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Cost Comparison of Perchlorate Treatment Options

Emma O. Nolan

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Cost Comparison of Perchlorate Treatment Options

by
Emma O. Nolan

Committee

Dr. Janie Chermak, Chair
Dr. Michele Minnis
Dr. Bruce Thomson

A Professional Project Report Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Water Resources

Hydroscience Concentration

Water Resources Program
University of New Mexico
Albuquerque, New Mexico
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Committee Approval

The Master of Water Resources Professional Project Report of **Emma O. Nolan**, entitled **Cost Comparison of Perchlorate Treatment Options** is approved by the committee:

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Abstract

Perchlorate (ClO_4^-) is used as an oxidizer for rocket fuel, fireworks, matches, air bags, and other mechanisms requiring enhanced explosions. Because perchlorate is extremely hydrophilic, it leaches into ground water and is eventually found in drinking water supplies. Public health is the primary reason agencies regulate perchlorate. Severe effects of perchlorate ingestion are hypothyroidism, goiter, and aplastic anemia.

The objectives of this study were isolate areas of perchlorate occurrence and compare costs of government sanctioned compliance methods. Two removal strategies meet the best available technology (BAT) criteria for perchlorate, single pass ion exchange and biological fluidized bed reactor. The former is the preferred method due to issues with possible pathogenic bacteria for the latter. Another compliance option is blending with a fresh water source. Costs were compared for ion exchange and blending for each of the water sources in each of two public water systems.

The study compared the relative prices of blending and ion exchange over a twenty-year period and found that in the \$60/acre-ft case, the inflation adjusted total cost of blending was \$9,595,263 for Pomona and \$15,152,463 for Riverside. For the average \$250/acre-ft case, the inflation adjusted total cost of blending was \$33,814,300 for Pomona and \$56,842,972 for Riverside. In the high estimate, \$500/acre-ft, the inflation adjusted total cost of blending was \$65,681,455 for Pomona and \$111,698,906 for Riverside. The inflation adjusted total cost for ion exchange was \$41,411,187 for Pomona and \$55,631,907 for Riverside. Thus, depending on the cost scenario used the costs determine varied recommendations.

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Introduction

Perchlorate (ClO_4^-) is a negatively charged ion and a strong oxidizing agent (Espenson, 2000). In the United States, perchlorate has been commercially manufactured for military and industrial products since the 1890s (NAS, 2005). The main use is as an oxidizer for solid rocket fuels, missiles, road flares, fireworks, and other munitions. Perchlorate is also used in the manufacturing process of matches and airbags. Further, it occurs naturally in most fertilizers containing nitrate rich Chilean saltpeter and caliche. (Susarla, 1999, 2000). Figure 1 shows areas of perchlorate releases throughout the United States.

EPA Published Perchlorate Releases as of April 2003

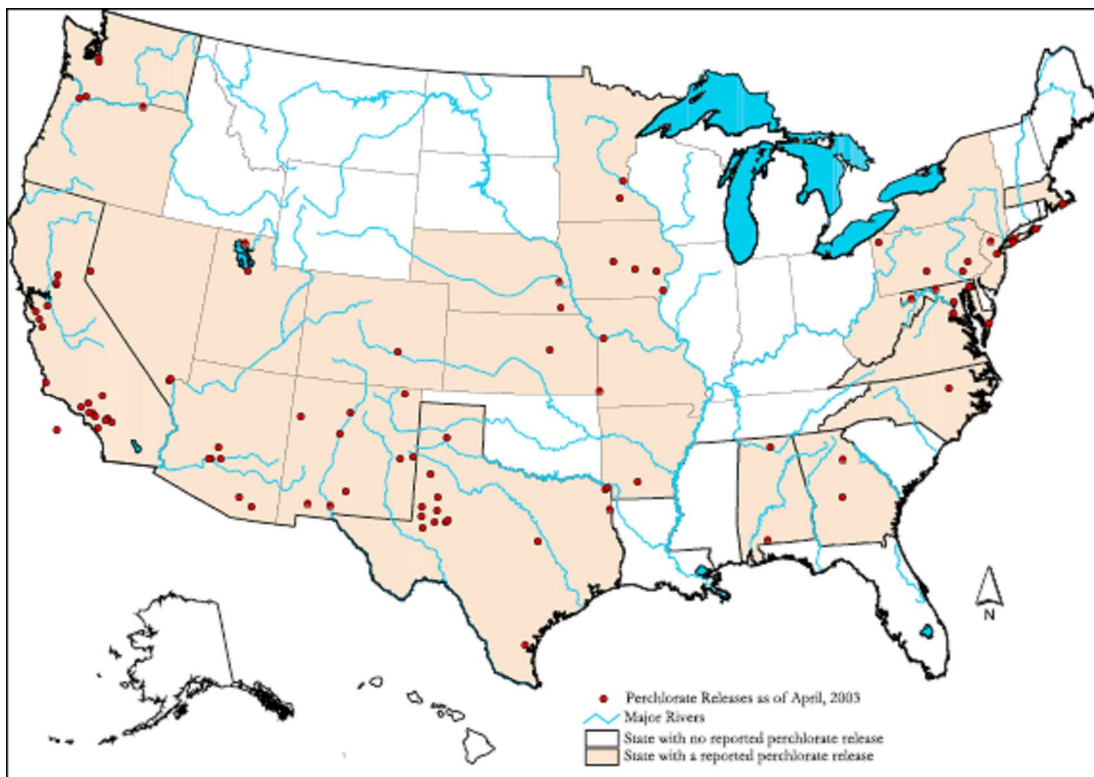


Figure 1: Perchlorate releases reported to the EPA as of April 2003 (EPA, 2003).

Perchlorate was used to treat Graves' disease (hyperthyroidism) in the 1950s and 1960s. A high dose (400 – 2,000 mg/day) was used as an inhibitor to iodide, which is the building block of thyroid hormones. Patients with hyperthyroidism have an overactive thyroid and produce too many hormones; therefore perchlorate (often potassium perchlorate) was used to regulate this overabundance of hormones. Although perchlorate was being used as a regulator for hormone production, side effects from the highest doses were still severe (NAS, 2005). These included nausea, blood disorders, vomiting, gastric inflammation, skin rashes, fever, lymph node enlargement, kidney dysfunction, and death. The frequency of side effects was proportional to the dose.

While there have been no studies observing long term effects of low doses on patients with normal thyroid function in the United States, both the U.S. Environmental Protection Agency (EPA) and State Agencies have begun to monitor perchlorate levels in groundwater and set reference for perchlorate. According to the EPA website, “a reference dose is a scientific estimate of a daily exposure level that is not expected to cause adverse health effects in humans.”

Perchlorate was first observed in ground water in California in 1985 and in drinking water sources in 1997. The EPA started national monitoring of public drinking water sources in 2001. In September of 2003, the EPA released a list of drinking water sources with measured perchlorate concentrations at or above 4µg/L (~ 4ppb). There were two hundred fifty-three total confirmed source detections (facilities) in thirty-five states and one territory. Table 1 shows the reported detections above 4µg/L by EPA region. Most of the facilities with known perchlorate releases were located in EPA Region 9 (EPA, 2004).

Known Perchlorate Release Detections above 4µg/L in Drinking Water Sources Reported to the EPA by Region

Region 1		3					
MA	ME	NH	RI	VT			
3	0	0	0	0			
Region 2		22					
NJ	NY	PR	VI				
8	13	1	0				
Region 3		16					
DC	DE	MD	PA	VA	WV		
0	0	7	5	3	1		
Region 4		21					
AL	FL	GA	KY	MS	NC	SC	TN
5	3	3	0	1	5	3	1
Region 5		20					
IL	IN	MI	MN	OH	WI		
3	2	2	3	10	0		
Region 6		38					
AR	LA	NM	OK	TX			
4	0	12	5	17			
Region 7		10					
IA	KS	MO	NE				
4	1	2	3				
Region 8		5					
CO	MT	ND	SD	UT	WY		
1	0	0	1	3	0		
Region 9		109					
AZ	CA	HI	NV				
18	86	0	5				
Region 10		9					
AK	ID	OR	WA				
0	0	4	5				

Table 1: EPA recorded perchlorate releases of at least 4ppb in the United States as of 9/23/04. Note: List includes data from self-reported sources (EPA, 2004).

As shown in Table 1, the EPA recorded a total of eighty-six facilities that reported releases of perchlorate into the ground water in California (EPA, 2004). As of June 2004, three hundred fifty wells in eighty-nine water systems contained measurable amounts (above 4µg/L) of perchlorate in California. Ninety percent of those detections were found in Southern California. Although, treatment of upstream contamination has been completed, residual perchlorate is still found in the Colorado River fed reservoirs in Southern California. Southern California's Imperial Valley is also irrigated with Colorado River water. (Bull et al., 2004). Officials from Pomona and Riverside, CA believe their high perchlorate incidence and concentration stems from high concentrations in Chilean fertilizers (Taylor, 2007; Monroe, 2007).

In February 2005, the EPA set a 0.0007 mg/kg/d reference dose (RfD) for perchlorate. The latest RfD approximately translates to a 24.5 µg/L drinking water equivalent level (DWEL). The Drinking Water Equivalent Level (DWEL) is used to show the amount of intake of a contaminant from drinking water and no other sources. The RfD is consistent with the National Academy of Science (NAS) report released in 2005. (Black, 2005). California, specifically the California Department of Public Health (CDPH), has been given "primacy" by the EPA to enforce regulations under the Clean Drinking Water Act. To maintain primacy, the CDPH has to create and enforce regulations that are more stringent than the federal regulations. The CDPH does not examine health effects of contaminants. This job is relegated to the California Office of Environmental Health Hazard Assessment (COEHHA). According to the California Health and Safety Code, the COEHHA creates the PHG by considering how public health is affected by risks with respect to contaminants in water (CDHS, 2006). In 2004,

COEHHA set the California public health goal (PHG) to 6µg/L after peer reviews by the University of California and the EPA. However, when a new maximum contaminant level (MCL) is deliberated by the CDPH, the COEHHA findings as well as technological and economic factors are considered (COEHHA, 2004).

This project estimates additional costs of the CDPH's new state MCL of 6 µg/L on public water systems (PWSs) in California. Table 2 shows the perchlorate levels found in public drinking water sources and systems in each county in Southern California. Los Angeles and Riverside counties contain the most occurrences of perchlorate above the reporting limit and the public health goal (PHG) in drinking water sources. The goal of this project is to compare the remediation costs of two pathways, single pass ion exchange *vs.* blending. The data in this study were taken from two previous studies that estimated costs of compliance for different MCLs. Both studies started with raw data from the California Water Quality Monitoring Database and estimated costs in general for several MCL scenarios for the entire state of California. One of the studies was done by the CDHS (now CDPH) and details costs for systems that are small (<200 connections) or large (≥200 connections). The CDHS paper provided the monitoring costs used in this project (CDHS, 2006). The other study was commissioned by a public affairs company and done by a private consulting firm, Kennedy/Jenks. The study in this paper used the data from the Kennedy/Jenks study to compare costs of blending *vs.* ion exchange and the CDHS' study for monitoring costs.

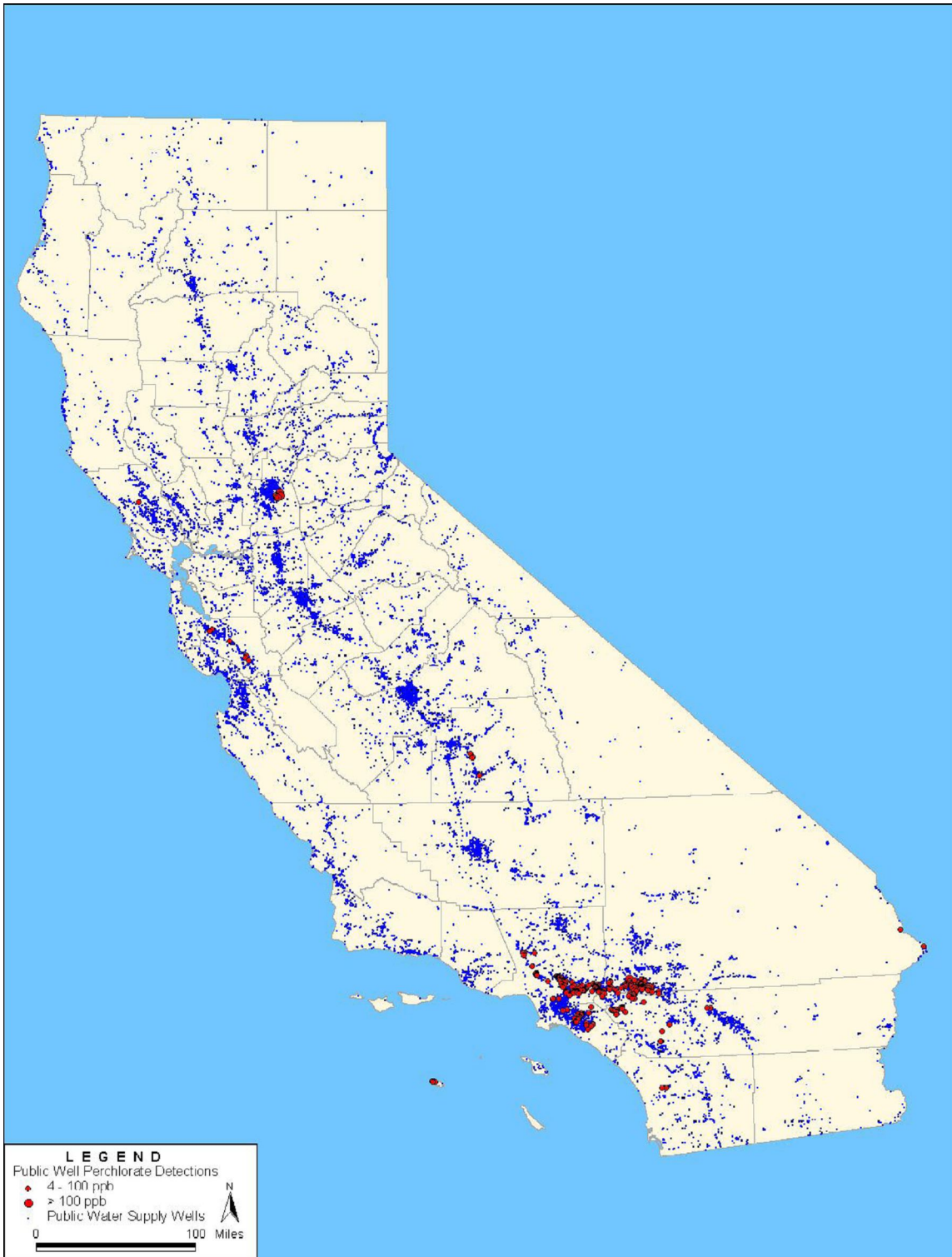


Figure 2: GIS Map showing perchlorate detections in public water supply wells. *Public Well Perchlorate Detections as of May 2003*: Courtesy of Santa Clara Valley Water District, San Jose, California for the cover of *Perchlorate in Drinking Water: a Science and Policy Review* (Bull et al., 2004).

Active and Standby Sources with Perchlorate Detections (April 1, 2002 – April 1, 2007)					
County	Perchlorate at or above 4-µg/L DLR *		Perchlorate above 6-µg/L NL**		Peak Conc. (µg/L)
	No. of Sources	No. of Systems	No. of Sources	No. of Systems	
Los Angeles	103	29	69	20	100
Riverside	64	9	50	7	73
San Bernardino	52	14	34	11	88
Orange	18	9	-	-	5.9
Santa Clara	9	4	3	3	8
Sacramento	4	2	1	1	95.9
San Diego	4	2	1	1	7
Imperial	2	1	-	-	5.4
Ventura	2	1	1	1	13
Tulare	1	1	-	-	5.6
TOTAL	259	72	159	44	--

* Detection limit for purposes of reporting. ** Notification level.

Table 2: This table contains draft data and can be found [Online] California Department of Health Services website [Accessed May 2007]:

<http://www.dhs.ca.gov/ps/ddwem/chemicals/perchl/default.htm>

Chemistry

Perchlorate is a negatively charged ion (anion) composed of a chlorine atom bonded with four oxygen atoms represented as ClO_4^- .

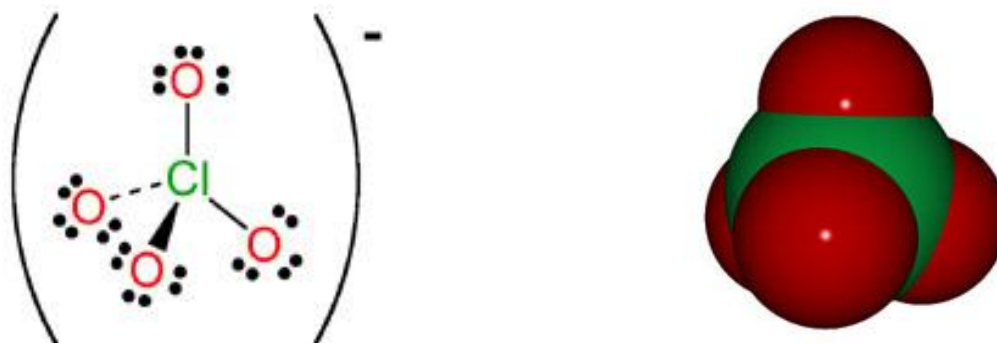
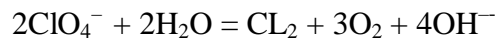


Figure 3: Illustrations showing perchlorate. [Online] Available:
<http://www.chemistry.wustl.edu/~courses/genchem/Tutorials/Ions/ions.html> [Accessed October 2007]

Perchlorate's negative charge is equally dispersed over its oxygen atoms. Because cations more readily bond to anions when the charge is concentrated, perchlorate forms extremely weak ionic bonds. Even though the bonds are fragile, perchlorate ions can still form salts and perchloric acid (Espenson, 2000). Sodium, lithium, ammonium, and potassium combine with perchlorate to make salts for military and industrial use (Susarla *et al.*, 1999, 2000; NAS, 2005). Since perchlorate salts completely dissociate in water, the terms perchlorate and perchlorate salts may be used interchangeably (COEHHA, 2004). According to the NAS report it is very "soluble in aqueous media and polar organic solvents." Predictions made from thermodynamic data state that perchlorate should be unstable and react vigorously. Perchlorate should, but does not oxidize water. The spontaneous reaction should be, but **is not**:



In practice, perchlorate salts act inert under normal conditions due to kinetic barriers (Espenson, 2000). Once perchlorate is in the ground or surface water, it can persist for many decades under typical conditions (Susarla, 1999, 2000). Perchlorate is a strong oxidizer when it comes in contact with organic compounds such as alcohols and dimethylsulfides. This property makes it useful for the military and industry (Espenson, 2000). Perchlorate is used for rocket propellant, road flares, fireworks, airbag inflators, and nuclear reactors (COEHHA, 2004).

Perchlorate Sources

The United States began production of perchlorate salts in the 1890s. Perchlorate was first discovered in several California superfund sites in 1985. Drinking water sources were not identified as containing perchlorate until 1997 (NAS, 2005). Most perchlorate studies are focused on past and present military and industrial sites. Other occurrences of perchlorate have been found where there are no anthropogenic sources present. Chilean saltpeter and caliche containing high levels of perchlorate were used in fertilizer and provided a way for perchlorate to enter ground water and food sources (Susarla *et al.*, 1999, 2000). In another study, Jackson *et al.* (2004) even found occurrences in Texas where no perchlorate plume was present. However, most perchlorate containing drinking water sources can be associated with at least one known source.

The most common perchlorate salts are ammonium perchlorate and potassium perchlorate. Ammonium perchlorate is used as an ignition source for fireworks and munitions. It is also used in solid rocket fuel. Road flares and airbag inflation systems use potassium perchlorate. Potassium perchlorate has also been used as a medication to treat hyperthyroidism (Clark, 2000). The production of ammonium perchlorate is described a paper by COEHHA in 2004.

“The manufacture of perchlorate salts begins with the electrolysis of brine (sodium chloride in water) to first form sodium chlorate (NaClO_3) and then sodium perchlorate (NaClO_4). The sodium perchlorate is reacted with ammonium chlorate to form ammonium perchlorate (NH_4ClO_4) and sodium chloride. The

solution is cooled, and the ammonium perchlorate crystals are dried and packaged.”

Perchlorate can only be used as an oxidizing agent with explosive compounds because as a rule perchlorate ions are highly unreactive. This inert salt creates an ionic environment for the explosive compounds (Espenson, 2000).

Interest in identifying potential sources of naturally occurring perchlorate stems from concern about sources found in ground and surface water as well as potential regulations. During the 1880s, naturally occurring perchlorate was discovered in fertilizer containing Chilean nitrates (Orris *et al.*, 2003). Even though Susarla *et al.* (1999, 2000) found trace amounts of perchlorate in other samples of fertilizer, the Chilean nitrate (saltpeter, caliche) samples contained 600% more. Because the other fertilizers still had trace amounts of perchlorate in the analysis, Susarla *et al.* (1999, 2000) postulated there was a variable during the manufacturing process that contaminated the samples. This does not negate the extremely high concentrations of perchlorate in the Chilean nitrate relative to the other samples.

Jackson *et al.* (2004) conducted their study in northwest Texas where perchlorate was found in drinking water with no obvious perchlorate source or plume in the area.

The investigators noted that, at the outset of the study,

“...the most likely sources (of perchlorate) were thought to be [1] a natural mineralogical impurity, [2] agricultural fertilizers containing perchlorate, [3] in situ generation of perchlorate by electrochemical reactions, or [4] some combination of the three.”

Although the scientists were unable to determine the source of perchlorate in the ground water, they believe it was "...atmospheric production and/or surface oxidative weathering" in their study (Jackson *et al.*, 2004)

Because most large utilities in California supply water from multiple sources, determining the exact cause of high perchlorate concentrations, up to 100 µg/L, is difficult. Although authorities from both communities in this study agree the most likely cause of their high concentrations is fertilizer with ingredients from Chile, the perchlorate level in general can be caused by multiple factors including natural sources and contaminant plumes (Taylor, 2007; Monroe, 2007). Because perchlorate is persistent in the environment, discovering a time of discharge is also unlikely. These variables create challenges in identifying and eliminating specific sources. Although several facilities have begun clean-up on sites they have contaminated, the municipalities will be ultimately responsible to adhere to the 6 µg/L MCL regulation.

Health Impacts

Metabolic activity as well as growth and development are controlled by the two hormones produced by the thyroid and perchlorate can affect them both. The hormones must flow constantly because they affect almost every organ system in the body. Homeostasis is kept as long as these hormones are regulated within their specified limits. Hyperthyroidism (Graves' disease) or hypothyroidism can occur, if there are too many or too few hormones, respectively (NAS, 2005). A third hormone, produced by the pituitary gland, aids in thyroid hormone regulation. If there are too many thyroid hormones, the

pituitary gland slows its hormone production and vice versa. Perchlorate can block the entry of the primary building block of the thyroid hormone. If the pituitary gland signals the thyroid to create more hormones, the thyroid may not have the ability to respond (Clark, 2000).

The hormones secreted by the thyroid, hypothalamus gland and pituitary gland regulate one another in a cyclical fashion. The hypothalamus secretes thyrotropin-releasing hormone (TRH). TRH then prompts the pituitary gland to secrete thyrotropin (thyroid-stimulating hormone, TSH). The production of the thyroid hormones, L-thyroxine (T_4) and L-triiodothyronine (T_3), is increased by TSH secretion. TRH production is retarded as T_4 and T_3 concentrations increase. Then, TSH production slows and, eventually, thyroid production is reduced, lowering the T_4 and T_3 . The amount of iodide in the system determines if the system will remain stable. If perchlorate blocks thyroid hormone production, TRH and then TSH levels rise because the T_4 and T_3 concentrations are not high enough to control them. While this cycle is functioning properly, the body does not slip into hyperthyroidism or hypothyroidism (Clark, 2000).

Iodide is the key ingredient in T_4 and T_3 . Transport of iodide to the thyroid is facilitated and mediated by the sodium/iodide symporter (NIS), a glycoprotein composed mostly of amino acids. This protein creates a gradient into the thyroid follicles to move iodide. Iodide and perchlorate are roughly the same shape and both have the same negative charge. This characteristic makes them true competitive inhibitors. Thus, both anions are capable of blocking the other at the NIS (NAS, 2005).

Iodide deficiency is noted if the patient does not ingest at least 20 μ g per day. Since perchlorate and iodide can both bind to the NIS with a strong affinity, the presence

of perchlorate can inhibit iodide transport into the thyroid and cause “intrathyroid deficiency,” lack of iodide in the thyroid which causes a slowdown of hormone production. Iodide deficiency on its own or caused by perchlorate can lead to hypothyroidism (NAS, 2005). Perchlorate caused intrathyroid deficiency is not permanent as it is eventually excreted through the urine (Clark, 2000). Further, as hormones already existing in the serum have half-lives of 20 hours to 7 days depending on the type hormone, a temporary halt in production is not as dramatic as a chronic drop in production (NAS, 2005). Thus, prolonged ingestion of perchlorate has the potential for far more devastation than an acute exposure.

A relevant case occurred in the 1950s and 1960s when high doses (400-2,000 mg/day) of potassium perchlorate were used to treat patients with Graves’ disease for weeks, months, and sometimes years. Since the patients were in need of antithyroid regulation, the treatments were relatively safe. However, some patients experienced side effects including: nausea, blood disorders, vomiting, gastric inflammation, skin rashes, fever, lymph node enlargement, kidney dysfunction, and death. The frequency of side effects was proportional to the dose.

“Thirteen patients who had taken 400 – 1,000 mg per day for 2 to 20 weeks developed aplastic anemia or agranulocytosis (cessation of production of red blood cells or white blood cells, respectively), and seven of them died.” (NAS, 2005)

Because of the side effects and mortality rates, this treatment has been discontinued. One use of perchlorate after these trials was in the treatment of patients who developed hyperthyroidism after being exposed to amiodarone (NAS, 2005).

Amiodarone treats cardiac tachyarrhythmias. Because it is nearly 40% iodine by mass and has an estimated half-life of eight months, perchlorate salts were used to reduce the amount of T₃ and T₄ (Clark, 2000). Another study, done in 1984, showed patients with Graves' disease got better with a treatment of 900 mg/day. As the dose was reduced slowly to 93 mg/day during the next twelve months, patients continued to improve and had normally functioning thyroids at the end of the study. The eighteen patients had normal T₄, T₃, and TSH concentrations at the end of the first year. They also received an additional dose of 40-120 mg/day for the next year and continued to have normal hormone rates. The NAS study postulated that these patients were equivalent to patients with no history of hyperthyroidism. Due to severe side effects, however, perchlorate is not approved by the Food and Drug Administration (FDA) to treat endocrine or metabolic disorders (NAS, 2005).

At present there are no studies that show health impacts of long term exposure to low concentrations of perchlorate in the United States. The NAS study (2005) summarized most of the relevant studies and made its recommendations. The EPA then set their RfD using NAS recommendations as a base. Even though exposure is defined as any route of ingestion, this project only considers the factors the EPA and CDHS takes into consideration when deriving an MCL: drinking water ingestion.

The discussion in this section shows that in contrast to other contaminants such as arsenic, the mechanism of perchlorate acute toxicity and its toxicology are well understood. The effects of long term low dose exposure have yet to be categorized.

Regulation

Currently, there is no national maximum contaminant level (MCL) for perchlorate in public water supplies. In 1998, the EPA's Contaminant Candidate List (CCL) was finalized in accordance with the 1996 amendments to the Safe Drinking Water Act (SDWA). Perchlorate was included among the contaminants listed to be considered for regulation. The EPA then began nationwide sampling for perchlorate in 2001. In late 2004, the EPA panel decided that there was not enough data to authorize a federal regulation (NAS, 2005). Perchlorate was added to the new CCL 2 that was released in February of 2005. When the CCL 2 was released, the EPA set the official reference dose (RfD) for perchlorate at 0.0007 mg/kg/day (Black, 2005). The preliminary regulatory determinations for the CCL 2 were released in May 2007 for the 60 day comment period. The determinations continue to state there is currently not enough data available to make a regulatory determination (EPA, 2007a).

The EPA uses a standard equation to find the maximum contaminant level goal (MCLG), which may be used to guide a maximum contaminant level (MCL). This equation is mapped in Figure 3. The RfD recommended by the EPA per the NAS (2005) study, 0.0007mg/kg/d, is multiplied by the average adult weight (70 kg). The result, 0.049mg*d, divided by the average daily water intake (2 L/d). The result is 0.0245mg/L. Perchlorate is measured in $\mu\text{g/L}$, so the result is divided by 1,000 to get the drinking water equivalent level (DWEL), 24.5 $\mu\text{g/L}$. The DWEL is then multiplied by the average daily exposure to the chemical through drinking water (usually 20%) to give the MCLG (EPA, 2007b). The MCLG in the case of a 24.5 $\mu\text{g/L}$ DWEL is 4.9 $\mu\text{g/L}$. If an MCL of

5µg/L was in place (i.e. California’s 6µg/L MCL), any current state regulations would be mandated to change to the EPA MCL or less. The SDWA states that the MCL is defined

“...as the level that may be achieved with the use of the best available technology, treatment techniques, and other means which EPA finds are available (after examination for efficiency under field conditions and not solely under laboratory conditions), taking cost into consideration.” (EPA, 2007b)

A treatment technique (TT) may be put into effect if there is no feasible way to measure the contaminant. The EPA website gives two examples of this: the Surface Water Treatment Rule which requires disinfection and filtration and the Lead and Copper Rule which requires optimized corrosion control (EPA, 2007b). Because perchlorate has been measured throughout the United States since 2001, a TT would not be a regulatory option.

EPA Regulatory Process Summary for Perchlorate: Reference Dose to Maximum Contaminant Level
<p>Reference dose (RfD) = 0.0007 mg/kg/d Average adult weight = 70 kg Average daily water intake = 2 L/d Drinking water equivalent level (DWEL) = RfD x Avg adult weight / Avg water intake DWEL = (0.0007 mg/kg/d) x (70 kg) / (2 L/d) = 0.0245 mg/L 1,000 :g = 1mg DWEL in µg/L = (0.0245 mg/L) x (1,000 :g/mg) = 24.5 µg/L Maximum contaminant level goal (MCLG) = DWEL x 20% MCLG = (24.5 µg/L) x (0.20) = 4.9 µg/L The maximum contaminant level (MCL) is set as close to the MCLG as possible.</p>

Figure 4: Methodology derived from EPA website: www.epa.gov/safewater/standard/setting.html

On July 28, 2006, Massachusetts became the first state to pass a maximum contaminant level (MCL) for perchlorate. The Massachusetts Department of

Environmental Protection (MassDEP) completed the same type of review the EPA follows to promulgate new contaminate MCLs. The MCL set by MassDEP was 2 µg/L (MassDEP, 2006). David Terry (2007) from MassDEP explained there are not many areas in the state of Massachusetts with measurable levels of perchlorate. The regulation was set as a preemptive measure to keep current levels from rising. The issue that concerned MassDEP was the perchlorate being dropped from fireworks displays. Currently, MassDEP is recommending granulated activated carbon (GAC) filtration for their preventative maintenance effort. GAC is used by Massachusetts PWSs to reduce perchlorate levels to or below the MCL. While this method works for low concentrations of perchlorate, it is not suitable for large scale operations or higher contaminant levels (Terry, 2007). Like the EPA, MassDEP reserves the right to review new studies and findings every 6 years after setting an MCL for possible rule revision (MassDEP, 2006).

Proposition 65, California's Safe Drinking Water and Toxic Enforcement Act of 1986, states that a chemical must be added to the contaminant list if the data clearly shows the committee in charge that the contaminant causes reproductive toxicity or cancer (COEHHA, 2005). Proposition 65 also states that the MCL must be set by the CDHS at a level as close to the PHG (6 µg/L for perchlorate) as possible. Unlike COEHHA, the CDHS must consider public health as well as technological and economic factors. According to Proposition 65, the CDHS "must balance public health concerns, economic impacts of treatment, and water availability in the state when setting the MCL for a substance..." (Bull *et al.*, 2004). A press release from the COEHHA on 8/11/2005 stated:

“Even though evidence of a substance’s adverse health effects may be considerable, Proposition 65 says the committee can list a substance only if it determines the substance has been ‘clearly shown’ to cause reproductive toxicity. A decision that a substance falls short of the ‘clearly shown’ standard does not mean that the committee believes the substance to be non-toxic. Substances that are not listed under Proposition 65 may still be subject to regulation under other state environmental programs.”

Although perchlorate was not listed by COEHHA under Proposition 65, CDHS regulated perchlorate by amending provisions under Title 22, California Code of Regulations (CDHS, 2006).

The California Department of Health Services (CDHS) was the agency in charge of the environmental rule-making process until July 1, 2007. At that time CDHS was split into two agencies, the California Department of Public Health (CDPH) and the Department of Health Care Services. The Division of Drinking Water and Environmental Management (DDWEM), the agency responsible for perchlorate regulation, is now part of the CDPH.

A California state MCL must go through a ten step process before it can be adopted as law. During the first five steps the rule is subject to internal scrutiny. Then, the rule must be approved by the Office of Regulations and Hearings, the Budget Office, the Department of Finance, the Health and Human Services Agency, and the Office of Administrative Law. Once the five agencies approve the rule, it is published in the California Regulatory Notice Register. This publication signals the beginning of the forty-five day public comment period. If comments prompt changes to the rule, an

additional fifteen day public comment period is held. Final responses for comments are drafted and the final rule package is put together for review by the Director of CDPH. Once the rule is signed by the CDPH Director, the rule is sent back to the Office of Administrative Law. The Office of Administrative Law does a final Administrative Procedure Act compliance review which can take up to thirty working days. After the compliance review, the rule is filed with the Secretary of State and becomes law in thirty days.

The perchlorate MCL rule proposed by CDHS DDWEM requested nine changes to Chapter 15, Division 4, Title 22 of the California Code of Regulations. The first amendment (to section 64413.1) reclassifies perchlorate-handling water systems by assigning perchlorate concentration point values. In California, facilities are given a classification, T1 through T5, depending on the number of influent contaminant level or source type points they have. The point value for any amount of perchlorate was zero prior to the new rule. Now, five points are added to facilities with perchlorate concentrations over the MCL. The second amendment (to section 64431) adds a perchlorate MCL to the list of maximum contaminant levels for inorganic compounds. The third amendment (to section 64432) updates monitoring requirements by specifying which water systems will be affected and includes perchlorate on the list of requirements with its reporting detection limit, 4 µg/L. The fourth amendment (addition of 64432.3) is the adoption of a new rule instructing facilities on perchlorate testing requirements and gives variances for facilities unable to afford compliance. Facilities must meet specific requirement to apply for a variance: PWS serving fewer than 10,000 persons with estimated annualized costs exceeding 1% of median household income in the community.

The fifth amendment (addition of 64432.8) is the adoption of a new section that requires monthly monitoring of treated water for perchlorate. The sixth amendment (to section 64447.2) adds perchlorate and its approved treatment options to the best available technology (BAT) table. The seventh amendment (repeal Article 17 and section 64450) takes away now obsolete deadlines for perchlorate when it was unregulated. The eighth amendment (to section 64465) changes health effect language to add perchlorate data. The ninth amendment (to section 64481) adds perchlorate origin data (CDHS, 2006). The regulation package has passed and became effective October 18, 2007.

Drinking Water Treatment Technology for Perchlorate Removal

The two categories of remediation are ion exchange and biological remediation. Of the two types of filtration, ion exchange is the only treatment currently being used by municipalities (Bull *et al.*, 2004). However, the CDHS (2006) also listed biological fluidized bed reactors among the approved remediation methods. Another type of biological remediation, heterotrophic biological reduction, is conditionally approved but not used on any potable water supplies. Most other treatment types are prohibitively expensive and have not been proven in field operations (Bull *et al.*, 2004). In 2004, the CDHS gave its approval to one method of perchlorate removal, ion exchange.

Ion exchange (IX) resin technologies have been in use since the 1950s (Tripp *et al.*, 2000). The key to ion exchange is the flow of water through a packed bed of synthetic IX resin. There are four different kinds of ion exchange removal mechanisms. The differences are related to the flow of the water current and the positioning of the

resin. Anions attach themselves to the resin and a bound chloride ion is released on the other side (Bull *et al.*, 2004). Tripp and Clifford (2000) found that a functional group's affinity for water on the resin can change its selectivity for perchlorate. The more hydrophobic a functional group is, the more perchlorate it can remove from solution. Each functional group contains a chloride that is released in exchange for the perchlorate ion (Tripp, 2000). Other ions including sulfate and nitrate are also caught in the resin functional groups (Kennedy/Jenks, 2004). Once all exchange sites have been saturated, the resin is exhausted. In the most popular type of filtration (conventional co-current, fixed bed ion exchange), the resin needs to be recharged by running a flow of saturated sodium chloride solution in the opposite direction of the original flow. This works because the chloride ions displace the perchlorate ions. The waste produced is a concentrated brine of perchlorate, sulfate and other anions. Disposing of this waste is the major drawback of this technology (Bull *et al.*, 2004).

A biological fluidized bed reactor (BFBR) is the only approved biological treatment method for perchlorate by the CDHS (2006). BFBRs use either sand or granular activated carbon (GAC) as the bed material. Sand is usually the preferred media for the fluidized bed due to GAC material loss through attrition from abrasion. Ethanol and methanol are used as electron donors for the reaction (Greene, *et al.*, 2000). The general reaction can be represented as:



During start-up the pH must be near neutral and the feed water is dosed with biological growth nutrients. The column is filled with sand or GAC and water fills the rest of the tube/tank (depending on the size of the unit). The perchlorate containing water is mixed

with ethanol, methanol, or a mixture of both and then fed into the bottom of the system. The water runs through the fluidized bed and is recycled or sent to a drain or feed container (Greene *et al.*, 2000).

As of 2004, heterotrophic biological reduction had conditional approval from the CDHS. Because it uses bacteria grown with an outside organic carbon source, this treatment creates more waste than the autotrophic bacteria treatment method. Both bacteria use enzymes that catalyze the reduction of perchlorate, using it as an electron sink. This process is very similar to the way other bacteria and animals respire. Heterotrophic bacteria are better suited for the process at present because they are able to catalyze the reaction at a faster rate. A column of sand or activated carbon houses the bacteria. Although this method has done well in test scenarios, no facilities are using this method to filter drinking water (Bull *et al.*, 2004). According to the CDHS (2006), other treatment methods besides biological fluid bed reactor (BFBR) have not been proven during field implementation. The main issue with this method becoming best available technology in the state of California is the potential for pathogenic bacteria to promulgate during the process (Bull, *et al.*, 2004)

Previous Cost Studies

There are two cost studies that were conducted to determine the economic impacts of different perchlorate MCLs in California. The CDHS (now CDPH) released a summary of their economic study as part of the Initial Statement of Reasons for the perchlorate rule package in July 2006. This study estimated costs to utilities vs. number of people exposed for each of three proposed MCLs (CDHS, 2006). The second study

was done for Kahl/Pownall Advocates, now KP Public Affairs, by Kennedy/Jenks Consultants, Inc. in June 2004. The Kennedy/Jenks study estimated costs that public water systems (PWS) would incur given three possible MCLs (Kennedy/Jenks, 2004).

The CDHS did the economic study as part of the requirement to make the MCL law. In the study, the CDHS looked at five possible MCLs beginning with $6\mu\text{g/L}$, the PHG set by COEHHA. The scope of the study includes PWSs from the entire state of California. The study first analyzes potential monitoring costs for MCL requirements. These costs are the same regardless of the MCL. The authors used single pass ion exchange as the remediation method of choice (CDHS, 2006). Of the two approved removal methods, ion exchange has lower capital costs, but the operations and maintenance costs are high due to resin regeneration and brine disposal. Costs notwithstanding, the biological fluid bed reactor requires further testing to prove the bacterium used in the process does not contain pathogens (CDHS, 2006). The study uses raw data to estimate all costs. Data from the CDHS study was also used to find the annualized cost of remediation per affected source using ion exchange. Costs were obtained from two large firms that deal with ion exchange systems. The method of testing was EPA 815-R-00-028, which is similar to the testing procedure used for arsenic. (McKibben, 2007). The estimated costs for individual systems were aggregated in order to estimate the total cost of remediation for small and for large systems. These cost estimates were summed to find total cost for all systems in California. The costs for sources are split into two groups, small and large water systems (CDHS, 2006). Small public water systems for the purposes of this study serve less than 200 connections (McKibben, 2007).

The Kennedy/Jenks study takes into account all costs that a PWS would incur to achieve compliance with a new perchlorate standard. This study showed cost of compliance for three MCLs. The costs of the impacts of each MCL were categorized and priced. Construction and land purchasing costs were included along with monitoring and technology upgrades. Because ion exchange resins not only remove perchlorate, but also background nitrate and sulfate in the water, the study also had to consider the decreased run length if these constituents are present. It provides cost differences due to perchlorate and background concentrations: low nitrate (10 mg/L), high nitrate (44 mg/L), low sulfate (30 mg/L), and high sulfate (180 mg/L). The study also assumes a fresh water source is available for blending calculations.

Methodology

This study provides a cost analysis for two different methods of meeting the new MCL standard. The drinking water treatment technology methodology unconditionally authorized by CDPH is ion exchange. The alternate method considered in this study is blending, which uses dilution with uncontaminated water to meet the MCL. The target for meeting the MCL is less than 6.5 µg/L due to data rounding. The analysis considers costs in three categories: capital costs, monitoring costs, and operations and management (O&M) costs. For the purpose of this study, each individual source stands alone. All costs were calculated for each source, no sharing of resources.

The following is an explanation of the cost calculations used to determine costs for each compliance method:

Total Cost (TC) is estimated for each well by

$$(1) TC = CC + CM + COM,$$

where

CC are capital costs that are upfront and non-reoccurring,

CM are monitoring costs, that are incurred on a quarterly basis, and

COM are annual operations and maintenance costs.

Capital costs are the costs to construct a treatment facility for each untreated source. For this study, I assume a treatment facility will be necessary for each well. All costs are incurred in the initial time period. Monitoring costs are incurred quarterly. They are aggregated to annual costs (4*quarterly costs, c_q), and are assumed to reoccur throughout the life of the project. Thus, total monitoring costs are estimated as

$$(2) CM = \sum_{t=1}^T 4c_{M,t},$$

where T is the life of the project in years. Operations and maintenance costs are incurred annually. Total operations and maintenance costs are estimated by

$$(3) COM = \sum_{t=1}^T c_{OM,t}.$$

Thus total, non-discounted costs are estimated by

$$(4) TC = CC_1 + \sum_{t=1}^T 4c_{M,t} + \sum_{t=1}^T c_{OM,t}.$$

The above cost equations are presented in current dollars. In addition constant and inflation adjusted dollar cost estimates are made. The constant dollar cost estimate discounts all future dollars back to the initial time period by

$$(5) TC = CC_1 + \sum_{t=1}^T \left(\frac{4c_{M,t}}{(1+d)^t} \right) + \sum_{t=1}^T \left(\frac{c_{OM,t}}{(1+d)^t} \right),$$

where d is the annual discount rate. Inflation adjusted costs are determined by

$$(6) TC_{INF} = CC_1 + \sum_{t=1}^T (4c_{M,t})(1+r)^t + \sum_{t=1}^T (c_{OM,t})(1+r)^t,$$

where r is the annual inflation rate.

For this analysis, the project life is assumed to be twenty years, so $T=20$, the annual discount factor used is 6.5%, so $d=.065$, and the annual inflation rate is assumed to be 2.45% per year, so $r=.0245$.

Capital Costs

To find capital costs, I estimated the total cost for constructing a new treatment facility for each source with an average perchlorate concentration of 6.5 $\mu\text{g/L}$ or greater. The design flow cases changed construction cost. For blending, there are two design flow cases, $\leq 1200\text{gpm}$ and $> 1200\text{gpm}$, that cost approximately \$164,000 and \$186,000, respectively. The design flow rates for ion exchange facility construction were $\leq 150\text{gpm}$, $\leq 300\text{gpm}$, $\leq 600\text{gpm}$, and $> 600\text{gpm}$, which cost approximately \$230,000, \$350,000, \$570,000, and \$670,000, respectively. These costs do not consider possible additional costs such as buying land, demolition, and cosmetic improvements.

Monitoring Costs

Monitoring costs were split into three categories, initial, routine, and quarterly. The average cost of a sample is \$88. The sources listed in this study have been monitored previously because of their “vulnerable” status, so they qualify for a reduced sampling frequency. Initial samples are not required because samples were collected under the unregulated chemical monitoring rule. The perchlorate concentration determines the frequency of sampling above or below the detectable level for reporting purposes (DLR), 4 $\mu\text{g/L}$. The DLR is also the effective detection level, so samples above

and below the DLR are considered detections or non detects, respectively. Samples that were below the DLR during the initial/previous monitoring are eligible for a routine monitoring schedule which consists of one sample every year for surface water sources and one sample every three years for ground water sources. Samples that were above the DLR during the initial/previous monitoring are required to follow quarterly monitoring schedule. If the samples consistently show the source is below the DLR for four consecutive quarters, the ground water source would be eligible for routine monitoring (CDHS, 2006). This project did not consider the possible source mobility between the two sampling strategies (quarterly vs. routine) for monitoring cost estimations. All the sources in this study were above the DLR and were listed with a quarterly sampling schedule and associated costs.

Operations and Maintenance Costs

Operations and maintenance (O&M) costs were estimated for each source and each type of compliance method. Assumptions that a separate perchlorate free water source was available for the blending operation and that single pass ion exchange resins costs increased by a constant value during the twenty-year lifetime of this cost estimate were used to give constant annualized costs for each source.

Translating the raw data into a useable format required further calculations. Raw data tables are located in Appendix B. Ratios were used to convert from acre-feet/day to gallons per minute and vice versa using: 1 acre ft/day = 226.285714736 gallon/minute. Acre-feet/year were found by multiplying acre-feet/day by 365. The total acre-feet for this year was calculated by the ratio:

$$(7) \frac{10}{12} = \frac{\sum Q_m}{Q_y}$$

where Q_m is monthly flow in acre-feet/month and Q_y is the calculated annual flow (acre-ft/year). The ratio, 10/12, comes from the data submitted from the municipalities. They sent flow data for each month in 2007 up to and including October.

Ion exchange resin replacement costs took background sulfate and nitrate as well as perchlorate concentration. Available data points were from the high and low ranges and a regression line showed the medium values. Pomona had a medium value for sulfate and Riverside had a medium value for nitrate. These graphs were repeated for each design flow rate. O&M Costs also fluctuated according to flow rate design case.

$$(8) \text{COM}_{RR1000S} = 1.0892 * [\text{ClO}_4^-] + 125.67$$

$$(9) \text{COM}_{RR600S} = 0.6481 * [\text{ClO}_4^-] + 75.31$$

$$(10) \text{COM}_{RR300S} = 0.3323 * [\text{ClO}_4^-] + 37.478$$

$$(11) \text{COM}_{RR1000N} = 1.4044 * [\text{ClO}_4^-] + 114.69$$

$$(12) \text{COM}_{RR600N} = 0.8342 * [\text{ClO}_4^-] + 68.918$$

$$(13) \text{COM}_{RR300N} = 0.4184 * [\text{ClO}_4^-] + 37.478$$

where the code in subscript is translated from RR1000S to Resin Replacement, 1000gpm design flow case, and 107 mg Sulfate level, and $[\text{ClO}_4^-]$ is perchlorate concentration.

Twenty-year O&M costs were found for three cases: constant dollars with a 6.5% discount rate, current dollars with a 0% discount rate, and inflation adjusted with a 2.45% inflation rate (USD, 2007).

Design flows were kept constant for the twenty-year period. Possible expansion or well shut down was not considered. Fresh water costs for blending facilities were calculated based on the amount of fresh water needed to dilute the perchlorate

concentration to 6.5 µg/L. If the utility has a source available of perchlorate-free water, the Kennedy/Jenks study estimated that pumping into the system to a pressure of 120 psig alone costs about \$60/acre-ft. The high estimate for purchasing water and pumping into the system is \$500/acre-ft. The average cost of perchlorate-free water and mixing it into the system was \$250/acre-ft (Kennedy/Jenks, 2004). For each acre-ft of water needing dilution, the amount of perchlorate-free water was calculated to bring the combined concentration under 6.5 µg/L by

$$(14) \text{ } COM_{Blending} = \left(\frac{[ClO_4^-]}{6.5} - 1 \right) * C_{Blending / acre-ft} * Q_y$$

State financial assistance is only available to small PWSs (<10,000 connections). Because PWSs in this study have more than 10,000 connections, neither qualifies for state aid.

Discussion of Data

California has 58 counties and had just over 37 million residents as of July 2006 (CDF, 2006). The U.S. Geological Survey (USGS, 2000) estimated the water usage for California at 51,172.91 million gallons per day (mgd) in 2000. Figure 1 (page 4) showed 90% of reported detections of perchlorate above 4 µg/L were found in Southern California (Bull, *et al.*, 2004). The seven counties in Southern California are Los Angeles, Orange, Riverside, San Bernardino, San Diego, Santa Barbara, and Ventura. Los Angeles and Riverside Counties were chosen for this study due to the number of contaminated sources of drinking water and the relatively high peak concentration values. The Cities of Pomona and Riverside both have drinking water sources that contain

concentrations of perchlorate higher than the 6 µg/L MCL. Also, these PWSs had the largest number of sources considered vulnerable by the CDHS in each chosen county.

Los Angeles County is 4,084 square miles and was incorporated in 1850. The county has a 75-mile coastline as well as the islands of Santa Catalina and San Clemente. The county population as of July 2006 was 10,292,723, nearly 28 percent of California's population. Although there are 88 incorporated cities in Los Angeles County, more than 65 percent of the county land is unincorporated. According to a 2005 estimate by Urban Research, the unincorporated area includes 1,095,592 residents (LACO, 2007). In 2000, the estimated water usage in Los Angeles County was 5,364.88 mgd (USGS, 2000). There were 9,332 samples taken from 56 water systems in the county over a 10 year period ending in March 2007. The Pomona Utility Services Department (Pomona USD) had 1,799 samples taken from sources within their system and 141 samples taken from imported water sources for a total of 1,940 samples (CDHS, 2005 and 2007, Pomona, 2007) The City of Pomona's population was estimated to be 161,850 by January 2006 (CDF, 2006). Pomona covers 22.84 square miles and owns the Pomona Division of Utility Services. The total city 2006-2007 fiscal year budgets for the general fund and capital improvements were \$87,766,477 and \$13,220,792, respectively. About 68% of Pomona's water comes from city-owned ground water wells. Some of the wells reach 1,000 ft into four aquifers, Chino, Pomona, Spadra, and Claremont Heights Basins. By 2008, construction on the anion exchange plant upgrade and expansion contract will be completed. Construction on new ion exchange plant serving a single well will begin when the plans are approved by the CDPH. The Metropolitan Water District of Southern California and Three Valleys Municipal Water District provide 28% of Pomona's water.

This water is treated by the delivering agency and comes from the Colorado River Aqueduct and the California State Water Project. The city also treats water from the San Antonio Canyon which accounts for 4% of their total supply (Pomona, 2007). The main source of perchlorate suspected in Pomona is Chilean fertilizer from the established agricultural legacy (Taylor, 2007). Current water well flow data for the vulnerable wells was provided by the Pomona Division of Utility Services and listed in Table 15 in Appendix B (Bolander, 2007).

Riverside County is 7,296 square miles and was incorporated in 1893. The California Department of Finance estimated the population in Riverside County at 1,953,330 in January 2006. All 24 incorporated cities are in the western half of the county. The estimated population in the unincorporated area of the county as of July 2006 is 1,437,511 residents (RCCDR, 2007). In 2000, the estimated water usage in Riverside County was 1,688.12 mgd (USGS, 2000). There were 3,534 samples taken from 15 water systems in the county over a 10-year period ending in March 2007. The Riverside Public Utilities (RPU) had 2,584 samples taken from sources within their system (CDHS, 2005 and 2007; Riverside, 2007). The City of Riverside's population was estimated to be 287,820 by January 2006 (CDF, 2006). Riverside takes up 77.7 square miles and owns Riverside Public Utility (RPU). The total city 2006-2007 fiscal year budget for public utilities, including administrative, electric, and water costs, was \$320,421,342. About 98% of Riverside's water comes from city-owned ground water wells. The 54 wells draw water from four basins, Bunker Hill, Colton, Arlington, and Riverside Basins. These wells produce an average of 67 to 118 million gallons per day (mgd). Four of the listed vulnerable sites in this study feed into treatment plants. The

other 2% is delivered by the Municipal Water District of Southern California (Riverside, 2007). Like Pomona, main source of perchlorate suspected in Riverside is Chilean fertilizer from the established agricultural legacy. RPU provided the current water well flow data, listed in Table 14 in Appendix B, for the vulnerable wells. (Monroe, 2007).

Data from the CPDH Water Quality Monitoring (WQM) database are available to the public upon request in the form of a CD (McKibben, 2007). The raw data were downloaded by Kennedy/Jenks from the WQM database in July 2003. Due to errors and inconsistencies in the data, the authors listed the nine data cases and charted the results. Two columns were used to find the case combinations: MOD and Finding. Basically, MOD describes any possible discrepancies in the data collected, whereas finding is the perchlorate value recorded. Examples of MOD values are <, 0, F, or blank. Any cases with F in the MOD column were discarded. Of the other seven cases, all but two were assigned 2 µg/L as their value. The other two cases were either assigned the value given if the value was above 4 µg/L or 2 µg/L if the value was less than 4 µg/L. These replacements were done on a case by case basis. Water sources' sampling frequencies varied from one to several samples taken for each month (Kennedy/Jenks, 2006). Also, under California's unregulated chemical monitoring requirements, only CDHS identified "vulnerable" sources were sampled (CDHS, 2006). The Kennedy/Jenks study used available data and took weighted averages against sampling frequency to find the perchlorate concentrations that were used in their cost study. The whole period of data was from 1 April 2002 to 30 June 2003. After calculations were complete, each source had one average perchlorate value (Kennedy/Jenks, 2004). These data were used in the analysis section for baseline concentrations in the two public water systems and are listed

in Appendix 2. For the purpose of calculating resin replacement frequency, nitrate and sulfate general values, high or low, were taken from PWS yearly consumer confidence / water quality reports. The specific cases provided in the Kennedy/Jenks paper give all the possible concentration combinations of high or low nitrate, sulfate, and perchlorate needed for the analysis. The source data used was for local PWS previously monitored wells. No imported or surface water sources were included in this analysis.

Analysis and Results

The numbering convention for well identification used in the data tables shows the system number followed by a dash and the well number. The system numbers are 1910126 for the City of Pomona Water Utility and 3310031 for the Riverside Public Utility wells. Information from these municipalities allowed an update of the inactive wells from the Kennedy/Jenks (2004) study. Because the possible number of combinations compliance methods available for the municipalities, estimates were found for a new treatment or blending facility for each untreated, noncompliant source. Even though the Kennedy/Jenks (2004) study states that blending is an unlikely choice for water containing perchlorate concentrations 25% or higher than the MCL ($< 7.5 \mu\text{g/L}$), this analysis compares costs of blending for all wells to cost of ion exchange. For this analysis, it is assumed that the project life is from 2007 to 2027.

The capital costs were estimated based on the type of treatment and the design flow rate. These costs were estimated per source as needed to make the perchlorate concentration less than $6.5 \mu\text{g/L}$. All sources currently averaging below the MCL did not incur capital costs. Two design flow cases were used for blending facility capital costs.

Wells with a flow rate ranging from 500 to 1,200 gallons per minute (gpm) incurred \$164,000 in capital costs, while wells with higher outputs had \$186,000. These estimates were listed in the Kennedy/Jenks paper and derived from their experience with nitrate blending. The capital costs that varied for IX facilities were the number of lead-lag trains, the number of vessels, and the vessels' diameter. The capital costs range from \$230,000 for the 150 gpm design case (1 lead-lag train, 2 vessels, 4 ft diameter) to \$3,300,000 for the 5,000 gpm design case (5 lead-lag trains, 10 vessels, 10 ft diameter). The combinations of these different factors change depending on the design flow rate and therefore change the cost. Capital costs for IX averaged almost four times the cost of new blending facilities in both municipalities. The total costs are shown in Table 3.

Total Construction Costs: Blending vs. Ion Exchange

System Number	System Name	Blending Construction Cost	IX Construction Costs
1910126	Pomona	\$1,804,000.00	\$6,970,000.00
3310031	Riverside	\$1,826,000.00	\$5,870,000.00

Table 3: Construction costs (capital investment) were calculated from data given in the Kennedy/Jenks (2004) paper. These costs show the costs if only one type of treatment was used and each source was equipped with a treatment plant.

Monitoring costs in this study were separated into three subgroups, initial, routine, and quarterly monitoring. Because all sources in the data set were considered “vulnerable” by the CDPH, they have prior data to draw from for categorization. Prior monitoring also exempts the sources from initial monitoring. Cost of initial monitoring was calculated as a savings in Table 4. The sources listed in this study have been monitored since 2001. Therefore, the start-up costs associated with initial monitoring do not apply and are considered savings. Further, all sources in this study showed detections

on their prior monitoring, so they are required to follow a quarterly monitoring schedule. Source information and quarterly monitoring costs for both Pomona and Riverside are detailed in Table 5 and 6. Routine monitoring would be used if any of the sources had samples with no detections for four consecutive quarters. Although treated wells must be monitored, they have no other costs associated with them. Table 7 compiled the monitoring costs and gives an annualized cost for each municipality. Costs for the twenty year life of this study were calculated for constant dollars, using a 6.5% discount rate, current dollars, using a 0% discount rate, and inflation adjusted, using a 2.45% inflation rate. The results are shown in Table 8. Because the monitoring results in this case are equal for all sources, these results reflect the number of wells in each municipality.

Cost Savings Due to Previously Collected Monitoring Data

System Number	System Name	Number of Sources	Initial Monitoring Cost / Source	Total Saved by Use of Previously Collected Data
1910126	Pomona	16	\$175.84	\$2,813.44
3310031	Riverside	20	\$175.84	\$3,516.80

Table 4: Data collected for the unregulated chemical monitoring protocol was approved to be used in lieu of initial monitoring (CDHS, 2006).

Annualized Costs for Monitoring Compliance for Riverside Wells

Well ID	System Name	Perchlorate (µg/L)	Current Status	Monitoring Frequency	Monitoring Cost per Year
3310031-027	Riverside	8.4	Active	quarterly	\$352.00
3310031-028	Riverside	6.1	Active	quarterly	\$352.00
3310031-029	Riverside	10.7	Active	quarterly	\$352.00
3310031-030	Riverside	9.4	Active	quarterly	\$352.00
3310031-031	Riverside	12.4	Treated	quarterly	\$352.00
3310031-032	Riverside	31.1	Treated	quarterly	\$352.00
3310031-034	Riverside	7.8	Active	quarterly	\$352.00
3310031-035	Riverside	15.5	Active	quarterly	\$352.00
3310031-036	Riverside	48.1	Treated	quarterly	\$352.00
3310031-038	Riverside	19.5	Active	quarterly	\$352.00
3310031-051	Riverside	7	Active	quarterly	\$352.00
3310031-052	Riverside	5.5	Active	quarterly	\$352.00
3310031-053	Riverside	6.8	Active	quarterly	\$352.00
3310031-067	Riverside	4.6	Active	quarterly	\$352.00
3310031-078	Riverside	10.3	Active	quarterly	\$352.00
3310031-080	Riverside	10.5	Active	quarterly	\$352.00
3310031-085	Riverside	10.3	Active	quarterly	\$352.00
3310031-093	Riverside	5.8	Active	quarterly	\$352.00
3310031-100	Riverside	4.6	Active	quarterly	\$352.00
3310031-111	Riverside	30.3	Treated	quarterly	\$352.00

Table 5: Required monitoring frequency and average cost of a sample was annualized in this table.

Annualized Costs for Monitoring Compliance for Pomona Wells

Well ID	System Name	Perchlorate (µg/L)	current status	Monitoring Frequency	Monitoring Cost per Year
1910126-049	Pomona	5.4	active	quarterly	\$352.00
1910126-003	Pomona	6	active	quarterly	\$352.00
1910126-026	Pomona	6	active	quarterly	\$352.00
1910126-051	Pomona	6.1	active	quarterly	\$352.00
1910126-010	Pomona	6.5	active	quarterly	\$352.00
1910126-023	Pomona	7.7	active	quarterly	\$352.00
1910126-014	Pomona	7.9	active	quarterly	\$352.00
1910126-015	Pomona	8.6	active	quarterly	\$352.00
1910126-004	Pomona	10.9	down	quarterly	\$0.00
1910126-006	Pomona	11.6	active	quarterly	\$352.00
1910126-018	Pomona	11.6	active	quarterly	\$352.00
1910126-017	Pomona	12.1	active	quarterly	\$352.00
1910126-011	Pomona	12.7	active	quarterly	\$352.00
1910126-012	Pomona	13.3	pulled	quarterly	\$0.00
1910126-016	Pomona	13.3	active	quarterly	\$352.00
1910126-052	Pomona	14.1	active	quarterly	\$352.00
1910126-054	Pomona	5.5	inactive	quarterly	\$0.00
1910126-050	Pomona	9.3	active	quarterly	\$352.00
1910126-007	Pomona	9.8	active	quarterly	\$352.00

Table 6: Required monitoring frequency and average cost of a sample was annualized in this table.

Annualized Costs for Monitoring Compliance

System Number	System Name	Number of Sources	Cost per Sample	Annualized Source Monitoring Costs
1910126	Pomona	16	\$88.00	\$5,632.00
3310031	Riverside	20	\$88.00	\$6,336.00

Table 7: The calculations in this table assume that the cost per sample will remain constant and the rules of routine and quarterly samples will remain constant.

Total Monitoring Costs for Twenty-Year Period

System Number	System Name	Constant Dollars	Current Dollars	Inflation Adjusted
1910126	Pomona	\$66,089.89	\$112,640.00	\$143,145.63
3310031	Riverside	\$74,351.12	\$126,720.00	\$161,038.83

Table 8: The discount rate used in the calculations was 6.5% for constant dollars, 0% for current dollars, and 2.45% for inflation adjusted.

Operations and Management (O&M) Costs had the most variations of the three cost categories in this study. The blending option dealt with an assumed supply of fresh water. The average cost of electricity to move the water through the blending station and the water itself was \$250/acre-ft. For each acre-ft of water needing dilution, the amount of fresh water was calculated to bring the combined concentration under 6.5 µg/L. IX resin replacement costs as well as electricity, repairs, and other costs were annualized after calculations for background chemicals were done.

Calculations for resin replacement costs for single pass IX, meaning the resin is replaced and not regenerated, used regression lines to find average data points between two sets of extreme cases. The Kennedy/Jenks (2004) study shows IX resin replacement costs for high (180 mg/L) and low (30 mg/L) sulfate levels. Figures 7, 8, and 9 show the prices for three design flow rates at different levels of perchlorate at 105 mg/L sulfate. The calculation was necessary to find costs at the sulfate level in Pomona which averages 107 mg/L (Pomona, 2007). The Kennedy/Jenks (2004) study shows IX resin replacement costs at high (44 mg/L) and low (10 mg/L) nitrate levels. Figures 4, 5, and 6 show the prices for three different design flow rates at different levels of perchlorate at 27 mg/L nitrate. The calculation was necessary to find costs at the sulfate level in Riverside which averages 23 mg/L (Riverside, 2007). The equations were used to find cost of resin replacement according to perchlorate level, design flow rate, and sulfate/nitrate concentration.

Average O&M cost is shown for both municipalities and compliance methods in Table 9. The average cost of fresh water blending at \$250/acre-ft was almost double the resin replacement cost for IX. In the \$60/acre-ft case, the average cost is about one third

of the resin replacement cost. Annualized costs are shown in Table 10. As with monitoring costs, the O&M costs for the twenty-year life of this study were calculated for constant dollars, using a 6.5% discount rate, current dollars, using a 0% discount rate, and inflation adjusted, using a 2.45% inflation rate. The twenty-year period results are shown in Table 11. The blending O&M costs are higher than IX in one third of cases in Table 9 and half of cases in Tables 10 and 11. If the municipality is able to provide the perchlorate-free water for the blending operation, the costs are about one fifth the IX total cost over 20 years. The \$250/acre-ft blending case is about even with IX and the \$500/acre-ft case costs are twice the IX costs.

Average Cost of Compliance per Acre-ft

System Name	Number of Sources	Nitrate	Sulfate	Avg Fresh Water Cost for Blending per acre-ft (\$60/acre-ft)	Avg Fresh Water Cost for Blending per acre-ft (\$250/acre-ft)	Avg Fresh Water Cost for Blending per acre-ft (\$500/acre-ft)	Avg IX Resin Replacement Cost (\$/acre-ft)
Pomona	16	low	medium	\$28.37	\$118.22	\$236.44	\$64.37
Riverside	16	medium	low	\$25.79	\$107.45	\$214.90	\$63.35

Table 9: This table shows average perchlorate compliance costs per acre-ft for the two remediation methods. The number of sources depends on the status of the inactive sources.

Annualized O&M Costs of Compliance

System Name	Total Estimated Well Flow (gpm)	Estimated Annualized Flow (acre-ft/yr)	Annualized Blending Cost (water = \$60/acre-ft)	Annualized Blending Cost (water = \$250/acre-ft)	Annualized Blending Cost (water = \$500/acre-ft)	Annualized IX Cost (\$)
Pomona	11620	10409.6	\$300,911.71	\$1,253,798.81	\$2,507,597.62	\$1,349,440.95
Riverside	19726	31818.6	\$517,987.66	\$2,158,281.92	\$4,316,563.85	\$1,951,523.77

Table 10: The table shows estimated annualized water usage in Pomona and Riverside with annualized costs for the two compliance methods.

20 Year O&M Costs for Blending and Ion Exchange

Blending (\$60/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$3,531,111.77	\$6,018,234.29	\$7,648,117.14
Riverside	\$6,078,435.10	\$10,359,753.23	\$13,165,424.01

Blending (\$250/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$14,712,965.72	\$25,075,976.22	\$31,867,154.74
Riverside	\$25,326,812.94	\$43,165,638.46	\$54,855,933.37

Blending (\$500/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$29,425,931.43	\$50,151,952.43	\$63,734,309.49
Riverside	\$50,653,625.87	\$86,331,276.92	\$109,711,866.74

Ion Exchange			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$15,835,299.00	\$26,988,819.00	\$34,298,041.40
Riverside	\$22,900,566.00	\$39,030,475.40	\$49,600,868.50

Table 11: This set of tables compares costs of the two compliance methods over a twenty year period.

Total Cost of Construction, Monitoring, and O&M Over 20 Years for Each Compliance Method

Blending (\$60/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$5,401,201.66	\$7,934,874.29	\$9,595,262.77
Riverside	\$7,978,786.22	\$12,312,473.23	\$15,152,462.84

Blending (\$250/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$16,583,055.61	\$26,992,616.22	\$33,814,300.37
Riverside	\$27,227,164.06	\$45,118,358.46	\$56,842,972.20

Blending (\$500/acre-ft)			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$31,296,021.32	\$52,068,592.43	\$65,681,455.12
Riverside	\$52,553,976.99	\$88,283,996.92	\$111,698,905.57

Ion Exchange			
System Name	Present Value	Constant Cost	Inflation Adjusted
Pomona	\$22,871,388.89	\$34,071,459.00	\$41,411,187.03
Riverside	\$28,844,917.12	\$45,027,195.40	\$55,631,907.33

Table 12: This table shows 20 year estimated costs for both blending and ion exchange.

Total cost combined the capital, monitoring, and O&M costs for current dollars, constant dollars, and inflation adjusted. The results are listed in Table 12. The total costs over the twenty-year period show that IX takes more investment in the beginning, but the low O&M costs eventually make a difference when compared to blending. Table 13 and 14 show cost differences per capita for the improvements compared in this study.

Estimated Total Cost per Capita for Treatment over 20 Years

		Estimated Total Blending Cost Per Person (\$60/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$33.37	\$49.03	\$59.28
Riverside	287,820	\$27.72	\$42.78	\$52.65

		Estimated Total Blending Cost Per Person (\$250/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$102.46	\$166.78	\$208.92
Riverside	287,820	\$94.60	\$156.76	\$197.49

		Estimated Total Blending Cost Per Person (\$500/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$193.36	\$321.71	\$405.82
Riverside	287,820	\$182.59	\$306.73	\$388.09

		Estimated IX Total Cost Per Person		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$141.31	\$210.51	\$255.86
Riverside	287,820	\$100.22	\$156.44	\$193.29

Table 13: Estimated 20 year costs per capita

Estimated Monthly Cost per Capita for Treatment over 20 Years

		Estimated Monthly Blending Cost Per Person (\$60/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$0.14	\$0.20	\$0.25
Riverside	287,820	\$0.12	\$0.18	\$0.22

		Estimated Monthly Blending Cost Per Person (\$250/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$0.43	\$0.69	\$0.87
Riverside	287,820	\$0.39	\$0.65	\$0.82

		Estimated Monthly Blending Cost Per Person (\$500/acre-ft)		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$0.81	\$1.34	\$1.69
Riverside	287,820	\$0.76	\$1.28	\$1.62

		Estimated Monthly IX Cost Per Person		
	Population	Present Value	Constant Cost	Inflation Adjusted
Pomona	161,850	\$0.59	\$0.88	\$1.07
Riverside	287,820	\$0.42	\$0.65	\$0.81

Table 14: Estimated 20 year costs per capita per month

Conclusion

The California MCL was set at 6 µg/L on October 19, 2007. Depending on variables beyond the scope of this study like major technological innovations or updated health information about perchlorate, there are many factors involved in deciding the most appropriate method of compliance. From the standpoint of costs over a twenty-year period, ion exchange is clearly the less expensive option. The drawback is its higher initial cost. However, it does more than recoup that price in a short amount of time. Although the total cost of using city-owned perchlorate-free water at \$60/acre-ft is about one-fifth of total ion exchange costs, municipalities are not likely to use blending for water

that is greater than 25% above the MCL. This may prompt municipalities to use water treated with ion exchange to blend water that has perchlorate levels under 7.5 µg/L. In the long run IX is the better option if a municipality were to choose one compliance method due to its low operations and maintenance costs and no need to have a constant source of fresh water.

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Appendix A: Abbreviations and Acronyms

Throughout this paper, I have used the following acronyms and abbreviations.

California Department of Finance (CDF)

California Department of Health Services (CDHS)

California Department of Public Health (CDPH)

California Office of Environmental Health Hazard Assessment (COEHHA)

Department of Defense (DoD)

Division of Drinking Water and Environmental Management (DDWEM)

Drinking Water Contaminant Candidate List (CCL)

Drinking Water Equivalent Level (DWEL)

Gallons per Minute (gpm)

Massachusetts Department of Environmental Protection (MassDEP)

Maximum Contaminant Level (MCL)

Million gallons per day (mgd)

National Academy of Science (NAS)

Public Health Goal (PHG)

Public Water System (PWS)

Reference Dose (RfD)

Safe Drinking Water Act (SDWA)

U.S. Environmental Protection Agency (EPA)

U.S. Geological Survey (USGS)

Appendix B: IX Resin Replacement Cost Regression

Linear Regression of Price vs. Perchlorate Level:
1,000 gpm Design Flow Rate and Medium Nitrate Level

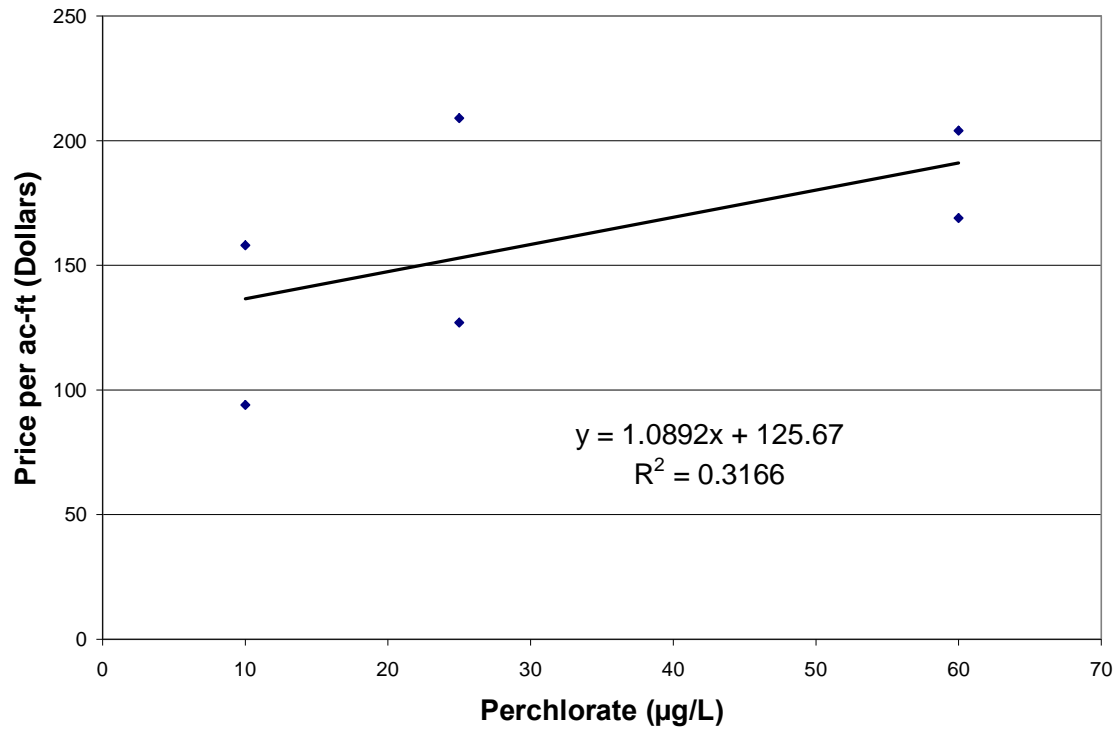


Figure 5: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 105 mg/L sulfate for a 1,000 gpm design flow rate.

Linear Regression of Price vs. Perchlorate Level:
600 gpm Design Flow Rate and Medium Nitrate Level

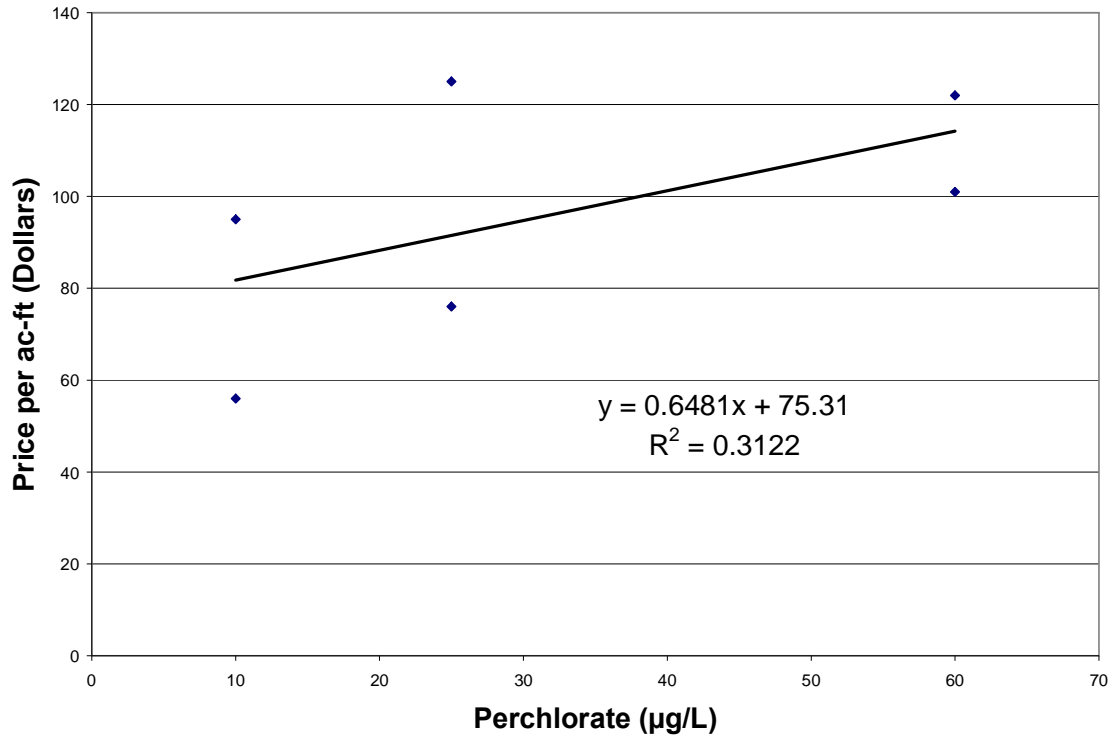


Figure 6: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 105 mg/L sulfate for a 600 gpm design flow rate.

Linear Regression of Price vs. Perchlorate Level:
300 gpm Design Flow Rate and Medium Nitrate Level

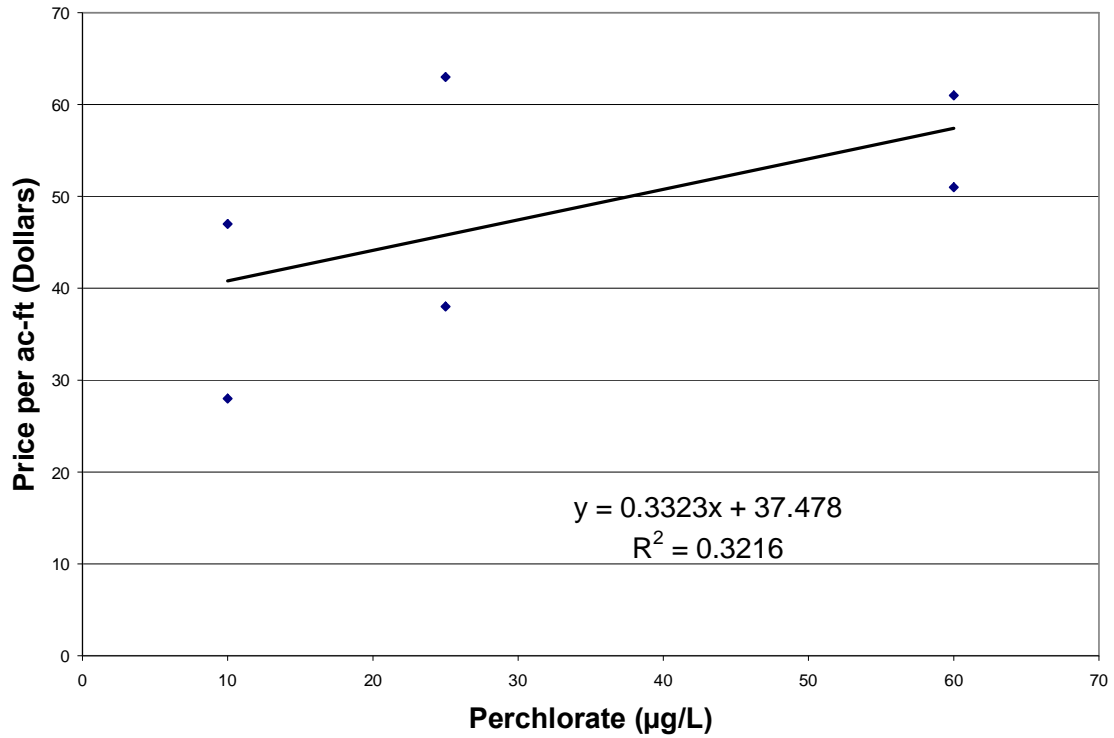


Figure 7: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 105 mg/L sulfate for a 300 gpm design flow rate.

Linear Regression of Price vs. Perchlorate Level:
1,000 gpm Design Flow Rate and Medium Sulfate Level

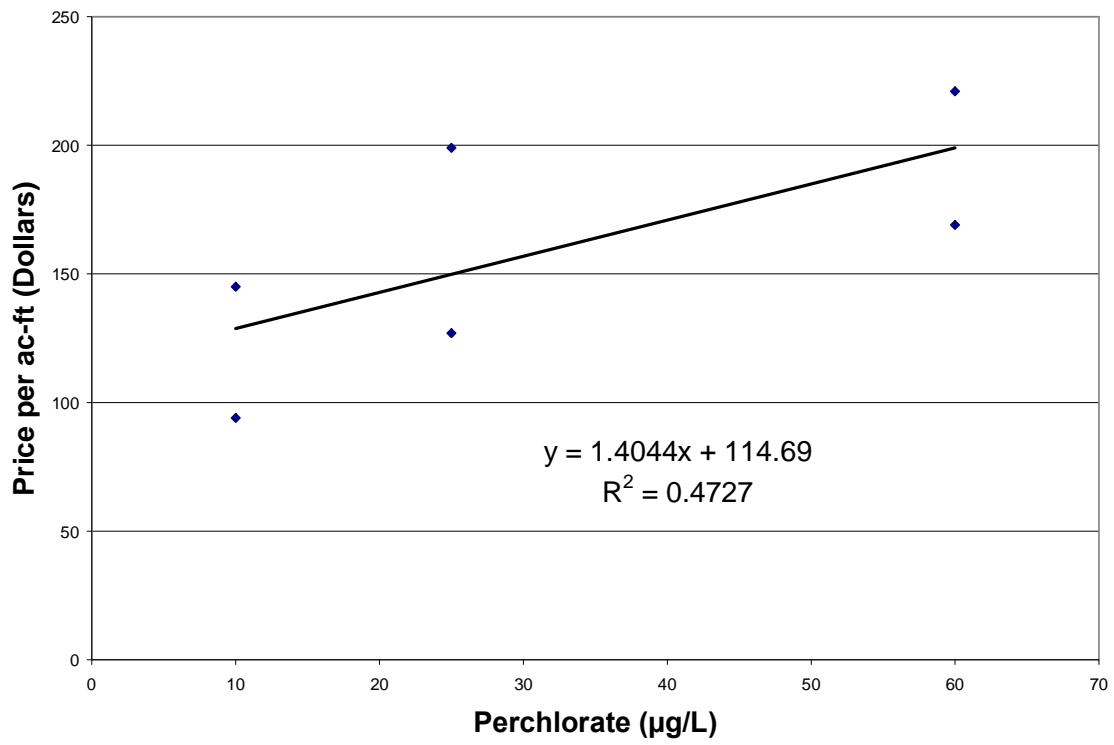


Figure 8: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 27 mg/L nitrate for a 1,000 gpm design flow rate.

Linear Regression of Price vs. Perchlorate Level:
600 gpm Design Flow Rate and Medium Sulfate Level

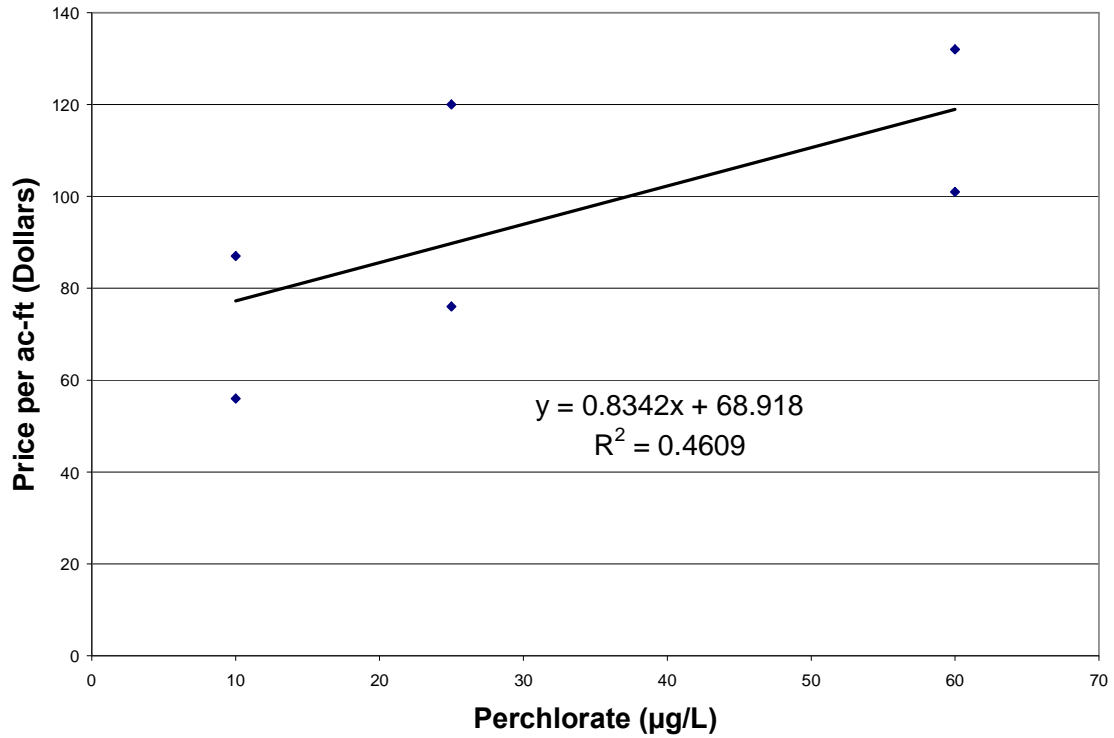


Figure 9: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 27 mg/L nitrate for a 600 gpm design flow rate.

Linear Regression of Price vs. Perchlorate Level:
300 gpm Design Flow Rate and Medium Sulfate Level

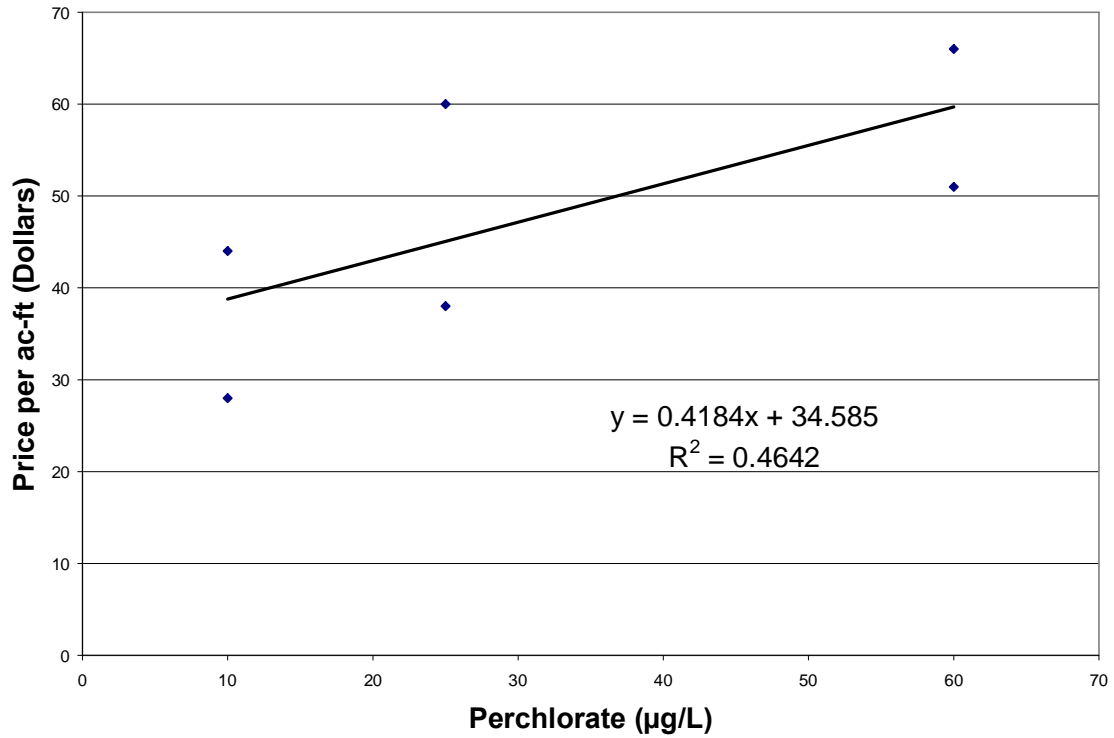


Figure 10: The regression line in this figure shows the price of IX resin replacement per acre-ft including labor and disposal at 27 mg/L nitrate for a 300 gpm design flow rate.

Appendix C: Perchlorate Concentration Data

The data in the following tables were used to find cost estimates for 6µg/L MCL compliance.

City of Pomona Water Department Weighted Average Water Data

Well ID	Source Name	County	System Name	Perchlorate (µg/L)	Current Status
1910126-049	well 5B	Los Angeles	Pomona - City Water Dept	5.4	Active
1910126-026	well 26	Los Angeles	Pomona - City Water Dept	6	Active
1910126-003	well 3	Los Angeles	Pomona - City Water Dept	6	Active
1910126-051	well 9B	Los Angeles	Pomona - City Water Dept	6.1	Active
1910126-010	well 10	Los Angeles	Pomona - City Water Dept	6.5	Active
1910126-023	well 23	Los Angeles	Pomona - City Water Dept	7.7	Active
1910126-014	well 14	Los Angeles	Pomona - City Water Dept	7.9	Active
1910126-015	well 15	Los Angeles	Pomona - City Water Dept	8.6	Active
1910126-004	well 4	Los Angeles	Pomona - City Water Dept	10.9	Active
1910126-018	well 18	Los Angeles	Pomona - City Water Dept	11.6	Active
1910126-006	well 6	Los Angeles	Pomona - City Water Dept	11.6	Active
1910126-017	well 17	Los Angeles	Pomona - City Water Dept	12.1	Active
1910126-011	well 11	Los Angeles	Pomona - City Water Dept	12.7	Active
1910126-012	well 12	Los Angeles	Pomona - City Water Dept	13.3	Active
1910126-016	well 16	Los Angeles	Pomona - City Water Dept	13.3	Active
1910126-052	well 34	Los Angeles	Pomona - City Water Dept	14.1	Active
1910126-054	well 01B	Los Angeles	Pomona - City Water Dept	5.5	Inactive
1910126-050	well 8B	Los Angeles	Pomona - City Water Dept	9.3	Inactive
1910126-007	well 7	Los Angeles	Pomona - City Water Dept	9.8	Inactive

Table 15: Averaged values of perchlorate are listed for each source over a 5 quarter sampling period (Kennedy/Jenks, 2004).

City of Riverside Public Utilities Weighted Average Water Data

Well ID	Source Name	County	System Name	Perchlorate (µg/L)	Current Status
3310031-100	warren well 1	Riverside	Riverside - City of	4.6	Active
3310031-052	hunt well 10	Riverside	Riverside - City of	5.5	Active
3310031-028	gw 27-1	Riverside	Riverside - City of	6.1	Active
3310031-083	scheuer	Riverside	Riverside - City of	6.1	Active
3310031-053	hunt well 11	Riverside	Riverside - City of	6.8	Active
3310031-051	hunt well 6	Riverside	Riverside - City of	7	Active
3310031-074	palmyrita well 2	Riverside	Riverside - City of	7	Active
3310031-034	gw 31-1	Riverside	Riverside - City of	7.8	Active
3310031-027	gage well 26-1	Riverside	Riverside - City of	8.4	Active
3310031-030	gw 29-1	Riverside	Riverside - City of	9.4	Active
3310031-078	raub well 2	Riverside	Riverside - City of	10.3	Active
3310031-085	stiles	Riverside	Riverside - City of	10.3	Active
3310031-080	raub well 4	Riverside	Riverside - City of	10.5	Active
3310031-029	gw 27-2	Riverside	Riverside - City of	10.7	Active
3310031-043	garner well 2	Riverside	Riverside - City of	11.7	Active
3310031-035	gw 46-1	Riverside	Riverside - City of	15.5	Active
3310031-038	gw 66-1	Riverside	Riverside - City of	19.5	Active
3310031-067	moore griffith	Riverside	Riverside - City of	4.6	Inactive
3310031-003	army well 3	Riverside	Riverside - City of	5.5	Inactive
3310031-093	twin springs	Riverside	Riverside - City of	5.8	Inactive
3310031-002	army well 1	Riverside	Riverside - City of	7.6	Inactive
3310031-056	Iselin well 2	Riverside	Riverside - City of	8.8	Inactive
3310031-019	fill well	Riverside	Riverside - City of	13	Inactive
3310031-016	11th st well	Riverside	Riverside - City of	15.5	Inactive
3310031-031	gw 29-2	Riverside	Riverside - City of	12.4	Treated
3310031-111	gw 92-1	Riverside	Riverside - City of	30.3	Treated
3310031-032	gw 29-3	Riverside	Riverside - City of	31.1	Treated
3310031-036	gw 51-1	Riverside	Riverside - City of	48.1	Treated

Table 16: Averaged values of perchlorate are listed for each source over a 5 quarter sampling period (Kennedy/Jenks, 2004)

Data from the City of Pomona

source name	current status	gpm	y t d ac ft	y t d run time hrs	comments
well 5b	active	825	22.5	138	
well 26	active	665	752.2	6497	
well 3	active	570	627.2	5913	
well 9b	active	380	47.6	1160	
well 10	active	940	1189.5	6468	
well 23	active	915	504.5	3440	
well 14	active	580	412.0	3935	
well 15	active	590	432.9	3897	
well 4	down	na	0	0	not run since 4/'02 low output
well 18	active	725	125.1	1001	
well 6	active	900	423.5	2757	
well 17	active	610	383.6	3741	
well 11	active	515	10.4	132	
well 12	pulled	na	0	0	no production since 6/'04
well 16	active	860	684.5	4206	
well 34	active	1105	1361.0	6473	
well 1b	inactive	na	0	0	
well 8b	active	900	1076.9	6201	active since 10/'04
well 7	active	540	621.4	6151	active since 10/'05
gpm, acft,and runtimes are for calendar year 2007 through September.					

Table 17: Well flow data sent via email by the City of Pomona (Bolander, 2007)

Name	No.	Jan-07	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	TOTAL
GAGE 26-1 WELL	6508	208.07	122.91	218.89	213.31	191.60	245.20	235.06	208.33	201.10	1844.47
GARNER NO.2 WELL	2132	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GAGE 27-1 WELL	6509	292.29	228.80	0.00	200.53	300.83	300.77	288.79	282.35	251.67	2146.03
GAGE 27-2 WELL	6511	41.71	0.00	213.52	56.26	152.52	244.50	251.50	251.34	133.91	1345.26
GAGE 29-1 WELL	6512	74.61	8.63	202.95	83.86	179.94	253.00	259.05	245.16	188.14	1495.34
GAGE 29-2 WELL	6506	62.32	0.00	28.03	14.34	360.54	205.45	353.99	366.78	351.24	1742.69
GAGE 29-3 WELL	6505	254.84	237.72	46.65	274.09	271.90	250.75	240.28	245.43	213.75	2035.41
GAGE 31-1 WELL	6502	245.58	85.09	120.56	15.74	8.39	154.90	243.23	234.22	170.78	1278.49
GAGE 46-1 WELL	6501	203.89	186.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	390.12
GAGE 51-1 WELL	6507	0.00	103.69	62.28	174.26	213.62	206.05	202.93	204.50	198.11	1365.44
GAGE 66-1 WELL	6510	0.00	0.00	204.77	215.87	194.44	224.01	239.44	152.77	235.30	1466.60
GAGE 92-1 WELL	6317	308.20	289.67	302.93	277.70	281.41	265.70	254.95	269.41	256.71	2506.68
HUNT NO.10 WELL	2242	5.51	0.00	40.22	2.49	16.73	54.00	50.69	56.85	20.48	246.97
HUNT NO.11 WELL	2243	2.86	0.00	14.76	0.00	10.96	35.62	33.98	0.00	0.00	98.18
HUNT NO.6 WELL	2241	2.29	0.00	13.25	0.00	13.17	50.54	64.58	68.50	22.36	234.69
MOORE-GRIFFITH WELL	1231	153.55	146.20	149.85	150.77	149.27	151.52	150.89	146.26	138.75	1337.06
RAUB NO.2 WELL	2211	12.50	47.64	43.33	35.75	33.93	26.13	26.77	41.10	26.63	293.78
RAUB NO.4 WELL	2213	198.52	181.55	183.17	169.49	168.80	151.49	156.43	155.45	76.78	1441.68
SCHEUER WELL	2121	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
STILES WELL	2101	49.68	55.68	57.79	59.66	61.65	59.66	61.65	61.65	59.66	527.08
TWIN SPRINGS WELL	1221	383.58	344.66	383.58	371.21	383.58	358.84	383.58	383.58	358.84	3351.45
WARREN NO.1 WELL	2231	81.58	0.00	92.65	131.52	180.12	238.36	228.33	251.05	164.49	1368.10

Table 18: Data sent from Riverside Public Utilities (Monroe, 2007)