste during an initial installation of the media, and no backwash is required during the operation. Once the media is saturated with contaminants, new media is installed and the spent media is hauled off for landfill. There are more than 30 media available for arsenic removal, and some of them can also remove chromium. These include granular ferric hydroxide (GFH from US Filter), granular ferric oxide (GFO from Severn Trent, Engelhard, etc.), iron-incorporated resin (Arsenex NP from Purolite or ASM from Resin Tech), and TiO_2 media (Adsorbisia from Dow) (Min et al., 2005).

These single-use media for arsenic are generally replaced every few months to a year depending on the water quality and operations.

The spent media are disposed of in various classes of landfills depending on leaching test (TTLC and STLC) results. Initial backwash water from this process contains low levels of contaminants that can be discharged to sewer. Certain types of media, such as Arsenex NP may be regenerated off-site similar to GAC reactivation. During the chemical regeneration, deterioration of media occurs and the arsenic or chromium sorption capacity typically diminishes in the subsequent cycle.

Similar to GAC and regenerable ion exchange resin, other anions are still a competing factor and affect the run length of the single-use media until arsenic or chromium breakthrough. Single-use type media may not be suitable for such application where nitrate or other competing ion levels are high because the breakthrough of competing anions may have “peaking” effects where competing anion levels in the effluent becomes high for a short period of time. Other parameters affecting the process include contaminant concentration, uranium, pH, silica, etc, as prolonged run time may contribute to generation of spent media that are either hazardous (due to arsenic and chromium) or low level radioactive (due to uranium).

3.2.7 Biological Reduction (anaerobic)

Anaerobic biological process uses indigenous microorganisms that are able to metabolize nitrate and other compounds such as perchlorate and some organics. Depending on the levels of nitrate, anaerobic biological reduction offers lower operating cost than comparable physical / chemical processes. It may also produce less waste product that allows easier dewatering and disposal of residual unlike ion exchange process, which generates high TDS spent brine. However, anaerobic biological treatment requires specific raw water qualities and conditions, and not all groundwaters or surface waters can be treated economically using this technology. Success of this treatment process depends on several factors such as nutrient availability, oxidation/reduction conditions, temperature, and filter operation strategy. Anaerobic biological process may require a special permitting for implementation at full scale, but DHS has conditionally accepted this process for perchlorate and nitrate in drinking water.

An electron donor, such as acetic acid, is dosed to the feed line just before raw water enters the biological reactor. Because a portion of the biological reactor must be anaerobic to allow for nitrate reduction, the influent DO concentrations determine the acetic acid dose and the empty-bed contact time (EBCT). Effluent from the anaerobic biological reactor is aerated and pumped to an aerobic biological filter as a post treatment. This process sequence is designed to achieve four goals: 1) oxygenate the water, 2) remove (microbially oxidize) residual biodegradable organic carbon, 3) remove (microbially oxidize or strip by aeration) any sulfide formed in the anaerobic biological reactor, and 4) capture microorganisms that slough from the anaerobic bioreactor. Excess biosolids waste streams would be produced by both the anaerobic and aerobic biological reactors, which must be discharged. The anaerobic biological process train would minimally impact flow, pH, chloride, and TDS.

3.2.8 Summary of Inorganic and Radionuclide Treatment

A summary of the advantages and disadvantages for each of the alternative for treatment of inorganic and radionuclide contaminants is presented in Table 7.

Table 7 Advantages and Disadvantages of Inorganics and Radionuclides Treatment		
Process	Advantages	Disadvantages
Air Stripping	<ul style="list-style-type: none"> • Established and proven technology 	<ul style="list-style-type: none"> • Phase change, not destruction • Often requires off-gas treatment
GAC	<ul style="list-style-type: none"> • Removes multi contaminants • Established and proven technology • Simple operation • Familiarity (currently used by Fresno) 	<ul style="list-style-type: none"> • Phase change, not destruction • Regeneration or replacement of GAC required
Ion Exchange (Regenerable)	<ul style="list-style-type: none"> • Proven technology • Can remove various anions • Resins are re-used after regeneration • Potentially high rate of treatment • Familiarity (currently used by Fresno) 	<ul style="list-style-type: none"> • Some resins may produce precursors to form NDMA in finished water • Efficiency depends on raw water quality • Generates brine with high TDS
Reverse Osmosis (RO)	<ul style="list-style-type: none"> • Can achieve rejection of multiple contaminants • Proven technology for drinking water 	<ul style="list-style-type: none"> • High capital and O&M costs • Generates a large quantity of concentrate waste • TDS and silica reduce efficiency of removal.
Coagulation / Oxidation Filtration	<ul style="list-style-type: none"> • Proven process • Effective for number of contaminants (Fe/Mn/As/Cr) • Cost-effective 	<ul style="list-style-type: none"> • Addition of chemicals (either oxidant for Fe/Mn or coagulant for As/Cr) • Generation of backwash water and sludge
Single-Use Media	<ul style="list-style-type: none"> • Well-demonstrated technology • Does not produce liquid brine • Can be easily implemented 	<ul style="list-style-type: none"> • Media must be replaced on a regular basis (high O&M cost) • Presence of uranium may limit run length to avoid generation of low level radioactive waste

Table 7 Advantages and Disadvantages of Inorganics and Radionuclides Treatment		
Process	Advantages	Disadvantages
Biological	<ul style="list-style-type: none"> • Complete destruction of nitrate • Can also remove some organics • Indigenous microorganisms can be used • Low O&M cost 	<ul style="list-style-type: none"> • High capital cost • Public acceptance • No current full-scale applications for direct drinking water treatment (in the U.S.) • Requires a post-treatment train for potable water applications • Requires NSF certified electron donor

4.0 TREATMENT COST DATA

4.1 Treatment Cost Data Assumptions

The generic cost information provided here is not site specific and should be used for informational purpose only. In order to develop a planning level estimate, additional data such as water quality specific to each well, site information, preferred treatment alternative, operational limitation, etc. will be needed. In addition, there are a number of uncertainties that will influence the actual cost of a treatment system as discussed in Section 4.3. These may include factors such as, interfering compounds, cost of labor, materials, equipment, services provided by others, contractor's methods of determining prices, competitive bidding or market conditions, practices or bidding strategies. As such, the cost information provided here does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs information presented herein. In order to compare options for the planning purpose, a more accurate site specific cost estimate must be developed.

The individual cost estimate curves presented below are from the United States Bureau of Reclamation (USBR) Fact Sheet cost curves derived from USBR's WaTER program, which is available at <http://www.usbr.gov/pmts/water/primer.html#factsheets>. The following is a disclaimer provided by the WaTER program on the cost estimate. "Construction and annual O&M costs were derived from the WaTER Program; Estimating Water Treatment Costs, volumes 1 and 2 of EPA-600/2-79-162a, August 1979; or from manufacturer's product data information. Cost estimates are as of March 2001, are considered accurate within +30% to -15%, and are primarily intended as a guide for comparing alternative water treatment options. More accurate cost estimates can be determined given site specific data and verification of assumptions." Additional assumption from USBR is provided in Appendix A of this memo.

The cost curves are presented here without any adjustment except to convert the flowrates from gallons per day (GPD) to gallons per minute (GPM). Unlike other cost estimation programs that

require the user to have information about the size of equipment and chemical dosage rates, the only inputs required for the WaTER program are the production capacity and raw water quality composition. The program employs cost indices as established by the Engineering News Record, Bureau of Labor Statistics, and the Producer Price Index, and derives cost data from Estimating Water Treatment Costs; volumes 1 and 2; EPA-600/2-79-162a; August 1979. The Cost Assumptions Fact Sheet provided by USBR for these generic cost curves are included in Appendix A.

The cost range figure shown in Section 4.3 is based on the Cost Estimates for Treatment Technologies from http://www.ci.modesto.ca.us/omd/01_ccr/pdf/phg_cost_treat.pdf and a presentation by Boodoo (2004). The Cost Estimate for Treatment Technologies provides a table with 24 case studies with conditions and total annual cost range (annualized capital cost and O&M cost) for each case study. The actual table used in compiling the cost range data is included as Appendix B. This includes short summaries of conditions, capacity, etc. for each case study.

4.2 Generic Cost Estimate for Contaminants of Concern

4.2.1 Generic Cost Estimate for Organics and Pesticides

As mentioned previously, the actual O&M cost of a GAC system will depend on the type of contaminant and its adsorption isotherm for a specific GAC type. This is true for the packed tower air stripping as well. Some organics such as DBCP and EDB, however, only GAC can be used as these cannot be effectively removed with air stripping (see Table 5). Figures 2 shows the capital and O&M costs for a GAC adsorption system in 2001 dollars. As mentioned, these generic cost curves are based on the assumptions provided previously. Air stripping cost strongly depends on the site conditions, and thus generic cost is not available.

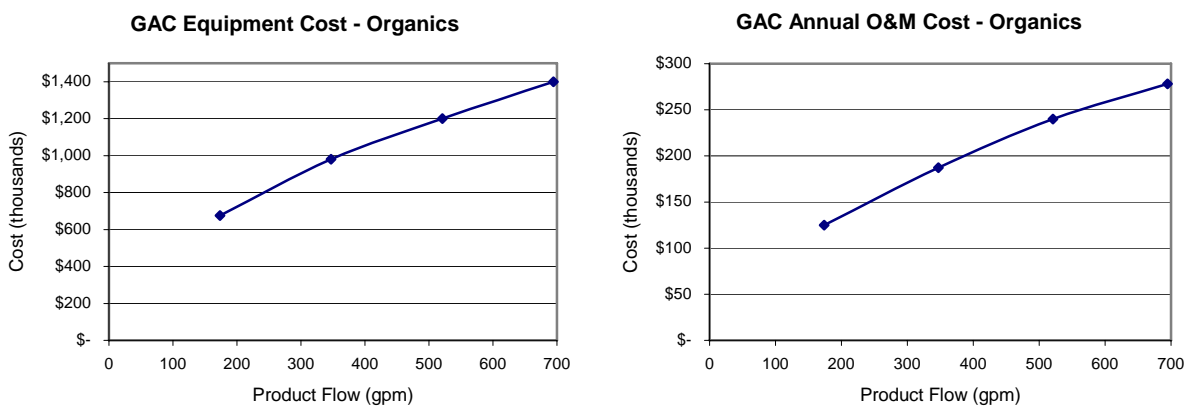


Figure 2. Capital and O&M costs for GAC to treat organics (USBR data in 2001 dollar)

4.2.2 Generic Cost Estimate for Radon

Similar to organics and pesticide, both radon and hydrogen sulfide may be removed with either GAC or air stripping. WaTER cost database does not provide cost data for hydrogen sulfide, so only GAC cost curves for Radon are included (Figure 3). Also, as mentioned previously, due to the site specific nature of the air stripping system, the generic costs curves are not available for Radon.

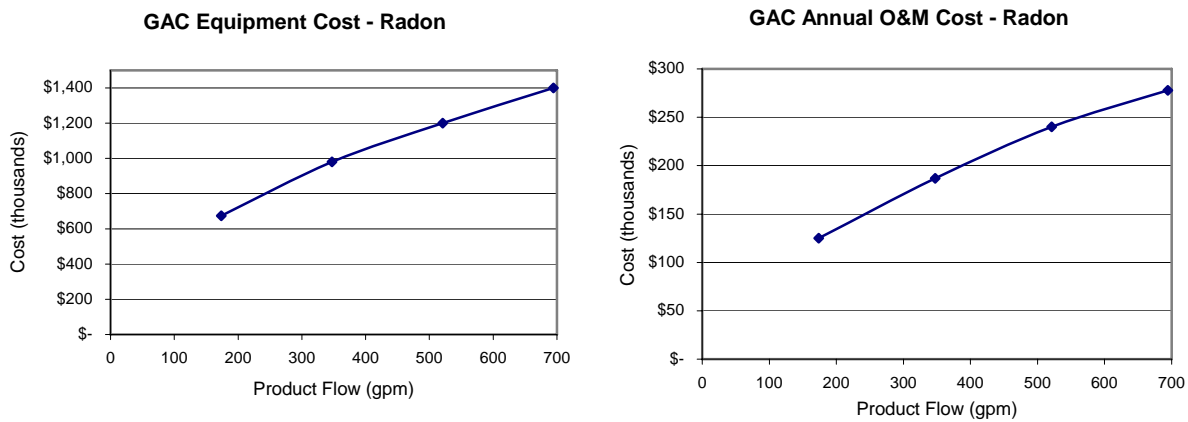


Figure 3. Capital and O&M costs for GAC to treat Radon (USBR data in 2001 dollar)

4.2.3 Generic Cost Estimate for Oxyanions (Arsenic, Chromium, and Nitrate)

Arsenic and chromium are similar in their chemical properties. The costs provided in Figures 4 and 5 are specific to coagulation/filtration for arsenic and ion exchange for chromium respectively. However, the cost curve for coagulation can also apply for chromium, and the cost curve for ion exchange can be used for arsenic as the cost range will be similar between the contaminants for each process.

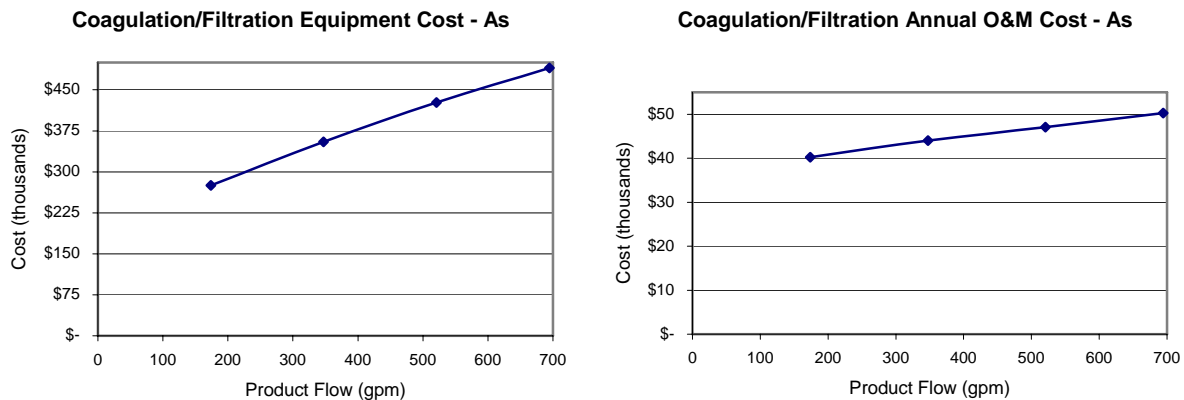


Figure 4. Capital and O&M costs for CF to treat arsenic (USBR data in 2001 dollar)

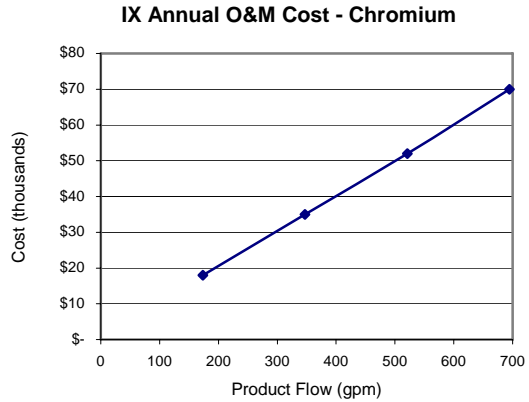
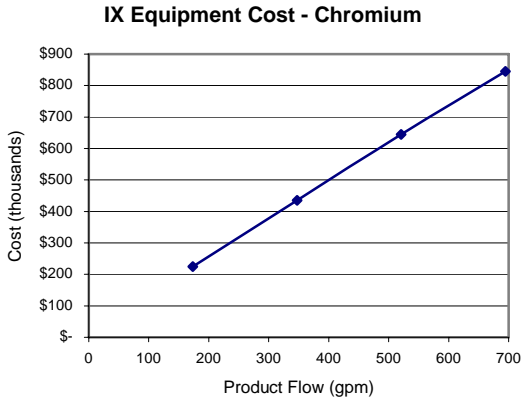


Figure 5. Capital and O&M costs for IX to treat chromium (USBR data in 2001 dollar)

Two treatment option costs are provided for nitrate below. Figure 6 shows the costs for ion exchange while Figure 7 shows the costs for RO option. These are costs associated for treatment only. If discharge of the brine will be a problem or if there are co-occurring contaminants, then RO option may be more acceptable alternative.

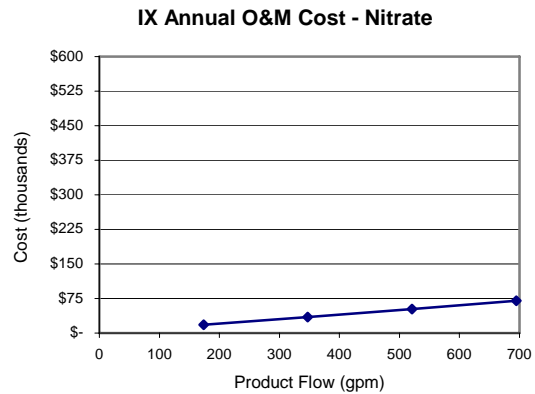
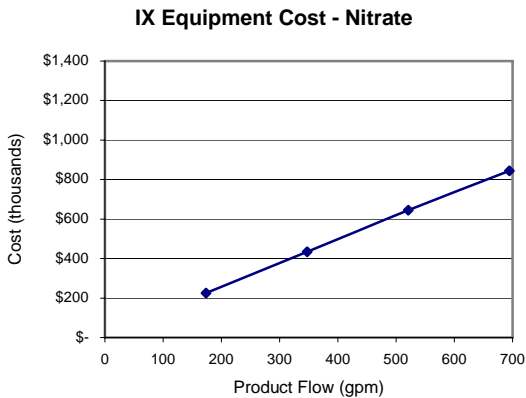


Figure 6 Capital and O&M costs for IX to treat nitrate (USBR data in 2001 dollar)

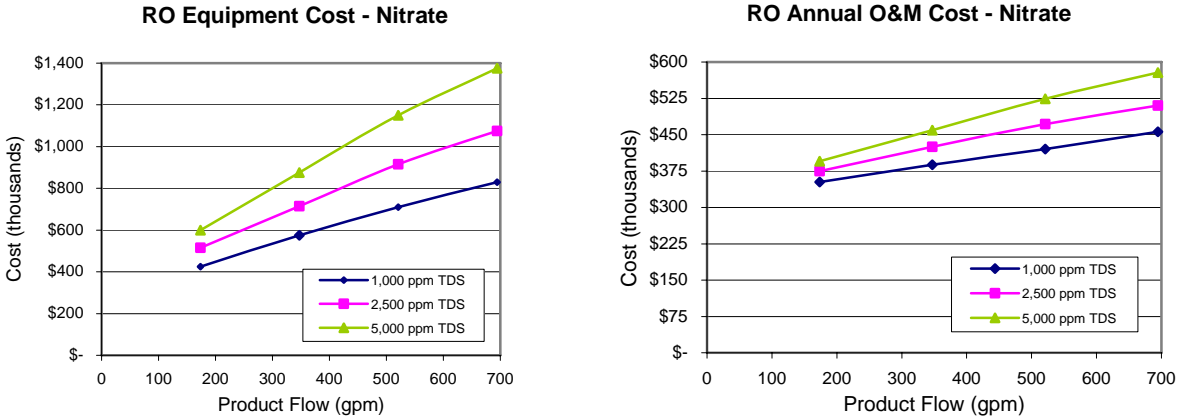


Figure 7 Capital and O&M costs for RO to treat nitrate (USBR data in 2001 dollar)

4.2.4 Generic Cost Estimate for Iron and Manganese

As previously mentioned, the most widely used option for iron and manganese is oxidation filtration. Figure 8 shows the oxidation option costs. The costs curves are similar to those for the coagulation filter option shown for arsenic. In fact, with minimum retrofit, oxidation filtration system can be modified to also remove arsenic or chromium by adding additional coagulant as required.

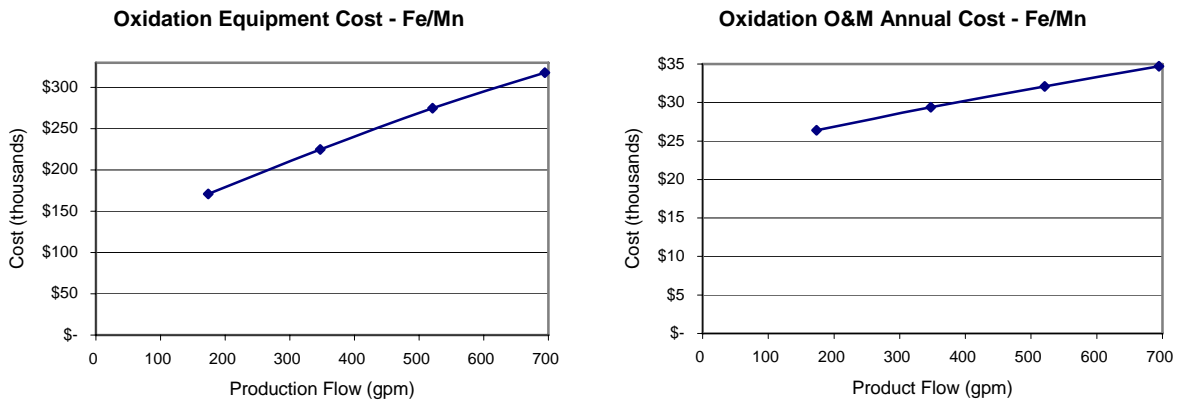


Figure 8 Capital and O&M costs for Oxidation Filtration to treat Fe/Mn (USBR data in 2001 dollar)

4.3 Cost Estimate Range by Process

As mentioned previously, the costs presented from WaTER estimates published by USBR are generic costs based on a number of assumptions. In addition to the contaminant concentrations,

the actual cost of treatment process will be affected by potential water quality interferences summarized in Table 8. Site specific conditions will also affect the cost, such as vessel, pump, tank size, etc. As such, based on the limited information available, the comparison of the range of total cost in \$/AF is presented in Figure 9 to illustrate the variability.

Table 8 Treatment Processes and Potential Interferences		
Process	Target Compounds	Potential Water Quality Interferences
Air Stripping	VOC, SVOC, radon, H ₂ S	NOM, iron, pH
Coagulation/oxidation Filtration	arsenic, chromium, iron, manganese	pH, hardness
Reverse Osmosis	nitrate, arsenic, chromium, iron, manganese	NOM, silica, barium, hardness, pH
Ion Exchange	nitrate, arsenic, chromium	sulfate, alkalinity, pH, hardness
Single-Use Media	arsenic, chromium	NOM, silica, hardness, pH, iron, manganese, vanadium
GAC	VOC, SVOC, pesticides, radon, H ₂ S	NOM, nitrate

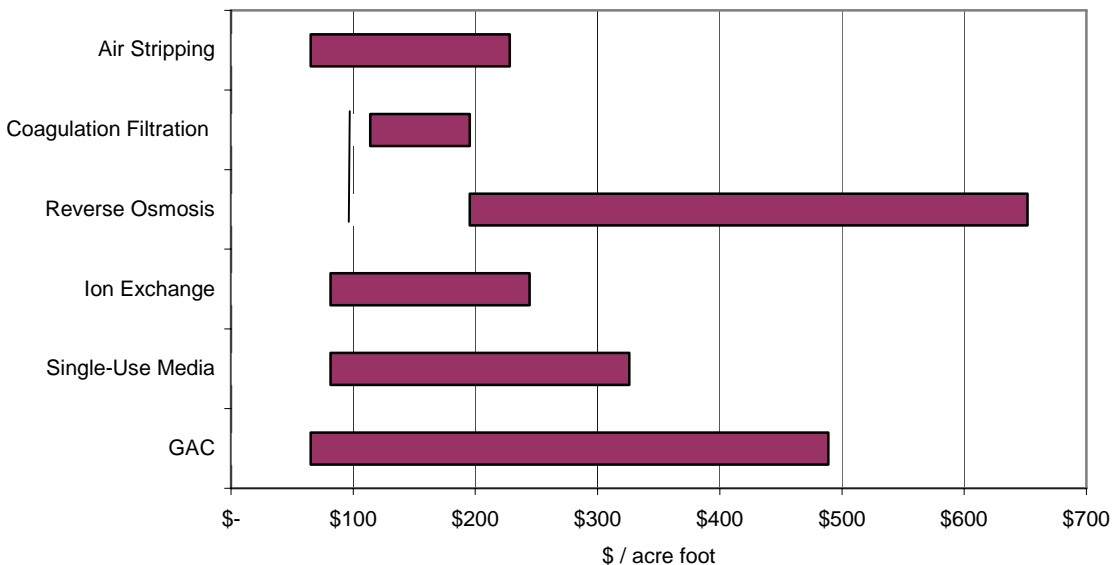


Figure 9 Comparison of the ranges of cost for the processes discussed (2001 dollar)

5.0 SUMMARY AND RECOMMENDATIONS

5.1 Summary

Based on the review of available documents provided by the City and other resources from similar projects, the following summary is provided.

- There are ten plumes in the City of Fresno that threaten the groundwater quality.
- The major contaminants include DBCP, TCE, and nitrate based on the number of impacted wells by these contaminants.
- New contaminants which may require treatment include 1,2,3-TCP and arsenic.
- Other contaminants include 1,2 DCP, cis 1,2-DCE, EDB, PCE , chromium, hydrogen sulfide, iron, manganese, and radon.
- The total number of wells currently shut down due to contamination is 31.
- Groundwater production lost due to contaminated wells is 25,000 gpm.
- USBR's cost curves for contaminant specific processes are presented (capital and O&M), and cost ranges are provided for a various treatment processes. The cost estimates are suitable for initial planning-level efforts but will need to be refined for future planning and alternative selection purpose.

5.2 Recommendations

In order to use the groundwater treatment cost information to compare with other project alternatives, the following recommendations are made.

- Develop well specific treatment evaluation based on well capacity, water quality, site constraints, truck access, piping requirements, etc.
- Develop a site specific cost estimate for each contaminated well based on the preferred treatment alternative.
- Consider centralized treatment if the well locations are conducive and the infrastructure exists such as pipeline, etc. for selected wells.
- Evaluate discharge impacts and cost of residual handling (e.g., discharge) for ion exchange, reverse osmosis, and coagulation / oxidation filtration technologies.

6.0 REFERENCES

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USBR's Cost Fact Sheet Assumptions

WaTER PROGRAM

FOR CONTAMINANT FACT SHEETS



See related Fact Sheets: Acronyms & Abbreviations; Glossary of Terms; Cost Assumption; Raw Water Composition; and Total Plant Costs.

Water Treatment Estimation Routine (WaTER)

Some cost estimates used to develop some of the contaminant Fact Sheet cost curves and the Total Plant Cost curves were derived from Reclamation's WaTER program. WaTER is an Excel spreadsheet application developed for use with Reclamation's MTP. The program is a result of a cooperative effort between Reclamation and the National Institute of Standards and Technology.

Unlike other cost estimation programs that require the user to have information about the size of equipment and chemical dosage rates, the only inputs required for the WaTER program are the production capacity and raw water quality composition. The program employs cost indices as established by the *Engineering News Record*, Bureau of Labor Statistics, and the Producer Price Index, and derives cost data from *Estimating Water Treatment Costs*; volumes 1 and 2; EPA-600/2-79-162a; August 1979. Refer to the Cost Assumptions Fact Sheet for detailed cost data information.

The program has the following capabilities: (1) provides cost estimates for all treatment processes used in the MTP; (2) contains default values which can be customized if more accurate values are available; (3) is expandable to include new processes as they are developed; and (4) is user friendly.

The following processes are included in the program: pumping systems; centrifugal pumps; metering pumps; alum coagulation (dry/liquid); ferric sulfate coagulation; lime-soda ash softening; acid feed; polymer addition; potassium permanganate oxidation; ion exchange; upflow solids contact clarifier; gravity filtration (sand/dual/mixed); granular activated carbon filtration; microfiltration; reverse osmosis; nanofiltration; electrodialysis; clearwell storage; chlorine disinfection; chloramine disinfection; and ozone disinfection.

The program (suitable for PC or Mac environments) and user manual are available for distribution to interested parties. Or they can be accessed at:

<http://www.usbr.gov/pmts/water/desal.html> - Task E (separate program for PC users and Mac users)

<http://www.usbr.gov/pmts/water/reports.html> - #43 (user manual)

As discussed on the Cost Assumptions Fact Sheet, construction and annual O&M costs not estimated by the WaTER program were derived from *Estimating Water Treatment Costs*, volumes 1 and 2, EPA-600/2-79-162a, August 1979; or from equipment manufacturer's product data information.

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Revision Date: 09/11/03

COST ASSUMPTIONS

FOR CONTAMINANT FACT SHEETS



See related Fact Sheets: Acronyms & Abbreviations; Glossary of Terms; Raw Water Composition; Total Plant Costs; and WaTER Program.

1. COST INDEX DATA

Construction and annual O&M costs were derived from: the WaTER Program; *Estimating Water Treatment Costs*, volumes 1 and 2 of EPA-600/2-79-162a, August 1979; or from manufacturer's product data information. Cost estimates are as of March 2001, are considered accurate within +30% to -15%, and are primarily intended as a guide for comparing alternative water treatment options. More accurate cost estimates can be determined given site specific data and verification of assumptions.

EPA cost index updates as follows:

October 1978 ENR construction cost index = 2581; February 1999 = 5992; March 2001 = 6273.
 October 1978 PPI O&M materials index = 71.6; February 1999 = 130.8; March 2001 = 137.8.
 October 1978 PPI O&M energy cost = \$0.03/kW-hr; February 1999 & March 2001 = \$0.07/kW-hr.
 October 1978 PPI O&M labor cost = \$10/hr; February 1999 = \$30/hr; March 2001 = \$32.5/hr.
 Total annual O&M cost = sum of materials, energy, and labor costs.

The following WaTER Program cost components are based on those used by *ENR* at www.enr.com or 212-512-2000:

<u>Category</u>	<u>2001 Value</u>	<u>Used For</u>
Construction cost index	6,279.45	Manufactured & electrical equipment
Building cost index	3,541.01	Housing
Skilled labor index	5,874.20	Excavation, site work, & labor
Materials index	2,115.65	Piping & valves
Steel cost (\$/cwt)	28.01	Steel
Cement cost (\$/ton)	80.35	Concrete
Materials index	2,115.65	Maintenance materials
Electricity cost (\$/kWhr)	0.07	Power
Labor rate (\$/hr)	32.5	Labor

2. PROCESS ASSUMPTIONS

A. Raw Water Pumps: Costs derived from WaTER program. No. of pumps: 2 centrifugal single stage. Pump efficiency: 75%, motor efficiency 90%. Horsepower based on flowrate.

B. Screening/Straining: Costs derived from manufacturer's product data information. Velocity: 2.5 ft/sec, "Water Supply and Pollution Control," second edition; J.W. Clark, W. Viessman Jr., and M.J. Hammer. Screen size opening: 1/4-inch. 3-, 4-, 5-, and 6-inch diameter screens for flows 0.25, 0.50, 0.75, and 1.0 MGD, respectively. Estimated annual O&M for all flows: \$1,000.

C. Rapid Mix: Costs derived from "Estimating Water Treatment Costs." DT: 30 sec, "Recommended Standards for Water Works;" 1982. G value = 900.

D. Polymer Addition: Costs derived from WaTER program. General settling aid: \$1.50/lb. Dosage: 3.0 mg/L.

E. Antiscalant: Costs derived from WaTER program. RO and EDR membrane aid: \$1.50/lb. Dosage: 0.5 mg/L.

F. Dry Alum Coagulation: Costs derived from WaTER program. $Al_2(SO_4)_3$ cost: \$22/100 lbs. Dosage: 230 mg/L.

G. Ferric Sulfate Coagulation: Costs derived from WaTER program. $Fe_2(SO_4)_3$ cost: \$260/short ton. Dosage: 3.0 mg/L.

H1. Lime Softening with Upflow Solids Contact Clarifier: Costs derived from WaTER program. $Ca(OH)_2$ cost: \$340/ton. Dosage: 84.3 mg/L. Two SCC units, each sized for 1/2 total flow. SCC DT: 120 min. SCC O&M G value = 150.

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H2. Lime/Soda Ash Softening with Upflow Solids Contact Clarifier: Costs derived from WaTER program. Ca(OH)_2 cost: \$340/ton. Na_2CO_3 cost: \$340/ton. Ca(OH)_2 dosage: 84.3 mg/L; Na_2CO_3 dosage: 278 mg/L. Two SCC units, each sized for 1/2 total flow. SCC DT: 120 min. SCC O&M G value = 150.

I. Horizontal Paddle Flocculator: Costs derived from "Estimating Water Treatment Costs." DT: 30 min, "Recommended Standards for Water Works;" 1982. G value = 80.

J1. Circular Clarifier: Costs derived from "Estimating Water Treatment Costs." SLR: 1.0 gal/min/ft², "Recommended Standards for Water Works;" 1982. DT @ 12' sidewall depth: 90 min. Structure is concrete.

J2. Tube Settler: Costs derived from "Estimating Water Treatment Costs." SLR: 2.5 gal/min/ft², "Estimating Water Treatment Costs;" volumes 1 and 2; EPA-600/2-79-162a; August 1979.

K. Dual Media Gravity Filter: Costs derived from WaTER program are based on two concrete basins. Dual media cost: \$938/m³@0.25 MGD; \$815/m³@0.50 MGD; \$701/m³@0.75 MGD; & \$582/m³@1.0 MGD. Dual media FLR: 5.0 gal/min/ft², "Estimating Water Treatment Costs;" volumes 1 and 2; EPA-600/2-79-162a; August 1979. 2 units, each sized for plant capacity. 24 hr wash cycle. Media depth: 1 m. Media volume: 3.2 m³@0.25 MGD; 6.5 m³@0.50 MGD; 9.7 m³@0.75 MGD; 12.9 m³@1.0 MGD. TSS density: 35 g/L. Costs include backwash pump, filter structure, and pipe gallery housing. Backwash piping: 7 ft/sec. Backwash pump: 50' TDH. Maximum backwash rate: 18 gal/min/ft².

L. Chlorine Disinfection: Costs derived from WaTER program. Gaseous Cl_2 cost: \$500/short ton, tank. Dosage (2.5 mg/L) = demand (2 mg/L) + residual (0.5 mg/L). Free chlorine residual of 0.2 - 0.5 mg/L and DT of 30 min for groundwater or 2 hrs for surface water, "Recommended Standards for Water Works;" 1982. Free chlorine residual = chlorine available as HOCl and OCl⁻.

M1. Ion Exchange (Anion): Costs derived from WaTER program. Regeneration cycle: 14 days. Resin cost: \$5,227/m³; 1.0 nominal equivalent/liter of resin for NO_3^- . NaCl regeneration at 10% strength. Regenerant storage tank included.

M2. Ion Exchange (Cation): Costs derived from WaTER program. Regeneration cycle: 14 days. Resin cost: \$1,819/m³; 1.9 nominal equivalent/liter of resin. NaCl regeneration at 10% strength.

M3. Ion Exchange (Mixed Bed): Costs derived from WaTER program. Regeneration cycle: 14 days. Nuclear grade resin mixture (cation:anion) generally 1:1. Resin cost: \$4,662/m³; 1.9 nominal equivalent/liter (cation) resin; and 1.4 nominal equivalent/liter (anion) resin. NaCl regeneration at 10% strength.

N. Oxidation with KMnO_4 followed by Greensand Filtration: Costs derived from WaTER program, adjusting gravity filtration for greensand filtration. KMnO_4 cost: \$2.10/lb (hopper truck). KMnO_4 dosage: 1.1 mg/L. Total gravel, greensand, and anthracite costs: \$1,750/m³@0.25 MGD; \$1,539/m³@0.50 MGD; \$1,361/m³@0.75 MGD; & \$1,202/m³@1.0 MGD. Greensand loading rate: 5.0 gal/min/ft². 2 units, each sized for plant capacity. 24 hr wash cycle. Media depth: 1 m. Media volume: 3.2 m³@0.25 MGD; 6.5 m³@0.50 MGD; 9.7 m³@0.75 MGD; 12.9 m³@1.0 MGD. TSS density: 35 g/L. Costs include backwash pump and filter structure.

O. Granular Activated Carbon: Costs derived from WaTER program. 6 month bed life.

P. Reverse Osmosis: Total direct capital costs derived from WaTER program and include cleaning system and some pretreatment (antiscalant) filters/chemicals. Operating pressure: 1380 kPa (200 psi). Membrane cost: \$525 per 8" module. Membrane life: 3 years. Product quality: 500 mg/L TDS. Two stage unit operating at 80% recovery with blending. Pretreatment not included.

Q. Microfiltration: Total direct capital costs derived from WaTER program and include cleaning system and some pretreatment filters/chemicals. Design feed pressure: 207 kPa (30 psi). Membrane cost: \$650. Membrane life: 5 years.

R. Electrodialysis Reversal: Costs derived from WaTER program and Ionics, Inc. Unit operates at 80% recovery. Product quality: 500 mg/L TDS. Pretreatment not included.

S. Clearwell: Costs derived from WaTER program. Below ground concrete tank sized based on water source (30 min DT for groundwater or 2 hr DT for surface water) and flowrate.

3. RAW WATER VARIABLES

An assumed raw water composition is shown on the Raw Water Composition Fact Sheet. Following are the only raw water variables used to determine the cost curves:

A. Flow: Costs for each BAT were prepared for flows of 0.25, 0.50, 0.75, and 1.0 MGD.

B. TDS: A TDS of 2,500 mg/L was assumed for all processes; except for RO and EDR where three TDS ranges were estimated at 1,000, 2,500, and 5,000 mg/L.

C. TSS: For dual media gravity and greensand filtration a TSS of 13.0 mg/L was estimated.

RAW WATER COMPOSITION

FOR CONTAMINANT FACT SHEETS



See related Fact Sheets: Acronyms & Abbreviations; Glossary of Terms; Cost Assumptions; Total Plant Costs; and WaTER Program.

The following raw water composition was used in determining cost curves for various treatment processes:

	<u>Component</u>	<u>Valence</u>	<u>MCL/SMCL</u>		<u>Units</u>	<u>Concentration</u>
			<u>MW</u>	<u>(mg/L)</u>		
METALS	Aluminum	3	26.97	0.05-0.2	mg/L	0.005
	Antimony	3	121.75	0.006	mg/L	--
	Arsenic	3	74.92	0.05	mg/L	0.002
	Barium	2	137.33	2	mg/L	0.11
	Beryllium	2	9.01	0.004	mg/L	--
	Cadmium	2	112.41	0.005	mg/L	0.001
	Calcium	2	40.08	--	mg/L	99
	Chromium	2	52	0.1	mg/L	0.002
	Copper	2	63.55	1	mg/L	0.001
	Iron	2	55.85	0.3	mg/L	0.005
	Lead	2	207.2	0.015	mg/L	--
	Magnesium	2	24.3	--	mg/L	19
	Manganese	2	54.94	0.05	mg/L	0.003
	Mercury	2	200.59	0.002	mg/L	--
	Nickel	2	58.71	0.1	mg/L	0.002
	Potassium	1	39.1	--	mg/L	12
	Selenium	4	78.96	0.05	mg/L	--
	Silver	1	197.87	0.1	mg/L	0.001
	Sodium	1	22.99	--	mg/L	31
	Strontium	2	87.6	--	mg/L	0.61
Thallium	1	204.37	0.002	mg/L	--	
Zinc	2	65.38	5	mg/L	0.02	
OTHER INORGANICS	Alkalinity-HCO ₃ ⁻	-1	61	--	--	100
	Alkalinity-CO ₃ ⁻²	-2	60	--	--	--
	Carbon Dioxide (aq)	0	44	--	--	--
	Asbestos	--	--	7	MF/L	--
	Chloride	-1	35.45	250	mg/L	--
	Residual disinfectant	--	71	detectable	mg/L	--
	Color	--	--	15	cu	--
	Conductivity	--	--	--	--	920
	Corrosivity	--	--	non-corrosive	mg/L	--
	Cyanide	--	--	0.2	mg/L	--
	Fluoride	-1	19	4	mg/L	0.2
	Foaming agents	--	--	0.5	mg/L	--
	Nitrate (as N)	-1	14	10	mg/L	12
	Nitrite (as N)	-1	14	1	mg/L	--
	Ammonium	1	--	10	mg/L	--
	Odor	--	--	3	ton	--
	pH	--	--	6.5-8.5	pH	7.2
	o-Phosphate	-3	95	--	--	--
	Silica	--	--	--	--	--
	Silicon	--	--	--	--	28
Solids (TDS)	--	--	500	mg/L	2500	
Sulfate	-2	96	250	mg/L	130	
Temperature	--	--	--	--	13	
Solids (TSS)	--	--	--	mg/L	--	

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Following are the only raw water variables applied to the above:

A. TDS: For RO and EDR, three TDS ranges were estimated at 1,000, 2,500, and 5,000 mg/L.

B. TSS: For dual media gravity and greensand filtration, a TSS of 13.0 mg/L was estimated.

C. Metals for Cl₂: The following concentrations were adjusted for use with Cryptosporidium/Giardia and Total Coliform/E-Coli:

Iron	550 mg/L
Manganese	550 mg/L
Chromium	200 mg/L
Nickel	200 mg/L
Nitrite	200 mg/L

Cost Estimate for Treatment Technologies Case Studies

**COST ESTIMATES FOR TREATMENT TECHNOLOGIES
(INCLUDES ANNUALIZED CAPITAL AND O&M COSTS)**

No.	Treatment Technology	Source of Information	Estimated 2001* Unit Cost (\$/1,000 gallons treated)
1	Granular Activated Carbon	Reference: Malcom Pimie estimated for California Urban Water Agencies, large surface water treatment plants treating water from the State Water Project to meet Stage 2 D/DBP and bromate regulation, 1998	0.371 - 0.7084
2	Granular Activated Carbon	Reference: Carolio Engineers, estimate for VOC treatment (PCE), 95% removal of PCE, Oct. 1994, 1900 gpm design capacity	0.17
3	Granular Activated Carbon	Reference: Carolio Engineers, est. for large No.Calif. Surface water treatment plant (90 mgd capacity) treating water from State Water Project, to reduce THM precursors, ENT construction cost index = 6262 (San Francisco area) - 1992	0.82
4	Granular Activated Carbon	Reference: CH2M Hill study on San Gabriel Basin, for 135 mgd central treatment facility for VOC and SOC removal by GAC, 1990	0.318 - 0.4664
5	Granular Activated Carbon	Reference: Southern California Water Co. - actual data for "rented" GAC to remove VOC's (1.1-DCE), 1.5 mgd capacity facility, 1998	1.47
6	Granular Activated Carbon	Reference: Southern California Water Co.-actual data for permanent GAC to remove VOC's (TCE), 2.16 mgd plant capacity, 1998	0.95
7	Reverse Osmosis	Reference: Malcolm Pimie estimate for California Urban Water Agencies, large surface water treatment plants treating water from the State Water Project to meet Stage 2 D/DBP and bromate Regulation, 1998	1.1024 - 2.1094
8	Reverse Osmosis	Reference: Boyle Engineering, RO cost to reduce 1000 ppm TDS in brackish groundwater in So. Calif., 1.0 mgd plant operated at 40% of design flow, high brine line cost, May 1991	2.60
9	Reverse Osmosis	Reference: Boyle Engineering, RO cost to reduce 1000 ppm TDS in brackish groundwater in So. Calif., 1.0 mgd plant operated at 100% of design flow, high brine line cost, May 1991	1.60
10	Reverse Osmosis	Reference: Boyle Engineering, RO cost to reduce 1000 ppm TDS in brackish groundwater in So. Calif., 10.0 mgd plant operated at 40% of design flow, high brine line cost, May 1991	2.15
11	Reverse Osmosis	Reference: Boyle Engineering, RO cost to reduce 1000 ppm TDS in brackish groundwater in So. Calif., 10.0 mgd plant operated at 100% of design flow, high brine line cost, May 1991	1.34
12	Reverse Osmosis	Reference: Arsenic Removal Study, City of Scottsdale, AZ - CH2M Hill, for a 1.0 mgd plant operated at 40% of design capacity, Oct. 1991	4.35
13	Reverse Osmosis	Reference: Arsenic Removal Study, City of Scottsdale, AZ - CH2M Hill, for a 1.0 mgd plant operated at 100% of design capacity, Oct. 1991	2.57
14	Reverse Osmosis	Reference: Arsenic Removal Study, City of Scottsdale, AZ - CH2M Hill, for a 10.0 mgd plant operated at 40% of design capacity, Oct. 1991	1.93
15	Reverse Osmosis	Reference: Arsenic Removal Study, City of Scottsdale, AZ - CH2M Hill, for a 10.0 mgd plant operated at 100% of design capacity, Oct. 1991	1.19

**COST ESTIMATES FOR TREATMENT TECHNOLOGIES
(INCLUDES ANNUALIZED CAPITAL AND O&M COSTS)**

No.	Treatment Technology	Source of Information	Estimated 2001* Unit Cost (\$/1,000 gallons treated)
16	Reverse Osmosis	Reference: CH2M Hill study on San Gabriel Basin, for 135 mgd central treatment facility with RO to remove nitrate, 1990	1.1972 - 2.1094
17	Packed Tower Aeration	Reference: Analysis of Costs for Radon Removal...(AWWARF publication), Kennedy/Jenks, for a 1.4 mgd facility operating at 40% of design capacity, Oct. 1991	0.69
18	Packed Tower Aeration	Reference: Analysis of Costs for Radon Removal...(AWWARF publication), Kennedy/Jenks, for a 14.0 mgd facility operating at 40% of design capacity, Oct. 1991	0.37
19	Packed Tower Aeration	Reference: Carollo Engineers, estimate for VOC treatment (PCE) by packed tower aeration, without off-gas treatment, O&M costs based on operation during 329 days/year at 10% downtime, 15 hr/day air stripping operation, 1900 gpm design capacity, Oct. 1994	0.18
20	Packed Tower Aeration	Reference: Carollo Engineers, for PCE treatment by Ecolo-Flo Enviro-Tower air stripping, without off-gas treatment, O&M costs based on operation during 329 days/year at 10% downtime, 16 hr/day air stripping operation, 1900 gpm design capacity, Oct. 1994	0.19
21	Packed Tower Aeration	Reference: CH2M Hill study on San Gabriel Basin, for 135 mgd central treatment facility - packed tower aeration for VOC and radon removal, 1990	0.2968 - 0.4876
22	Advanced Oxidation Processes	Reference: Carollo Engineers, estimate for VOC treatment (PCE) by UV Light, Ozone, Hydrogen Peroxide, O & M costs based on operation during 329 days/year at 10% downtime, 24 hr/day AOP operation, 1900 gpm capacity, Oct. 1994	0.36
23	Ozonation	Reference: Malcolm Pirnie estimate for CUWA, large surface water treatment plants using ozone to treat water from the State Water Project to meet Stage 2 D/DBP and bromate regulation, <i>Cryptosporidium</i> inactivation requirements. 1998	0.0848 - 0.1678
24	Ion Exchange	Reference: CH2M Hill study on San Gabriel Basin, for 135 mgd central treatment facility - ion exchange to remove nitrate, 1990	0.4028 - 0.5194

Note:

*Costs were escalated from date of original estimates to present, where appropriate, using Engineering News Record (ENR) construction indices for Los Angeles and San Francisco.

3/19/01

http://www.ci.modesto.ca.us/omd/01_ccr/pdf/phg_cost_treat.pdf