A WATER SUPPLY OPTIMIZATION STRATEGY

Santa Ynez River Water Conservation District, Improvement District No. 1

BREN SCHOOL OF
ENVIRONMENTAL SCIENCE & MANAGEMENT
UNIVERSITY OF CALIFORNIA SANTA BARBARA

A 2013 Master's Thesis Group Project

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DEVELOPING A WATER SUPPLY OPTIMIZATION STRATEGY FOR THE SANTA YNEZ RIVER WATER CONSERVATION DISTRICT, IMPROVEMENT DISTRICT NO. 1

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The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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April 2013

Abstract

Hexavalent chromium (Cr(VI)) is a carcinogenic contaminant that can be found in drinking water sources world-wide, occurring from both natural and anthropogenic sources. In 2011, the State of California Office of Environmental Health Hazard Assessment (OEHHA) set a new public health goal (PHG) for Cr(VI) at 0.02 parts per billion (ppb) in drinking water (Brown et al 2011). Though a maximum contaminant level (MCL) currently exists for total chromium (Cr(III) + Cr(VI)) in California, in response to the PHG, the California Department of Public Health (CDPH) is expected to announce a draft MCL for Cr(VI) in July 2013. The proposed standard will potentially have financial and strategic impacts on water purveyors throughout the state – particularly small districts. One such district is the Santa Ynez River Water Conservation District, Improvement District No. 1, located in Santa Barbara County, California, which has recently tested positive for trace levels of hexavalent chromium in one of its four drinking water sources. Given the possible reduction in supply, this project developed a model that optimizes the District's monthly system reliability, defined as the ratio of total system capacity to monthly demand. Though meeting demand is key, a reliability of 1.0 is not ideal because it does not enable the District to adapt to unforeseen circumstances and provides little flexibility in the management of water sources. Analysis of the system under very dry climatic conditions with the current *total* chromium MCL was used to determine a baseline threshold of reliability. After establishing this level, the model was used to simulate the impacts of potential options to address the decrease in system reliability as a result of the loss in supply under various climate and hypothetical Cr(VI) MCL scenarios. Results show that under a very dry climate and/or a strict Cr(VI) MCL meeting the desirable threshold of reliability is not feasible even with a large investment in different management options. This research and analysis further suggests that though reliability and resilience (the system's ability to respond to sudden changes) are impacted by potential future regulations, they may be increased through both supply and demand-side management actions.

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Executive Summary

Chromium is a transition metal element derived from both geologic and anthropogenic sources. In the aqueous phase, chromium, which has two preferred oxidation states – hexavalent and trivalent – is federally regulated as *total* chromium. High levels of total chromium (defined as the sum of the concentrations of both oxidation states present in a water sample) have been measured in groundwater in California, Mexico, the Mediterranean, and the South Pacific. Concentrations of hexavalent chromium in some areas of California have been found to exceed the standard set by the California Department of Public Health (CDPH): 50 parts per billion (ppb). Recent media exposure has raised concern over the presence of hexavalent chromium (Cr(VI)) in municipal drinking water. Hexavalent chromium is classified as a known human carcinogen, and studies suggest that risks to human health may be increased above baseline levels when the metal is consumed at low levels over long periods of time.

In 2011, the State of California Office of Environmental Health Hazard Assessment (OEHHA) set a new public health goal (PHG) for hexavalent chromium (Cr(VI)) at 0.02 parts per billion (ppb) in drinking water. While a public health goal represents the concentration of a substance that will pose “no significant health risks” if consumed at that level for the entirety of a human life, establishing the regulatory maximum contaminant level (MCL) allowed in drinking water must take the economic feasibility of treating water to a given proposed standard into consideration. Thus, the PHG is often much lower than the MCL. Though an MCL currently exists for total chromium in California, in response to the PHG, the CDPH is expected to announce a draft MCL for Cr(VI) in July 2013. The proposed standard will potentially have financial and strategic impacts on water purveyors throughout the state – particularly small districts. One such district is the Santa Ynez River Water Conservation District, Improvement District No. 1 (ID1 or “the District”), located in Santa Barbara County, California, which has recently tested positive for trace levels of hexavalent chromium in one of its water sources.

As a result of the impending regulation, ID1 managers asked us to analyze and provide suggestions on the District’s water distribution system to enable them to adapt to unforeseen circumstances and future regulations. As such, the objective of this project was to develop an updated and viable water optimization supply plan that optimizes for system reliability, defined as the ratio of capacity, the total amount of water available to the district, to demand. A reliability of 1.0 indicates the point at which supply is exactly equal to projected demand. In ID1’s case, this would not represent desirable conditions because there is no flexibility to adapt to future sudden changes in the system. Instead, we established a threshold for reliability by modeling the current state of the District’s supply and demand based on the assumption that, at this point, they have not taken actions to increase reliability in light of forthcoming Cr(VI) regulation.

To model reliability, data must be input for the water supply and demand of the District. The District’s unique water supply portfolio – which includes multiple sources of water – provides some flexibility in the supply. Approximately 50% of the water used by ID1 in a given year is supplied by the State Water Project (SWP) with the remaining 50% split evenly between alluvial wells and upland wells. The percentage of the state water allotment available to ID1 varies annually based on climate conditions and the winter snowpack of the Sierra Nevada Mountains of Northern California. Alluvial wells draw water from the underflow of the Santa Ynez River at the Southern boundary of the District, while upland wells draw from the local groundwater basin. The only source that currently contains trace amounts of chromium is the upland wells, though all measured concentrations are below the current total chromium MCL of 50 ppb.

Demand for water in ID1 is split evenly between residential and agricultural users and is higher in the summer months. Data from the period January 1998 – September 2012 were used to calculate the mean monthly demand used in this project.

Using this supply and demand data, we created a model for ID1 designed to simulate system reliability under three climate conditions (average, dry, very dry – which serve as a proxy for SWP availability) and four potential Cr(VI) MCLs (0.02, 10, 20, 50 ppb – which impact the amount of upland well water available) giving a total of 12 different model scenarios. If the amount of total chromium measured in a specific well has ever been above the MCL used in that scenario, no water from that well was used for that scenario. The model optimized the delivery from each water source on a monthly basis over a year-long time frame with the goal of maximizing the minimum monthly reliability.

Because the 50 ppb MCL represents current regulatory conditions, the three scenarios run with this MCL were used to establish a threshold for baseline reliability. Out of these scenarios, the reliability in a very dry year was chosen to represent the minimum acceptable reliability to ID1: 1.69. To date, District managers have not implemented operational changes, suggesting this level achieves an acceptable margin of safety above anticipated demand. The resulting reliability of the remaining nine climate-MCL simulations fall below this threshold, indicating that in the event of a more restrictive MCL ID1 managers would need to take action to increase reliability.

Direct treatment of Cr(VI) is an expensive operation that requires both a significant capital investment and regular system maintenance. Because the District lacks a centralized treatment and distribution facility, treating Cr(VI) would require an extensive construction project to link several wells in order to be most effective. An appropriately-sized treatment system for ID1 would likely cost between $4 million and $8 million. In addition, once the system is in use, a comprehensive waste management plan will also need to be implemented to address the resulting toxic waste generated from Cr(VI) treatment.

For this reason, we first examined a number of non-treatment options that would serve to either increase supply or decrease demand. These options could allow the District to maintain the desired reliability at a lower cost. Out of a number of possible non-treatment options, we chose to model the four that we felt were most realistic for the District to implement: purchasing additional water, fixing broken alluvial wells, and the adoption of two different levels of water conservation practices. These measures are described in detail below:

- ***Water Purchase***: Due to the relatively inexpensive nature of water purchasing, we implemented this measure first to increase total reliability. The SWP has multiple methods for purchasing water, including Article 21 water and Turnback Pool water. A limited amount of water may be available to ID1 in any given year depending on the climate conditions, with costs ranging from $1,275 to $6,375.

- ***Alluvial Well Repair***: Though ID1 is licensed to use two separate alluvial well fields, damages from past flooding events have taken one of these two fields offline. Repairing infrastructure at these alluvial wells would be a significant undertaking, with a preliminary estimated cost of $75,000 in addition to permitting, with extensive engagement of regulators and stakeholders.

- ***Water Conservation***: We selected two scenarios to reflect the changes in demand that can result from implementing different conservation measures at ID1. The District supplies 50% of its water to residential customers and very little conservation is currently practiced, providing a tremendous opportunity for water savings. We chose two values – 5 and 10 percent – to reflect what can reasonably be achieved with two conservation strategies: low-flow fixtures and Xeriscaping. The investment required for these programs was estimated at $460,000 for a 5% reduction in demand and $2.4 million for a 10% reduction.

If the reliability threshold had still not been met after these measures, we then considered treating wells affected by Cr(VI) with a cluster system setup. The management actions were applied to each original scenario that fell below the 1.69 threshold in a step-wise manner, beginning with the most feasible and relatively economical short-term solution and ending with the most cost-intensive long-term solution. As soon as a scenario reached a minimum reliability of 1.69, no additional measures were applied.

The remaining nine scenarios were grouped based on climate condition before additional management measures were applied. In an average climate condition with an MCL of 20 ppb, ID1 would be able to meet the 1.69 threshold after repairing the broken alluvial well field. At an MCL of 10 ppb, the threshold is reached after installing the cluster treatment system. This is also the case for dry climate conditions at an MCL of 20 ppb. The remaining scenarios in these climates were unable to reach the threshold even after all modeled management options were implemented.

Because reliability levels are very low under the very dry climate condition, a second metric of meeting demand (represented by a reliability of 1) was used for analysis of these three scenarios. While we recognize that this is not an ideal level of reliability for ID1, it does represent an important management objective, especially when faced with serious supply constraints. While ID1 would be able to meet demand at an MCL of 20 ppb in a very dry climate, it is never able to reach the reliability threshold. At both an MCL of 10 ppb and 0.02 ppb, reliability does not exceed demand until installing the cluster system, and the threshold is never reached.

For the six scenarios that were unable to meet the reliability threshold, we calculated a shortfall measure for each month to determine how much extra water would be needed to bring those months up to the threshold value. The largest monthly shortfall occurs in the very dry climate conditions at an MCL of 0.02 ppb, amounting to 302 acre-feet (AF). Based on this, ID1 would be able to meet our reliability threshold if it can find a way, beyond the options set forward, to ensure an extra 300 AF/month is available at any given time.

After we examined our results, we recognized some additional benefits of treating Cr(VI) that were not captured when using reliability as the sole metric for determining the viability of a system. District managers should not be satisfied with their supply portfolio based solely on the fact that it achieves a high level of system reliability. The best supply systems will also be able to withstand sudden threats and quickly recover from system upsets. This idea represents what we define as system resilience, the second factor captured by our optimization model.

A number of potential scenarios were posed as examples of challenges to the resiliency of a system, including additional new water quality standards, population and land use change, and natural disasters. Out of these, we chose to model a one-time severe flood, which prevented the use of alluvial wells throughout the year, to test how the management actions that we used to increase reliability also affected resilience. Two floods were compared: one that occurred when none of the chosen management actions had been implemented and one that occurred after all actions including a cluster-treatment system had been installed, even if those actions had not been originally required to meet the reliability threshold.

Though our original results implied that there were some scenarios that would not require all of the management actions, additional resiliency results showed that there is value in implementing these actions even if reliability is already high. Across climate scenarios and MCLs, the system that included all management actions was able to retain a higher reliability after the flood when compared to the system with no management actions applied. Though the very dry climate condition scenarios all had reliabilities below the threshold after the initial model runs, these systems were still able to deliver water with near the same reliability even after flooding occurred. This is primarily because the upland wells could be used to fill the gaps left by the missing alluvial well field.

The results of our analysis indicate the significance of the upland wells in providing a buffer against water supply shortfalls of all kinds including drought, fluctuations in demand, and adverse operating conditions. All of the modeled scenarios showed that the impacts of a strict Cr(VI) MCL would decrease the reliability of the system. Given the regulatory uncertainty of water use entitlements, and the vulnerability of supply infrastructure, the importance of groundwater cannot be overstated for small water districts without surface water treatment plants. This speaks to the need to protect the water quality of this source and the merit of at least seriously considering capital investments for some centralized water treatment techniques such as our modeled clustered-well system. Preparation and development for tailored water conservation programs is advisable as a low cost method of increasing system reliability, although it may not be a manager’s primary goal.

An advantage of using an optimization tool such as the model we have created here is that it exposes potential weaknesses throughout the system. By anticipating these weaknesses, water managers can engineer a better supply system that aims to protect both reliability and resilience. Outside factors such as population growth and climate change are likely to lead to constricted water supplies in the future, and being able to optimize the supply that is available is only going to become more important.

Key Acronyms

AF – Acre Feet

CDPH – California Department of Public Health

Cr(VI) – Hexavalent Chromium

EPA – United Stated Environmental Protection Agency

ID1 – Santa Ynez River Water Conservation District, Improvement District No. 1

MCL – Maximum Contaminant Level

OEHHA – Office Environmental Health Hazard Assessment

PHG – Public Health Goal

PPM – Parts Per Million

PPB – Parts Per Billion

RCF – Reduction-Coagulation-Filtration

SBA – Strong Base Anion Exchange

SWP – State Water Project

WBA – Weak Base Anion Exchange

I Objectives

Based on the anticipated ruling by the State of California of a new maximum contaminant level (MCL) for hexavalent chromium (Cr(VI)), this project seeks to develop an updated and viable water supply optimization plan for Santa Ynez River Water Conservation District, Improvement District No. 1 (or ID1) recommending strategies for long-term management that protect the future stability of ID1 water supplies. Specifically, this project aims to:

- Construct a model that determines system reliability as a function of water sources and water demand,
- Assess how various scenarios affect system reliability and resilience,
- Analyze the cost and feasibility of Cr(VI) treatment for ID1 wells, and
- Review alternatives to Cr(VI) treatment.

II Project Significance

Recently, the presence of hexavalent chromium – from both anthropogenic and geologic activity – in municipal drinking water has become a growing international concern. Naturally-occurring hexavalent chromium (Cr(VI)) is derived from chromite, a mineral found most abundantly in ultramafic rocks and serpentinites, geological strata that exist near convergent plate margins – such as the Western United States, Mexico, the Mediterranean, and areas of the South Pacific. Chromite in these strata is typically unreactive, but in soils containing the manganese-rich mineral, birnessite, the chromite reacts with birnessite to produce the oxidized chrom*ate* (Oze et al 2007). Chromate is the most common form of naturally-occurring Cr(VI). Regardless of the source, however, Cr(VI) is a toxic pollutant at certain levels of exposure and is classified as a class A (human) carcinogen by the United States Environmental Protection Agency (Zhitkovich 2011; Watts 1998).

The Santa Ynez River Water Conservation District, Improvement District No. 1 (ID1 or “District”) has recently measured traces of hexavalent chromium in some of its drinking water supply wells, though measured levels fall well below the current maximum contaminant level (MCL) for *total* chromium set at 50 parts per billion (ppb) by the California Department of Public Health. Given its location near a convergent plate margin, it is likely that the aforementioned geochemical pathway is the source of the high levels of hexavalent chromium in the upland basin of ID1. Furthermore, the lack of evidence of industrial contamination and the periodic nature of hexavalent chromium presence in ID1 wells suggest a natural source of the contaminant. While all of ID1’s wells are currently well within the limits for total chromium, a new MCL for hexavalent chromium will likely cause some of the wells to fall out of compliance. To the District, losing these wells also means losing a supplemental source of water during periods of peak demand and an important buffer against uncertain future changes in water allocations. For example, climate change is likely to increase the inter-annual variability in precipitation, thus affecting the amount of available water from the State Water Project (SWP) and other important sources of water. Proposed chromium regulation in combination with annual fluctuations in supply and demand underscore the need to develop a strategy for optimized water management .

II.a Chromium Overview

Chromium, like most transition metal elements, may be found in multiple electron configurations in the natural environment. In an aqueous environment, chromium may be present in the trivalent form (Cr(III)), which is commonly oxidized to chromium (III) oxide. Depending on the pH and reduction potential of the surrounding environment, chromium may also be present in its hexavalent form (Cr(VI)), which commonly appears as chromate or dichromate anions. At increasingly basic pH levels and low redox conditions, Cr(III) may readily form the solid chromium (III) hydroxide and precipitate out of the aqueous state (Rai et al 1989). Cr(VI) is considerably more mobile in aqueous environments, but it may be readily reduced to the more stable Cr(III) in environments that are acidic or that contain organic material. Conversely, other environments may encourage the oxidation of Cr(III) to Cr(VI); therefore, it should not be assumed that sources currently containing only Cr(III) may never contain Cr(VI) (Jacobs and Testa 2004). In some instances, the presence of Cr(VI) is associated with human activity and industrial processes; however, naturally-occurring Cr(VI) is widespread in areas characterized by certain unique geological features.

Naturally-occurring chromium is associated with chromium-rich iron oxides, which are most abundant in peridotites and serpertinite and in mafic igneous rocks (Ernst 2012). Often these formations are found along convergent plate margins, where subducting oceanic crust is deposited on uplifting continental crust, exposing mafic materials to weathering (Ernst 2012). Weathering of chromium-rich deposits leads to naturally high concentrations of chromium as both Cr(III) and Cr(VI) (Oze et al 2007). Outside of California, sources of natural chromium are found in the Lake Superior District, Mexico, Central America, throughout the Pacific, specifically New Caledonia, the Mediterranean, and Oman (Ernst 2012; Oze et al 2007).

Figure 2.1 below displays concentrations of total chromium (not specifically Cr(VI)) in stream sediments across the United States (Ernst 2012). If conditions are highly oxidizing during the weathering process, more chromium will be present in the form of Cr(VI) (Oze et al 2007). Areas with high reported chromium concentrations tend to have more deposits of chromium-bearing minerals.

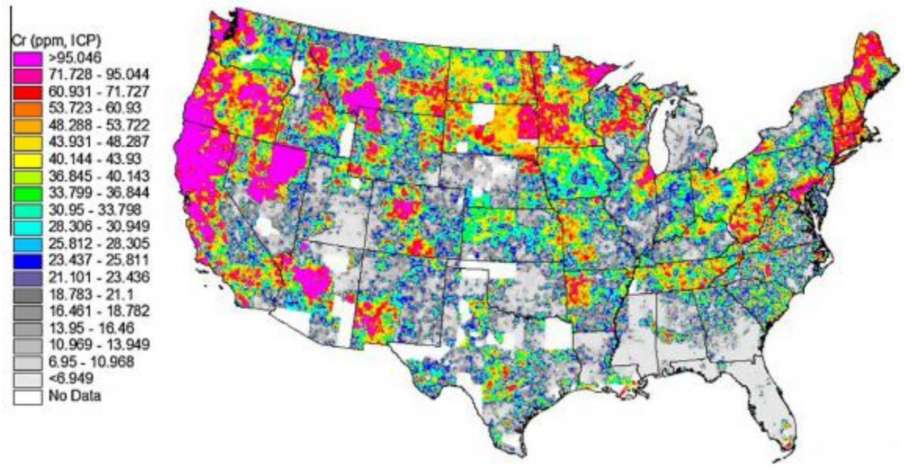


Figure 2.1 In progress USGS mapping of the chromium content of stream sediments of the contiguous United States and its potential bioavailability. Source: http://tin.er.usgs.gov/geochem/map/image/lower48/cr_icp40.jpg

The geology of the San Rafael Mountains surrounding ID1 favors Cr(VI) formation in the Upland Basin groundwater. Formed at a convergent plate boundary, this mountain range is part of the transverse range known as the Franciscan Complex (Wahl 1995). The Franciscan is the oldest formation in the area, originating in the Late Jurassic or Early Cretaceous Period (Dibblee 1966). Among other rock types, the Franciscan formation is made up of a serpentinite matrix, known to result in the oxidation of chromite to Cr(VI) (Wahl 1995; Oze et al 2007). In addition to the serpentinite rock type, there are areas of lherzolite, other ultramafic igneous rock, which contains chromite (Wahl 1995). Magnesium contained in the serpentinite rock reacts with chromite, causing both the magnesium and chromite to become more soluble and oxidize Cr(III) to Cr(VI) (Oze et al 2007).

II.a.i Health Effects of Chromium Ingestion

While increased concentrations of total chromium may be hazardous to humans, the body does need trace amounts of Cr(III) for essential metabolic functions (Zhitkovich 2011). In the case of Cr(VI), studies were conducted to determine if both inhalation of vapors and ingestion via drinking water carried equal potential for health risks (i.e. if residents shower in water with a high concentration of Cr(VI), they can reasonably be expected to inhale vapors containing the metal). While some negative effects have been associated with inhalation, these generally occur at concentrations much higher than is typically detected in drinking water. For this reason, the primary path of exposure has been determined by the California Department of Public Health (CDPH) to be through drinking water consumption (Brown et al 2011).

Animal trials suggest that the acid levels, coupled with the low redox conditions in the stomach are sufficient to reduce much of the Cr(VI) that is consumed to Cr(III), which may pass harmlessly out of the body. Even so, at higher concentrations of Cr(VI), some of the Cr(VI) has been shown to enter the bloodstream before reduction can occur (Zhitkovich 2011; Brown et al 2011). Because the chromate anion is structurally similar to sulfate, another essential compound, it may enter cells through sulfate receptors. Once inside the cell, the chromium can bind to DNA forming cancer-causing adducts (Zhitkovich, 2011). Studies have shown this to be a particular concern in liver cells (NTP 2008). For example, a population in Greece, whose drinking water was sourced from wells that had Cr(VI) concentrations ranging from 44 to 156 ppb, showed a statistically significant increase in liver cancers when compared to surrounding populations (Linos et al 2011).

Most animal tests are performed with levels of Cr(VI) far above those present in ID1's well water. Existing studies suggest that the level at which no Cr(VI) can be expected to escape reduction by stomach acid is 5 parts per million (ppm), far greater than the current established MCL for total chromium – 50 parts per billion (ppb) (Thompson et al 2011). The EPA plans to publish additional studies on this phenomenon in 2013, but until then ID1 anticipates using a precautionary water treatment plan aiming to minimize potential health effects.

II.a.ii Hexavalent Chromium Incidences in California

In addition to broad geographic studies, a considerable amount of data is made available by the CDPH on incidences of Cr(VI) presence in California drinking water (California DPH 2012). CDPH has made available a regularly updated spreadsheet that tracks concentrations of Cr(VI) found in drinking water sources across the state. It is important to note, reported values were collected from drinking water sources, but these values do not necessarily always represent water that is being *consumed*. According to the CDPH website, water may be "blended, treated, or not used to provide drinking water at this time". The data include a sample of water sources that reported a Cr(VI) level over a set detection limit of 1 part per billion (ppb) starting in 2000. The dataset itself contains over 14,000 data points on over 2,300 unique water sources, and is updated periodically with new values. It was last updated November 15, 2011.

It should also be noted that the data include both naturally-occurring Cr(VI) and Cr(VI) resulting from industrial activities. As this project is primarily concerned with natural sources of Cr(VI), the results presented below represent a subset of the data that only includes reported maximum and average Cr(VI) concentrations below 50 ppb (Table 2.1) – the current MCL for total chromium (Cr(VI) + Cr(III)). It was assumed that any sources above this level were likely anthropogenic and should already be undergoing treatment as they are above allowable limits. According to the data, Cr(VI) was reported in 53 of 58 California counties over this time period. For maximum and average values for each county, see Table 2.1.

Table 2.1: *California counties with Cr(VI) presence <50 ppb in drinking water. Source: California Dept. of Public Health, 2012.*

County	Mean [Cr(VI)] ppb	Max [Cr(VI)] ppb	County	Mean [Cr(VI)] ppb	Max [Cr(VI)] ppb
Alameda	5.3	13	**Orange**	1.7	3.4
Amador	1.6	3	**Placer**	2.5	4.3
Butte	3.4	13	**Riverside**	5.9	24
Calaveras	1.6	1.9	**Sacramento**	4.7	27

Colusa	11.1	26	**San Benito**	8.6	21
Contra costa	3.0	7.9	**San Bernardino**	5.8	42
Del Norte	9.3	34	**San Diego**	1.9	5.6
El dorado	1.3	1.6	**San Francisco**	5.5	5.9
Fresno	2.6	28	**San Joaquin**	3.9	16
Glenn	10.1	23	**San Luis Obispo**	4.3	17
Humboldt	3.4	16	**San Mateo**	10.6	28
Imperial	2.1	2.4	**Santa Barbara**	6.9	43
Inyo	2.1	3	**Santa Clara**	2.8	19.3
Kern	2.9	34.6	**Santa Cruz**	15.5	39
Kings	2.3	2.5	**Shasta**	2.1	6.1
Lake	13.0	29	**Solano**	13.6	25.6
Lassen	1.6	1.6	**Sonoma**	4.5	19
Los Angeles	7.9	49.9	**Stanislaus**	4.5	24.6
Madera	1.8	4.9	**Sutter**	9.0	16
Mariposa	2.7	2.7	**Tehama**	5.5	19
Mendocino	2.3	10	**Trinity**	15	16
Merced	10.4	37	**Tulare**	2.1	13
Modoc	1.2	1.5	**Tuolumne**	4	7
Mono	1.9	1.9	**Ventura**	4.5	16
Monterey	4.5	23	**Yolo**	17.5	44
Napa	1.7	1.7	**Yuba**	1.6	3
Nevada	1.4	2.3			

The majority of measurements are small in magnitude, with roughly 65% of the data made up of concentrations between 1 and 5 ppb, and an additional 21% coming from data between 5 and 10 ppb. Of the counties for which data are available, 32 have at least one sampled source that is over 10 ppb. While this data is the main source for statistics on Cr(VI) in California, it has some limitations and should not be considered a perfectly representative sample. More populous counties in Southern California (e.g. Los Angeles and San Bernardino Counties) appear to have higher values than other counties, but they also had far more data points than counties in the northern part of the state. Additionally, the accuracy of older data from the early 2000s that has not been updated is limited in part by the fact that considerable fluctuations in naturally-occurring Cr(VI) concentrations over time are common.

II.b Development of Maximum Contaminant Levels in California

The first step toward developing an MCL for previously unregulated substances in California is establishing a public health goal (PHG) for the substance of interest. The public health goal is set by the California EPA's Office of Environmental Health Hazard Assessment (OEHHA) at whatever concentration of a substance will pose "no significant health risks" if consumed at that level for the entirety of a human life (Brown et al 2011). Because of these standards, PHGs are often much lower than what can realistically be accomplished by available technology. In 2011, OEHHA set a PHG for hexavalent chromium (Cr(VI)) at 0.02 parts per billion (ppb) in drinking water (Brown 2011). In order to establish the MCL, the California Department of Public Health (CDPH) takes into consideration the PHG, the level of health risk presented at concentrations above it, and availability and costs of treatment technology according to State Health and Safety Code §116365(a). Unlike some regulatory measures such as the PHG, CDPH is legally required to consider economic costs during the decision making process (California DPH 1999).

When developing a new MCL from a public health goal, CDPH will generally provide a range of potential MCLs that will not significantly increase the public health risk of the substance, and then consider recorded occurrences of the substance to determine the number of affected parties. Knowing the estimated population exposure means that hypothetical expenses can be determined from known treatment costs. If not enough is known about feasible treatment methods to determine costs, as is the case for the Cr(VI) regulation, additional studies on treatment also need to be undertaken. Once both the exposed population and the potential costs of best available treatment technologies are known, the range of MCLs that were chosen for initial analysis can be reviewed and the lowest concentration that is technically and economically feasible will be proposed as the new regulatory standard. Economic feasibility is determined by looking at the entire range of treatment costs including waste disposal and compliance sampling. Costs need to be such that an average utility would have the ability to treat the substance of interest without requiring large rate increases or becoming non-compliant (California DPH 1999).

Arsenic is a contaminant similar to hexavalent chromium that can be found in water sources from both anthropogenic and geologic processes. In the 1960s, the US EPA established an MCL for arsenic of 50 ppb. Following well-publicized exposure cases in India and Bangladesh, additional research demonstrated long-term exposure to concentrations greater than 50 ppb can result in cancer of the bladder, lung, kidney, or skin. California created a public health goal of 4 parts per trillion (ppt) for arsenic in 2004 because the metalloid has been found to result in non-cancerous damage to the skin and lungs. The public health goal was established based on toxicology and risk evaluations and did not account for the cost of treatment to achieve this goal or other economic factors. In 2008, The California EPA adopted a lower MCL of 10 ppb because of the considerable cost of treatment and limited available technology. The technology used to remove arsenic from water is comparable to methods being evaluated for Cr(VI) removal (California DPH 2008).

Numerous checks are in place to prevent an unrealistic standard from becoming law because reaching the established MCL needs to be both technically and economically feasible. After a proposed MCL is approved by the California Department of Finance, CDPH then initiates a minimum 45-day long public comment period. If the responses generated from the public comment period are determined to be adequate, the MCL is submitted for a final time to the Office of Administrative Law and can be added to written law within 30 days. The entire process generally takes about two to four years on average due to the multiple approval processes that are required, giving responsible utilities enough time to devise methods for attaining compliance with new regulations (California DPH 1999).

After performing a thorough review of available literature on both human and animal exposure to Cr(VI), the state of California has set a PHG of 0.02 ppb for aqueous Cr(VI). As stated previously, PHGs are set at the level of consumption estimated to cause no adverse health effects to an exposed population. Because toxic effects have been observed in some populations as a result of Cr(VI) inhalation (Luippold et al 2003), airborne exposure was included in the formation of the public health goal. However, due to the small amount of available data, and uncertainties in the particular study, a far greater weight was given to exposure through consumption (Brown et al 2011).

There are several factors that contribute to the uncertainty of a chemical's toxicity level. A public health goal aims to be as conservative as possible when accounting for these uncertainties so as to achieve the actual concentration that will have no negative impacts. Because much of the data used for establishing health goals is typically drawn from animal-based studies, a sensitivity factor is included in the analysis to account for potentially increased sensitivity of humans to the contaminant of concern. Additionally, factors accounting for human variability when exposed to the same level of a chemical are also considered (Brown et al 2011).

There are currently no federal standards for Cr(VI), though the federal EPA has established a total chromium (Cr(VI) + Cr(III)) standard of 100 ppb. The EPA began a review period for the creation of a Cr(VI) standard in 2008, but no date has been set for the completion of the current study.

III District Overview

The Santa Ynez River Water Conservation District, Improvement District No. 1 (ID1 or "District") serves residential, commercial, and agricultural customers in central Santa Barbara County, California (Figure ?). The ID1 distribution system includes three pressure zones and covers a 10,850-acre service area. A population of 7,165 in the communities of Santa Ynez, Los Olivos, Ballard, the Santa Ynez Band of Chumash Indians, and the City of Solvang is served by the District. Approximately half of the ID1 annual water demand comes from its 118 agricultural service connections, the remainder from 2,533 residential and commercial customers. Many users within and outside of the service area maintain private wells.

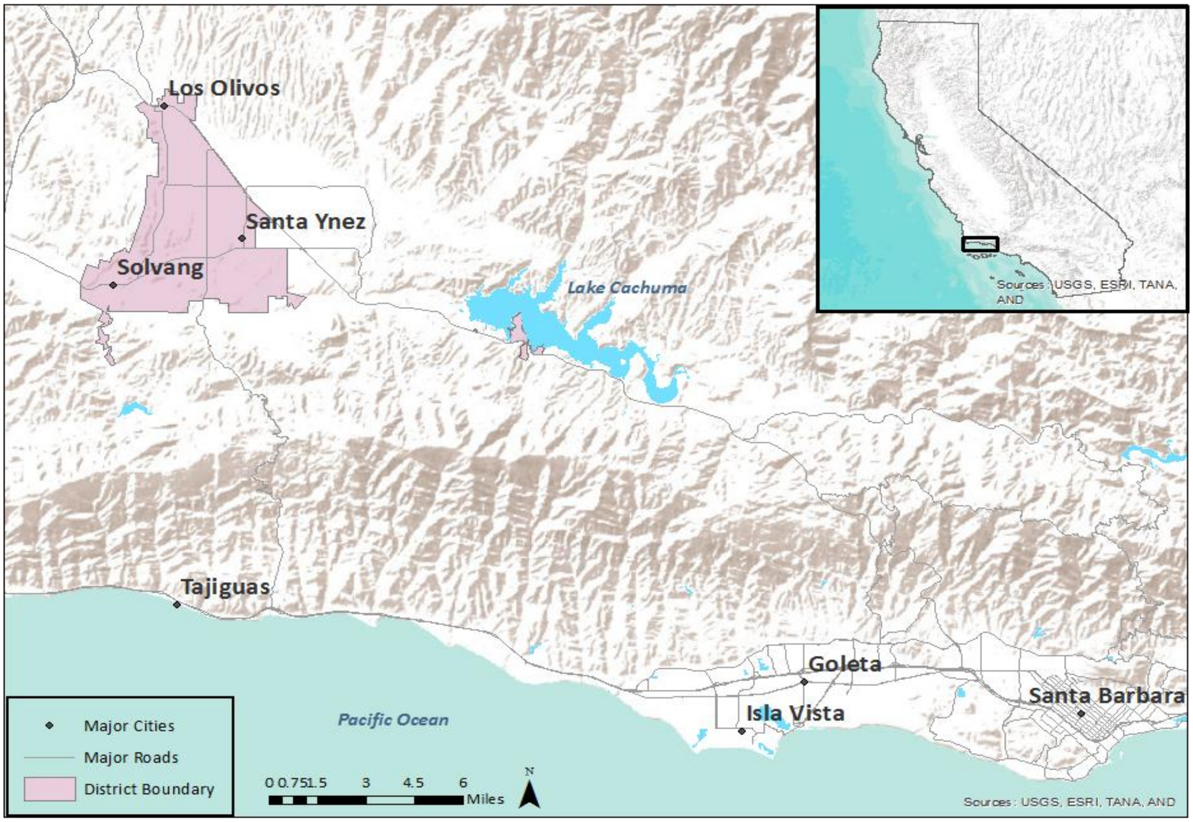


Figure 3.1 Location of the Santa Ynez River Water Conservation District, Improvement District No. 1. Source: USGS, ESRI

III.a Water Supply

The District utilizes four distinct water sources: the State Water Project, the Cachuma Project, two alluvial well fields, and several upland wells. The alluvial well fields and upland wells each contribute about 25% to the District's supply, the State Water Project supplies approximately 10-15%, and the Cachuma Project supplies the remaining 35-40% (Figure 3.2)(UWMP 2000). Each of these sources can vary from year to year depending on environmental and regulatory factors, but these percentages have been relatively constant since the early 2000s. A discussion of each source and the factors that may change its contribution to future water supply follows.

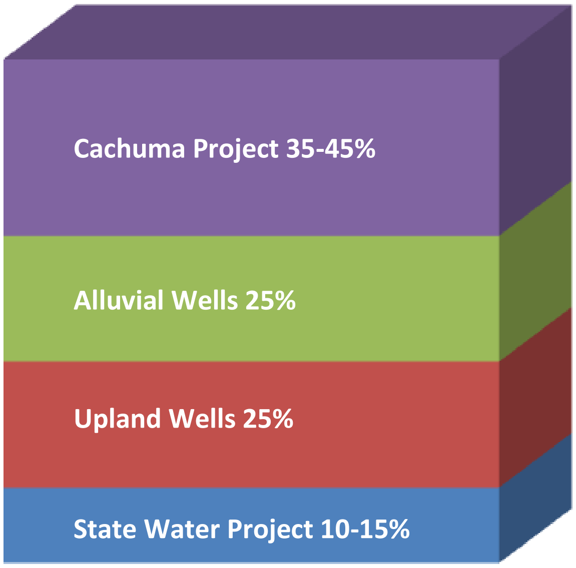


Figure 3.2: Relative distribution of water sources in ID1. Note: Cachuma Exchange agreement results in a total State Water Project supply of about 45-60%.

III.a.i State Water Project

The California State Water Project (SWP), which delivers water from Northern California to the more arid regions of the South, was extended to the District and the rest of the Central Coast via the 102-mile Coastal Branch of the State Aqueduct in the late 1990s. The District is allotted 500 acre-feet (AF) per year in what is termed the “Table A entitlement”, with an additional 200 AF as a drought buffer. The amount of water actually received by ID1 out of this 700 AF depends on the amount of state water available in a given year. Variability in precipitation, runoff, and the size of the snow pack, coupled with variable inter-annual demand of state water cause the amount available to ID1 to fluctuate. The percentage of ID1’s full entitlement of SWP water allotted in any given year is intended to supplement local supplies. This is given as a percentage of the total allotment that is updated throughout the preceding water year (October-September). In addition to this Table A entitlement, the District can receive State Water in the following three ways:

- *Carryover* – If ID1 does not use its entire Table A entitlement by December 31 of any given year, it can carry over to the next year. This water is stored in the San Luis Reservoir; however, if the storage of this water would interfere with the storage of non-carryover state water, the District loses this carryover entitlement. The water does not go to waste though; it becomes available for purchase by ID1 and other SWP participants, in the form of Article 21 water (UWMP 2000).

- *Article 21* – In the event that any party in the State Water Project loses carryover water due to the previously mentioned storage conflict, this water becomes available for purchase by that party and any other party in the SWP as Article 21 water. The SWP sells this water at the cost of transportation to the purchasing party. ID1 uses this source of water when it is available, but it does not represent a reliable source of water for the District (UWMP 2000).

- ***Turnback Pool*** – In February of each year, SWP parties can sell back a portion of the SWP water that they are not going to use at a lower price than the price at which it was purchased. Then, in March, the parties are allowed to purchase this extra water at a higher price than Table A entitlements. This ensures that the SWP breaks even without eliminating the incentive of any party to conserve. Though the Turnback Pool remains an option, it is not utilized very often by the District due to periodic unavailability and prohibitive expense (UWMP 2000).

III.a.ii Cachuma Project

Built in 1953, the United States Bureau of Reclamation's Cachuma Project represents the largest single source of water for ID1, accounting for 35-40% of its supply. The Cachuma Project consists of Lake Cachuma, the Bradbury Dam, which controls flow out to the Santa Ynez River, and the Tecolote Tunnel and the South Coast Conduit, which together supply water to the rest of the South Coast. When the State Water Project reached the Central Coast in the 1990s, the District negotiated an agreement with the other users of the Cachuma Project on the South Coast such that ID1 would exchange its share of the water stored in Lake Cachuma for an equal amount of State Water from those users' entitlements. The pipeline through which ID1 had previously drawn water from the Lake was sold to those South Coast users – now known collectively as the South Coast Water Authority (SCWA) – as a way to convey water from the terminus of the Central Coast Branch of the State Aqueduct in Santa Ynez into the Cachuma Project. This allowed the County to avoid building excess infrastructure and the District to receive treated state water at no additional cost (UWMP 2000).

The Cachuma Project Exchange, as it is referred to by District managers, amounts to 2,651 AF per year. This number could change in future if the capacity of Cachuma decreases due to sedimentation or if ID1 is required to provide more water to the Cachuma Park Recreation Area (UWMP 2000).

III.a.iii Wells

In addition to state water, the District also relies on local groundwater from the Santa Ynez River alluvium and the upland basin for approximately half of its total supply.

Fed by the Santa Ynez River on the southern boundary of ID1's service area, the river alluvium, or "underflow", supplies 20 -30% of the District's water. Two well fields draw from this aquifer, one with a capacity of 4.0 cubic feet per second (CFS) and the other at 6.0 CFS. The licenses for the wells state that no more than 2,200 AF/year and 3,400 AF/year be withdrawn from the wells respectively, and that together the total withdrawal cannot exceed 3,308.9 AF/year (UWMP 2000; SYRWCD ID1, Personal Comminication 2013). The well fields are frequently damaged in storm events and repairs are difficult; therefore, ID1 currently withdraws only about 1,600 AF per year from the river wells (UWMP 2000). This source of water is also subject to regulation by the Department of Public Health with regard to surface water treatment when the water level of the river rises to within 150 feet of the wells. Under these circumstances, the wells are deemed unusable because the District does not have a surface water treatment plant. Due to regulatory restrictions and variability in the flow of the Santa Ynez River, ID1 has water rights that go unused.

This alluvial water source may also be impacted by requirements of state and federal agencies with regard to endangered species conservation. Withdrawing more than the current amount could lead to reduced flows in the Santa Ynez River – a target for steelhead habitat restoration – likely causing the District to come under scrutiny from government and non-government organizations alike.

III.a.iv Upland Basin

The last source of water, accounting for another 25% of supply, is the upland groundwater basin, currently serving eight active wells spread out throughout the District. These deep wells draw from the Paso Robles formation between 700 and 1,200 feet below ground surface and Carreaga Sand at approximately 1,800 to 3,000 feet below ground surface (UWMP 2000; LaFreniere and French 1968). The production of these wells varies from year to year, depending on the state of repair of the wells, the height of water in the aquifer, and the availability of other water sources. In 2011, Upland Basin well water accounted for about 62% of the groundwater supply or roughly 12% of the total District water supply. The wells are used in sequence according to a prioritization scheme for each of the three pressure zones.

Certain Upland Basin wells are not in use due to low capacity or undesirable levels of nitrate. Potential sources of nitrate include residential septic systems, agricultural fertilizer use, and livestock waste. Well development and/or nitrate reduction could make use of these inoperable wells or contribute to an excess capacity buffer.

III.b Drought & the State Water Project

The high degree of seasonality of California precipitation causes water availability to fluctuate throughout the year. The amount of water available through the SWP is governed by snowpack levels in the Sierra Nevada Mountains and can vary significantly depending on the amount of snowfall from the previous winter. As previously noted, the District relies on SWP water gained from the Cachuma Exchange Project for about 3,000 AF/year, or around 35-40% of their annual demand. Because of this, water supply pressures would significantly increase if California were to enter an extreme drought that severely limited the amount of available water.

The District’s current Urban Water Management Plan (UWMP) indicates that contingency plans are in place in the event of possible water shortage scenarios (UWMP 2000). When California experienced a large-scale drought from 1985 to 1991, the UWMP notes that the District was able to meet demands through heavy use of the upland basin wells, though this drought took place before the District had any access to SWP water (which occurred in 1997). Most importantly, if a similar drought were to occur today, the District would likely have limited access to state water, though the amount could be greatly reduced from current levels. Additionally, the potential Cr(VI) MCL would eliminate the use of at least some portion of the upland basin wells without additional treatment. For this reason, the amount of available SWP water, along with the MCL is one of the main determining scenarios that we chose to model for this report.

Since 1996, there has never been a significant enough water shortage to stop the District from receiving SWP exchange water with Santa Barbara County. Current agreements surrounding the exchange allow the District to receive its full allotment of water until SWP deliveries drop below 25%. Below this point, the District would receive a declining percentage of its exchange agreement proportionate to how far below 25% the allocation was. For instance, if there was a 20% allocation of SWP water, the district would be eligible to take 80% (or 20/25) of their original water allocation that year. For this reason, the pressure on the district does not become intense unless a fairly significant drought event occurs.

The total delivery percentages for the SWP for 1996 through 2012 are shown in Table 3.1 below. The Sacramento Valley 40-30-30 Index and the San Joaquin 60-20-20 Index are used by the California Department of Water Resources (DWR) to determine the general annual hydrologic conditions in the state. These river systems are considered representative of SWP deliveries due to their proximity to where most SWP water is stored in the snowpack (Brown et al 2012). Both indices examine total runoff levels in their respective river basins at various points throughout the winter season and use these totals to classify a year as “wet”, “above normal”, “below normal”, “dry”, or “critical” by May of that calendar year. For this reason, years with considerable amounts of late season precipitation may not be a perfect match with the index classification.

Table 3.1: *Percentage of SWP allocations delivered by year including information on water year type according to the Sacramento and San Joaquin River Valley Indices.*

Year	SWP Delivery*	Sacramento Valley 40-30-30 Index**		San Joaquin 60-20-20 Index**	
1996	90%	Wet	N/A	Wet	N/A
1997	100%	Wet	N/A	Wet	N/A
1998	100%	Wet	N/A	Wet	N/A
1999	100%	Wet	10	Above Normal	3.5
2000	90%	Wet	9.2	Above Normal	3.4
2001	39%	Dry	5.9	Dry	2.5
2002	70%	Dry	6.5	Dry	2.4
2003	90%	Above Normal	8	Below Normal	2.8
2004	65%	Below Normal	7.7	Dry	2.3
2005	90%	Below Normal	7.4	Wet	4.3
2006	100%	Wet	13	Wet	5.6
2007	60%	Dry	6.2	Critical	1.9
2008	35%	Critical	5.4	Critical	2.1
2009	40%	Dry	5.5	Dry	2.4
2010	50%	Below Normal	6.9	Above Normal	3.5
2011	80%	Wet	10	Wet	5.1
2012	65%	Below Normal	6.9	Dry	2.2

***California State Water Project: http://www.water.ca.gov/swpao/deliveries.cfm**
****California Bulletin 120:**
http://cdec.water.ca.gov/snow/bulletin120/index.html?CFID=86477541&CFTOKEN= 79996281

During this time period (1996-2012), the lowest percentage of water delivered to SWP contractors was 35% in 2008, a year classified as "critical" by both indices. This year fell in the middle of what the DWR classified as the last major drought in California history, which ran from 2007 to 2009 (State of California 2010). This is the only official drought that has taken place since the District began receiving SWP allocations in 1996. While this drought event did not significantly impact District water supplies, historic data indicate that this was a relatively less intense drought when compared to other observed dry periods.

Runoff levels in the Sacramento and San Joaquin Valleys during the 2007-2009 drought were actually higher than other significant droughts in California's history (Table 3.2). These values indicate that if a major drought were to occur again, there is a possibility that it could be intense enough in magnitude to reduce water deliveries below the 25% SWP threshold. Work done by the California Climate Action Team (CAT) and other groups also suggests that a general climatic warming trend may also lead to warmer winters and reduced snowpack levels in the future (California EPA 2010; Mastrandrea & Luers 2011). This reduced water storage could also decrease expected water deliveries during future droughts.

Table 3.2: *Runoff values for the Sacramento and San Joaquin Valleys during four major drought periods in California. Note that runoff levels in 2007-2009 were still higher than past droughts. Source: State of California 2010*

	Sacramento Valley Runoff		San Joaquin Valley Runoff	
Drought Period	**(MAF/yr)**	**(% average 1901–2009)**	**(MAF/yr)**	**(% average 1901–2009)**
1929 - 1934	9.8	56	3.3	56
1976 - 1977	6.6	38	1.5	26
1987 - 1992	10.0	57	2.8	48
2007 - 2009	11.2	64	3.7	63

Additionally, while there is no way to predict the duration of a drought period, three of the four major droughts on record lasted more than one year (Table 3.2). It is possible that the challenges the District faces with regards to water supply shortages may increase along with the length of the drought.

In the event of an extreme drought scenario that restricts the amount of available SWP water, the District does have a number of additional water supply alternatives; though these alternatives were not quantitatively considered for this project due to their relatively expensive and planning-intensive nature.

First, much of the analysis conducted on drought conditions assumes that the South Coast Water Authority (SCWA), the party with which the District exchanges Cachuma Project water for SWP water, would not be able to meet the Cachuma Exchange agreements in the case of decreased SWP allocations. There is the possibility, however, that SCWA would turn to additional reliability measures it has available, such as desalination, to meet demand and would thus be willing to exchange for the full contract agreement at an additional cost. Nevertheless, the lack of available drought data since the

Cachuma Exchange system was put into place in 1996 limits the degree of certainty to which this plan could be implemented.

Second, the District has the legal right under the Cachuma Exchange agreements to pump water back from Lake Cachuma if SCWA is unable to complete trades for SWP water. However, the repair of a currently-inoperable pipe and the construction of a centralized water treatment plant within the District would be necessary to use Cachuma water (SYRWCD ID1, Personal Communication 2012). In extreme drought conditions, there is also no guarantee that there would be enough water in Cachuma to make it a significant reliable source compared to groundwater. The extent to which ID1 could implement these possible contingency plans – under current and future DWR regulations – is beyond the scope of this project.

IV Hexavalent Chromium Treatment

To ensure a consistent supply of safe and affordable drinking water, the District would like to plan for both future droughts and future regulations, such as the impending MCL for Cr(VI). Here we examine various treatment options discussed in the scientific literature relating to remediation of Cr(VI) in drinking water, with special consideration for the costs and the land area required.

IV.a Ion exchange

A common method for treating chromium-containing water is to pass it through an ion exchange resin that captures and removes the chromium from the water. Hexavalent chromium is present in aqueous form as chromate, which is a negatively charged ion, or anion. Typical ion exchange resins for Cr(VI) treatment use positively charged amine groups to capture the chromate anions. The resin is originally saturated with chloride anions that bind to the amine groups, but the resin will preferentially bind chromate over chloride. Different resins are available that have different affinities for certain anions and different capacities for ion capture. Resins commonly used for Cr(VI) remediation preferentially bind chromate over most other common anions, except for sulfate. As a result, high sulfate levels in the influent will reduce the effectiveness of the resin for Cr(VI) removal. Furthermore, resins become exhausted after a period of use and must be backwashed, regenerated, and rinsed, or replaced. Two types of ion exchange are typically utilized in chromium treatment – weak base and strong base – which differ in both their set-up and their use of resin (Blute and Wu 2012).

IV.a.i Weak Base Anion Exchange

The specific amine group cation used in weak base anion exchange (WBA) to capture the target anion increases sensitivity to pH, requiring pH adjustment equipment for most applications. Weak base resin is not capable of regeneration; however, for Cr(VI) treatment, the weak base resin employed, PWA-7, lasts significantly longer than the strong base resin. For drinking water treatment, ion exchange systems utilize a lead-lag configuration (Fig. 4.1). This type of system allows the effluent of the lead column to be tested for contaminant levels, and when breakthrough occurs in the lead column, the lag column becomes the lead and the original lead column has its resin exchanged. This prevents the need for excess testing and reduces the risk of exposure (Blute and Wu 2012).

When compared with a similar setup for SBA, WBA has higher initial capital costs as the weak base resin costs more, and the pH equipment adds to the cost as well. It is unclear, however, how the long-term costs will compare between the two and will likely need to be determined on a case-by-case basis.

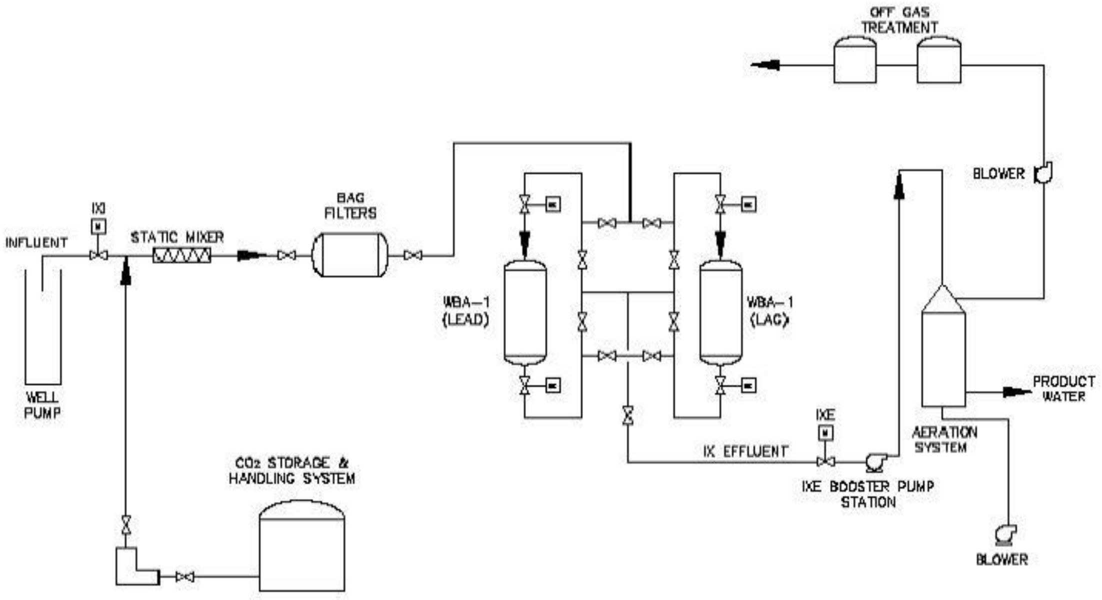


Figure 4.1: Process flow diagram of weak base anion exchange for Cr(VI) treatment. Source: Blute and Wu 2012

IV.a.ii Strong Base Anion Exchange

Strong base anion exchange (SBA) has a number of advantages over WBA; however, the resin used in SBA does not come without certain limitations. First, although SBA utilizes a less selective resin than WBA, it must be replaced more often due to the buildup of non-target contaminants. In lieu of total replacement, the resin may be regenerated using a simple salt solution, though the resulting capacity of the resin decreases over time. Also, when the resin is being exchanged in any given tank, that tank must be taken offline for at least a few hours, causing an interruption in treatment in a simple lead-lag system (Fig. 2, Bahowick et al 1996). A counter current system has been developed to prevent the need to take the system offline for resin maintenance and to reduce waste. Multiple columns of resin are utilized concurrently with a valve system to move water and control the direction of flow. Typically twenty columns are used, though this can vary depending on the amount of water being treated, with fourteen columns adsorbing, one in the backwash/displacement phase, three in the regeneration phase, and two in the regeneration rinse phase. The status of each column is controlled by a central process disk to ensure all columns are maintained (Rochette 2010). In the United Kingdom, such systems have been successfully in operation since 2005 reducing the volume of ion exchange resin needed by 50% and consuming 75% less water than conventional resin treatment options (Rochette 2010).

Using the multiple column set-up greatly increases the capital investment necessary for SBA; however, for small-scale applications that can absorb lost capacity from the regeneration time with other water sources, a simple lead-lag set-up can be employed (Fig. 4.2). Since SBA does not need pH adjustment, such a simple system reduces the initial capital costs below those of WBA. Unfortunately, operation and maintenance costs remain fairly high, as regeneration and replacement of resin must be performed frequently (Blute and Wu 2012).

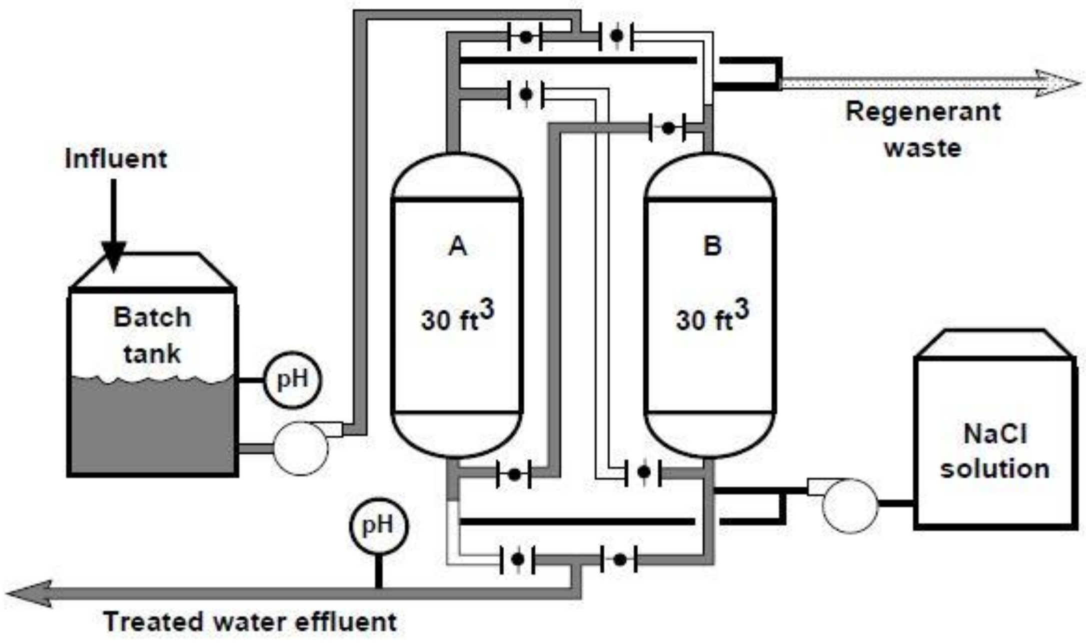


Figure 4.1: Process flow diagram of strong base anion exchange for Cr(VI) treatment. Source: Bahowick et al 1996

An additional consideration for both ion exchange systems is the management of waste. Resins concentrate chemicals that would otherwise be found in low concentrations. This can lead to used resin or regeneration brine being treated as hazardous waste (Blute and Wu 2012). This will be an additional cost, but it is hard to estimate without knowing the specific make-up of the influent water as well as the actual use of the resin between regenerations or replacements.

Finally, the ease-of-use of these systems is important to consider, especially for smaller scale applications. In pilot and demonstration scale studies, WBA has proven to be much easier to use than SBA and other treatment methods for those running the treatment equipment (N. Blute, Personal Communication 2013). Harder to use set-ups could require, retraining, or hiring of employees specialized in using this equipment, which is an additional cost consideration. It is also important to note that if the systems are mismanaged their effectiveness can decrease greatly. For instance, if SBA is not regenerated and backwashed appropriately, preferential flow channels can form in the resin and lead to rapid breakthrough (Bahowick et al 1996). If testing schedules are based on a certain time to breakthrough, these errors could presumably go unnoticed for a period of time, exposing water users to higher levels of Cr(VI).

IV.b Chemical Treatment: Reduction-Coagulation-Filtration

Another method for treating water containing Cr(VI) is by introducing additional chemicals that will reduce available Cr(VI) to Cr(III). Following reduction, the Cr(III) compounds precipitate out of solution, allowing for easy removal through filtration. Treatment systems that employ this method to remove Cr(VI) are typically known as Reduction-Coagulation-Filtration (RCF) systems.

Chemical processes are commonly facilitated by ferrous sulfate ($FeSO_4$) or stannous chloride ($SnCl_2$) (American Water Works Association 2005; Hawley et al 2006; Ludwig et al 2008). The reaction that takes place when using both of these compounds is modeled below: (American Water Works Association 2005)

Ferrous sulfate: $3Fe(OH)_2 + CrO_4^{2-} + 4H_2O \rightarrow 3Fe(OH)_3 + Cr(OH)_3 + 2OH^-$

Stannous chloride: $2H+ + 3/2Sn(OH)_2 + CrO_4^{2-} + 4H_2O \rightarrow 3/2SnO_2 + Cr(OH)_3 + H_2O$

The reducing chemical of choice may be added to the water that is to be treated either *in situ* or *ex situ,* depending on specific site characteristics and the concentration of chromium present. For the treatment to be successful, the reducing agent needs to fully mix with the water source (American Water Works Association, 2005). After the reducing agent has been mixed, there is a lag time during which the reduced Cr(III) complexes are allowed to coagulate and precipitate out of solution. This lag time can range anywhere from 10-45 minutes depending on the specific chemicals used (American Water Works Association, 2005; Qin et al 2005).

One of the main concerns regarding chemical treatment is that the chemicals commonly used for water purification (i.e. chlorines and chloramines) may re-oxidize Cr(III) back into Cr(VI) before it can be filtered out of solution. Studies conducted by the American Water Works Association suggest that up to 65% of Cr(III) in solution may be re-oxidized when using chlorine at neutral or low pH levels (American Water Works Association 2005). This concern can be mitigated to some degree by using ferrous sulfate rather than stannous chloride. With ferrous sulfate, the ferrous hydroxides that are formed by the reduction process tend to adsorb onto the Cr(III) hydroxides, preventing them from becoming re-oxidized before filtration can take place (N. Blute, Personal Communication 2012).

Because of this advantage, most pilot studies that have examined the effectiveness of RCF systems use ferrous sulfate systems. In order to ensure that the driving reaction (oxidation of ferrous sulfate to ferrous hydroxide) runs to completion, the solution may need to be aerated before the filtration step. Research is still being completed on the ideal filtration process. Using a filtration system with a very small pore size will ensure that no excess precipitate bypasses the filter, but also increases the energy required to keep the system operational. Removal efficiency will be dependent on filter pore size and the time allowed for reduction. Ideal pH levels for the ferrous sulfate reduction reaction range from 7.0 to 7.5, so it is possible that water may need pH adjustment pre-treatment before being run through such a system (Qin et al 2005; I. Najm, Personal Communication 2012). A schematic diagram of a sample RCF system is shown below in Figure 4.3.

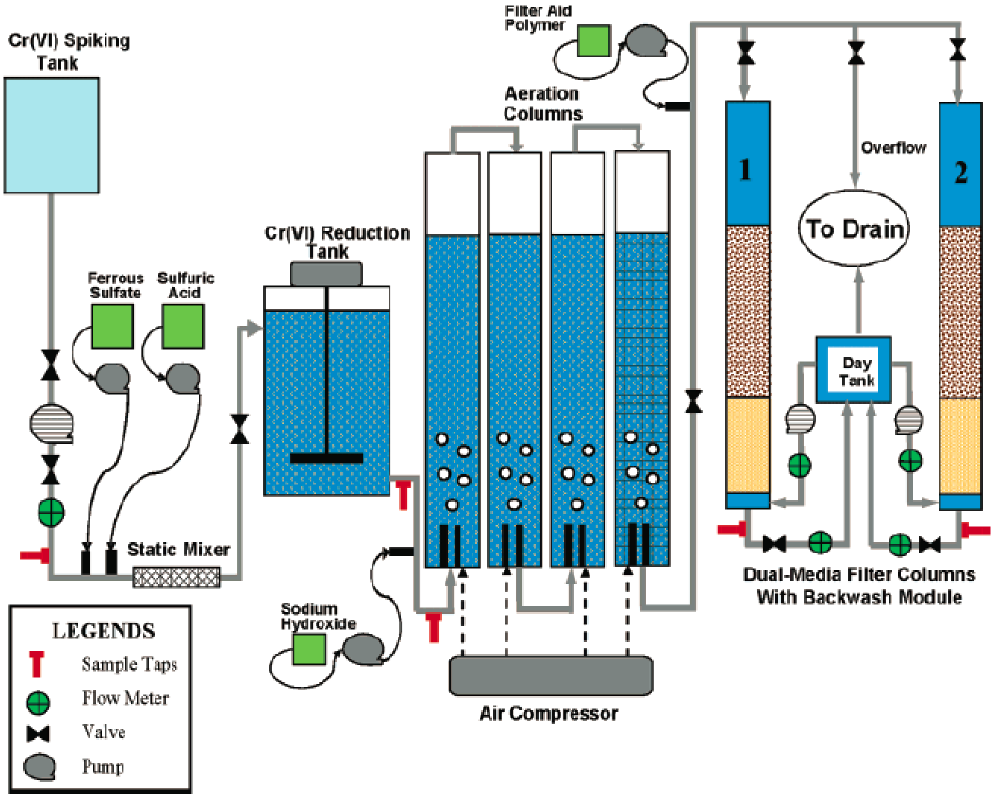


Figure 4.3: Process flow diagram of a sample RCF system used for Cr(VI) treatment. Source: Qin et al 2005.

Pilot studies done on RCF systems suggest that removal of Cr(VI) can occur at rates greater than 95% (Qin et al 2005; Blute and Wu 2012). An advantage of using a chemical treatment method such as RCF over one of the filtration techniques described above is that additional water quality measures such as sulfate and nitrate concentrations do not strongly affect treatment efficiency. Additionally, initial construction costs for RCF systems are similar to those for WBA and SBA, and preliminary studies suggest that the operation and maintenance costs will also be similar or lower depending on waste (Blute and Wu 2012).

IV.c Reverse Osmosis

Currently all water delivered in California is required to meet potable standards regardless of its end use. The implementation of increasingly stringent water quality standards has increased the cost of treating and supplying water to residents. A proposed alternative to treating all water supplied to residents is to treat only the water utilized for drinking and cooking by installing reverse osmosis devices in each household, or at various points-of-use. This would limit the costs of system-wide water treatment and eliminate the cost of treating water used for agriculture, landscaping, laundry, and other purposes to the same standard. Reverse osmosis (RO) removes a wide range of known contaminants, including Cr(VI), and produces high quality water. In fact, current California drinking water regulations allow for the use of a point-of-use system in lieu of centralized treatment for complying with MCLs; however, the law limits the use of these systems to districts with fewer than 200 connections and for a maximum of three years (CA Code of Regulations 22.4.15 Article 2.5 Section 64417) Prior to RO systems becoming viable solutions for larger-scale water management issues, barriers to their use including waste management, the creation of new water quality issues, energy intensity, and legal restrictions must be addressed.

These systems use pressure to push water through a semi-permeable membrane which removes constituents of concern. Systems consist of a prefilter, which removes fouling agents (rust and hardness), a membrane, an activated carbon postfilter to remove residual taste, odor and some organic compounds from treated water, and a storage tank (Kamrin et al 1991). This technology is most commonly employed in desalinization systems, but it can be applied to address local water quality problems. It is important to evaluate the constituents of concern and characteristics of the water to determine if the installation of RO systems is a viable option.

Not all contaminants and minerals can be removed from the water with current RO technology. If there is a shift in water treatment to RO, precautions need to be taken to ensure that all constituents of concern can be consistently and reliably managed. Multiple membranes have been developed and can be employed depending on the characteristics of the water. Membranes have different properties and not all remove the contaminants at the same efficiency; therefore, a membrane must be selected to ensure that treated water meets water quality standards. Furthermore, the wastewater (or brine) is highly concentrated in contaminants and requires proper disposal. Depending on the characteristics of the water, concentrated waste may be classified as hazardous waste and subject to state and federal regulations. The amount of waste generated is proportional to the amount of water treated and the pressure on the system, and can be up to 90% of the incoming water (Kamrin et al 1991). If waste is not properly disposed, it may contaminate other water sources and create new water quality problems. Initial water quality parameters that impact the efficiency of the system include total dissolved solids (TDS), acidity, hardness, water temperature, and chlorine content (Kamrin et al 1991).

Additionally, RO systems are energy intensive and produce limited water; only 30-80% of the volume of water input is of a usable quality (Cooley et al 2006). A typical in-home system is only capable of producing three to ten gallons of water per day. To increase the efficiency of the system, pressure can be increased; however, this increases the energy required to operate the system (Kamrin et al 1991). Energy is just one of many costs associated with this technology. Initial installation costs of RO systems can be $300-900 depending on the system, in addition to the high costs of regular maintenance and system updates. On a small scale (i.e. in-home use) these costs may be less than those of a central treatment station; however, for larger areas this may not be a practical method for managing water quality.

The most significant barrier to this water treatment option is the legality of water districts supplying water that does not meet water quality standards. The legality of this option needs to be explored further before being viable for ID1. Other important factors to consider include: identifying the party that will be responsible for the costs associated with installation, maintenance, and operation of the system, as well as the best method for monitoring and managing water quality.

Arsenic is frequently referenced to predict future Cr(VI) regulations due to similarities in toxicity and high natural occurrences in groundwater associated with natural geologic features. In Lahontan Valley, Nevada, many residents have installed RO systems in their homes to address high concentrations of arsenic in drinking water (Walker et al 2008). A study of about sixty households revealed that the effectiveness of these systems was remarkably variable. The median removal rate was 80.2% with a 28.1% standard deviation. RO reduced arsenic concentrations to less than 10 ppb in 36 of the 54 households. Consumers were surprised to learn that their water did not meet the standards despite improvements in taste resulting from improvements in total dissolved solids (TDS) and specific conductance. A proposed explanation for the failure of RO systems to produce water that meets standards is the chemical properties and state of the arsenic. The arsenic present in the Nevada wells existed primarily in dissolved form and not as particulates, which RO systems remove more efficiently. Chlorination can, however, damage the filtration membranes and should be used with caution when utilizing RO systems. This case study underscores the complexity of using RO treatment to address local water quality concerns and suggests that while RO may be a viable choice for Cr(VI) treatment, it is not a straightforward option.

IV.d Cluster treatment

Constructing a centralized treatment system reduces the capital and operational costs associated with multiple well head treatment systems. Furthermore, the location of the centralized treatment facility can reduce the need for water to be pumped from different pressure zones.

The type of treatment system used at such a facility depends on water quality, capital costs, and operation and maintenance costs. Considering only the cost associated with such a system, the Strong Base Anion Exchange (SBA) may be the most appropriate. Assuming the system is only used during summer peak demand, or in the case of a dry or very dry year (i.e. very little SWP water), a facility that has low capital costs relative to operating costs may be more appropriate. Thus far, the system with the lowest estimated capital cost is SBA (Najm 2013). SBA also has fewer space constraints compared to Weak Base Anion Exchange (WBA) or Reduction-Coagulation-Filtration (RCF), due to less operational components (Cr(VI) Workshop, 2013). The operation and maintenance costs are, however, higher for the District when compared to RCF, due to the disposal of the brine waste used to regenerate the resin (Najm 2013). This brine waste may be disposed of in the sewer (Najm 2013); however, the small sewer district in ID1 is not equipped to handle such waste (SYRWCD ID1, Personal Comminication 2013).

RCF is the more appropriate choice for water treatment when water quality and operational costs are considered. Due to the elevated levels of pH and sulfate in ID1's water, SBA and WBA may not be as effective. The resin used in SBA has a stronger affinity for sulfate than Cr(VI), thus resulting in a quicker Cr(VI) breakthrough (Najm 2013). Faster breakthrough time requires more regular regeneration or replacement of the SBA resin, which will increase the costs and the possibility of delivering water above the MCL. Additionally, the elevated pH of ID1 water would require costly pretreatment pH adjustments which limits the application of the pH-sensitive WBA (Blute and Wu 2012; Najm 2013). Since ID1 does not have a sewer system within the area considered for the cluster treatment system, the waste would need to be shipped to a disposal site, further increasing the operational cost of treatment (Najm 2013).

The RCF system allows for a concentrated waste of Cr(VI), which can be dewatered, thus lowering shipping costs (Najm 2013).

The final decision of which treatment system to use will ultimately depend on the capital, operational, and maintenance costs; however, important analysis needs to be done to determine the appropriate treatment system based on water quality. The water quality of ID1 water can affect the operational cost of the treatment system, thus it is important to identify these potential issues upfront.

V Ongoing Cr(VI) Treatment Studies

Numerous studies specific to California and pertinent the upcoming MCL are currently underway through government agencies and the Water Research Foundation. These studies and their findings can be used to aid ID1 with its decision in choosing the most effective and cost appropriate Cr(VI) treatment and are briefly explained below.

Water Quality Solutions & Treatment, Inc. built upon initial findings of the Glendale study to review the affect that various water parameters can have on treatment technologies. From the upcoming Cr(VI) MCL change the Coachella Valley Water District recognized the need to prepare for this due to the elevated levels of naturally occurring Cr(VI) and its reliance on groundwater. These studies and their findings can be used to aid ID1 with its decision in choosing the most effective and cost appropriate Cr(VI) treatment.

V.a City of Glendale Water and Power

The first major Cr(VI) treatment research effort began at the City of Glendale Water and Power after a settlement was reached with the community of Hinkley, CA over industrial Cr(VI) contamination in drinking water in the late 1990s. In the aftermath of the settlement, the City of Glendale set a 5 ppb MCL for Cr(VI) in drinking water and began a study of possible treatment options. The study began as a collaboration of the City of Glendale with other local utilities, funded by state, federal, and private groups, and includes three phases: Phase I Bench-Scale Study, Phase II Pilot Testing, and Phase III Demonstration Testing (Blute and Wu 2012).

V.a.i Phase I

The Phase I study was conducted to investigate the redox potential of Cr(VI), evaluate potential Cr(VI) removal technologies, and determine the nationwide occurrence of chromium in drinking water. The study found elevated levels of Cr(VI) throughout the country, with 1,654 potable groundwater sites with a mean Cr(VI) concentration of 4.9 parts per billion (ppb). A variety of technologies were tested as well: adsorption/chelation, ion exchange, coagulation with precipitation, and membrane filtration (Blute and Wu 2012).

V.a.ii Phase II

Phase II pilot testing was conducted in two segments. Phase IIA analyzed vendors proof-of technology validations, while Phase IIB involved the evaluation of other technologies and an in-depth look into current effective technologies. Phase I of the study identified seven removal options that have the potential to reduce Cr(VI) concentrations to less than 5 ppb. These technologies included three types of anion exchange, zeolite media, iron-impregnated granular activated carbon, and two types of reduction/filtration. Strong Base Anion Exchange (SBA), Weak Base Anion Exchange (WBA), and Reduction/Coagulation/Filtration (RCF) were found to be capable of achieving single-digit Cr(VI) ppb concentrations (Blute and Wu 2012).

V.a.iii Phase III

Phase III involved the setup of demonstration facilities that tested WBA and RCF at full scale and an on-going pilot-scale SBA set up. The RCF facility was constructed on an EPA Superfund site, and the WBA Cr(VI) removal demonstration facility was constructed on the site of a former chrome plating factory. Congruently, the WBA site shares the same site as the pilot scale SBA Cr(VI) removal system (N. Blute, Personal Communication 2012).

V.a.iii.1 Reduction-Coagulation-Filtration

The RCF Cr(VI) removal facility operated at a rate of 100 gpm. The Glendale water has the appropriate pH of 7.2, with ideal pH needs for this system being at 7 – 7.5; therefore there was no need to adjust the pH for this operation. The intake water has approximately 80 ppb of Cr(VI) and the removal process was able to achieve 1 ppb. First, ferrous sulfate was injected into the water via a side stream, which was then sent to a mixing tank for reduction. From the reduction tanks, the water was then pumped into an aeration tank to convert the Iron (II) to Iron (III). Next, the water was mixed with a coagulant aiding polymer, sent to a rapid mixing tank, and then into a granular filter of anthracite and sand that collects the iron-chromium particulates.

Capital cost was estimated for the RCF system with a 2,000gpm setup at $8.7 million in 2011 dollars. Costs were also calculated with a level 5 Association for the Advancement of Cost Engineering (AACE) accuracy range of -30% to + 50% of $6.1 – $13 million. Unit treatment costs for influent concentrations of 10 ppb are estimated at $517/Acre Foot (AF) and for 20 ppb at $567/AF. Other cost estimates for various flow rates and assumed MCLs can be found in the Glendale report (Blute and Wu 2012).

V.a.iii.2 Weak Base Anion Exchange

The WBA testing treatment site produced 425 gpm and required a pH reduction from 6.8 to 6, the optimal level for WBA treatment. The pH adjustment process began with liquid CO_2 injected via a side stream. The water was then moved through bag filters to remove any sand from the well and to help mix the CO_2. With the pH change, the resin is optimized, allowing for a bed volume of 200,000. Bed volumes are used to normalize the quantity of water treated and are calculated as the ratio of water to the volume of resin. The removal system utilized the Amberlite^{TM} PWA7 resin flakes by DOW Chemical and has been the only resin proven to work. The resin was added to two tanks in a lead lag setup. This allows the lead tank to be used to capacity with the lag tank removing the excess Cr(VI). Before the system began operation, the resin was put through a pre-treatment procedure in order to remove excess formaldehyde that is released during the initial filtration process. The resin was also back-washed to allow it to filter and settle evenly within the tank. The tanks used in this operation are oversized (8-foot diameter), however, a smaller tank of 6-foot diameter may be utilized to achieve similar results. Once the water leaves the resin tanks the pH was then brought back up to 8 via aeration, since a pH of 6 is corrosive to water distribution pipes (N. Blute, Personal Communication 2012). Assuming a consistent pH level, effluent concentrations of Cr(VI) were below 5ppb with under 172,000 bed volumes and as low as 0.02ppb with less than 50,000 bed volumes. Capitol cost for WBA was estimated at $8.1 million in 2011 dollars. Costs were also calculated with a level 5 AACE accuracy range of -30% to +50% of $5.6-$12 million. A unit treatment cost estimation of $538/AF for an assumed 10ppb MCL was also calculated (Blute and Wu 2012). Other cost estimates for various flow rates and assumed MCLs can be found in the Glendale report.

V.a.iii.3 Strong Base Anion Exchange

In conjunction with the WBA testing site is a SBA pilot scale study running at less than 1 gpm. This pilot study is testing two new resins and is using the pH adjusted water from the WBA site. Without the pH adjustment the resins will last approximately 5,000 bed volumes. These resins are re-generable with a brine rinse, however the Cr(III) removal is unknown. The Cr(III) removal is a potential issue since the conversion of Cr(III) to Cr(VI) when mixed with chlorine is also unknown (N. Blute, Personal Communication 2012). No cost estimations for SBA were completed during the Glendale study.

In summary, the potential to reach low concentration levels of Cr(VI), such as 1ppb, has been demonstrated even with influent levels as high as 80 ppb. The RCF system is able to reach a concentration of Cr(VI) at 1 ppb; however, the site is fairly large and was only running at 100 gpm. Conversely, the WBA site was slightly smaller, and was able to maintain a 5 ppb or lower concentration of Cr(VI) removal at 425 gpm. Despite their ability to remove Cr(VI), these technologies may not be appropriate for well-head treatment or for sites with naturally-occurring Cr(VI) contamination, such as ID1. The District has minimal space around water well pumping sites, no centralized treatment facility to blend or treat the water, and a continuous influx of Cr(VI) from a naturally occurring source. With these factors in mind as well as other water quality factors in ID1, RCF may be the best choice for well head treatment at select sites in the District.

V.b Coachella Valley Water District

In response to the updated arsenic MCL in California in 2008 and the release of the PHG for Cr(VI) in 2011, the Coachella Valley Water District (CVWD) conducted a review of SBA, WBA, and RCF to address local water quality concerns. The SBA system was chosen for its ability to remove arsenic and Cr(VI). This anion exchange system is also easier to use than other systems, and so is preferred by operators. Initial testing of the system was completed with a pilot study, housed in a trailer located at a well site and operated at 1,000 gpm. After success of the pilot study, CVWD constructed a 4,000 gpm SBA system. This configuration is a centralized treatment operation built on property purchased by CVWD, with affected wells piped to the location (Bigley 2013). Cost estimates were gathered from this study and a systematic framework was developed that could be used for other water districts (Bigley 2013).

A cost analysis was also conducted by CVWD for various Cr(VI) MCL scenarios in response to the anticipated draft MCL and the potentially large number of affected wells. The analysis reviewed the number of wells, length of pipe needed for connections, size of treatment system, and best treatment options. If an MCL of 1 ppb were to be established, 91% of wells in the district would require treatment. Alternatively, if the MCL were 10 ppb, approximately 55% of CVWD wells would still require treatment. Furthermore, many of the CVWD wells are located on sites too small to construct a treatment plant (Bigley 2013).

Findings from this study could be relevant to ID1's treatment scenario options. Initial findings emphasize the importance of various water quality data on treatment options. It was found that a higher pH improved the Cr(VI) removal in RCF and that the presence of sulfate did not affect the removal (Bigley 2013). This data is an important consideration for ID1 since it has elevated sulfate and pH levels.

V.c Water Quality & Treatment Solutions, Inc.

Water Quality & Treatment Solutions, Inc. (WQTS) began a study in the fall of 2012 utilizing drinking water from ten water districts across the western United States, and conducted bench scale testing of three Cr(VI) and total chromium removal systems. The study is going to be used to analyze the technologic and economic feasibility of Cr(VI) removal for drinking water to the public health goal of 0.02 ppb. Three removal options identified in the Glendale study are also being tested in this study: SBA, WBA, and RCF (Najm 2013).

The water used in the study was tested at ambient Cr(VI) levels and spiked with a Cr(VI) addition of 30 and 60 ppb. Pretreatment water parameters were also measured for pH levels, temperature, turbidity, alkalinity, hardness, conductivity, dissolved oxygen, and nitrate. These parameters are measured in order to assess any potential affect upon the chromium removal technology. It was found that sulfate causes early breakthrough of Cr(VI) in SBA (Najm, 2013), a finding pertinent to ID1, which has levels of sulfate in a (SYRWCD ID1, personal communication, 2013).

Initial data released approximately half way through the study shows promising results for potential total chromium and hexavalent chromium removal down to levels below the PHG. Initial results also found that a nitrate flushing is needed for the WBA and SBA resin systems. This nitrate flushing is required due to the buildup of nitrate and subsequent release, as the chromium ions are preferred by the resin media. It is recommended that this study be followed and findings be analyzed for use in reviewing treatment options (Najm 2013).

V.d City of Davis

In anticipation of the upcoming MCL for Cr(VI) the City of Davis, California partnered with other public and private agencies to conduct a study through the Water Research Foundation on biological treatment for Cr(VI) removal. The goals of the study were to compare efficiency of technology and costs to other current studies, removal of multiple contaminants, and assess potential for Cr(III) remnants to be converted to Cr(VI) via disinfection. Biological fluidize bed reactor (FBR) is the best available technology for perchlorate removal and will be applied to this study. Regulatory requirements for biological treatment in California call for the use of indigenous microbes, post aeration, filtration, and disinfection.

Nitrate is the main food source for the microbes during this process. An anoxic environment is required for the growth of the bacteria, which reduces the nitrate and chromium to less toxic forms. Selenium and perchlorate could also potentially be removed (Drago 2013).

Preliminary results found removal of total chromium and hexavalent chromium from approximately 40-50 ppb influent to about 0-10 ppb effluent. Nitrate removal preliminary results showed approximately 8ppm influent with effluent approximately 0-2 ppm. Furthermore, initial results found that reformation of Cr(III) to Cr(VI) after filtration and disinfection was not significant. The next steps planned in the study are to improve total chromium removal via a coagulant, estimate capital and operation and maintenance costs, determine system footprint, and attempt full scale demonstration project (Drago 2013).

With ID1 affected by both chromium and nitrates in some of its wells, this treatment method could be considered as a more cost effective approach as compared to individual treatment of chromium and nitrate via conventional methods.

VI Alternatives to Cr(VI) Treatment

Given the potentially prohibitive cost of Cr(VI) treatment, District managers may choose to employ a number of strategies that will allow for a consistent supply of water to meet demand *before* resorting to system-wide Cr(VI) treatment. Conversely, instead of trying to solely meet demand, a number of measures could also be employed to reduce demand, thus alleviating pressure on water sources.

VI.a Conservation

Residential water usage in ID1 is among the highest of all water districts in Santa Barbara County (Fig 6.1). ID1 residential per capita demand amounts to 242 gallons per capita per day (gpcd). This rate is second highest in the county, only to Montecito (264 gpcd), and a close third is Hope Ranch (228 gpcd) (SBWCA 2011). Due to the high residential per capita use within ID1, it is possible to target this group for various conservation efforts – such as education, plumbing retrofits, and xeriscaping – could potentially achieve a large amount of water and cost savings. Other potential water reduction opportunities can be met within the agricultural sector, which represents approximately 50% of total demand, through the use of water use audits and converting to more water efficient irrigation methods.

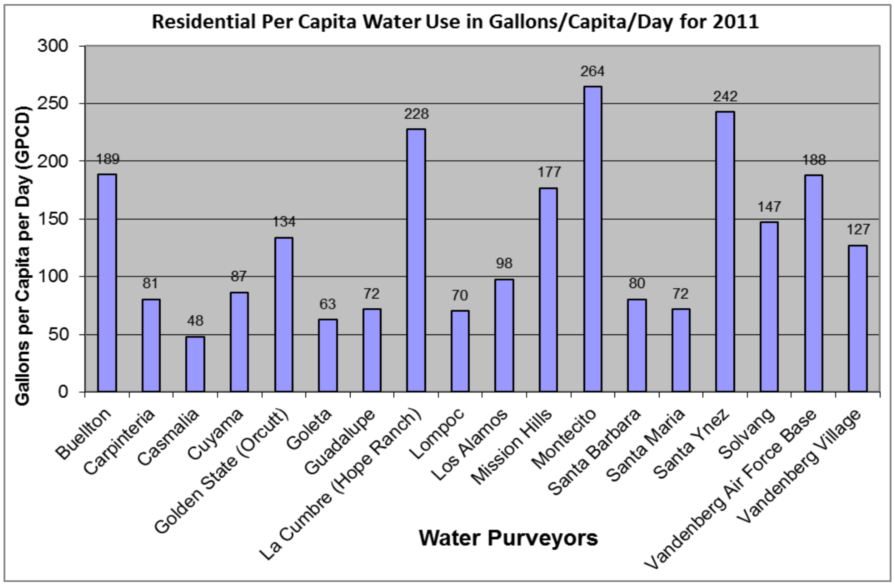


Figure 6.1: Residential water usage (GPCD) among water purveyors in Santa Barbara County, California. Source: (SBWCA 2011)

VI.a.i Education and Plumbing Retrofits

Programs that promote replacing appliances such as toilets, showers, and washing machines with low-flow alternatives are easy to implement, and government-sponsored grants are often available to help fund these efforts (California DWR et al 2010). The District already offers a program that will replace shower heads for no cost to consumers, but participation has been minimal. This is a common problem among plumbing retrofit programs, which can either deliver large water savings to participating water districts (discussed further in case studies found in Appendix A) or have little to no overall effect (Olmstead & Stavins 2009). Low-maintenance conservation options such as those offered by the District may provide significant returns if they are expanded to more of the customer base.

The amount of water that is saved by plumbing retrofit programs varies and is dependent on the initial quality of plumbing (Inman & Jeffrey 2006). Studies suggest that water savings may range from 5% to 20% per household for a total retrofit of all major appliances with an average savings of 8%. The exact science of water conservation is complex and a program's success will often depend on the reception of the public.

Education programs to accompany conservation efforts may improve results at an additional cost. In the case of the District, publicizing the benefits of additional water conservation in the face of the high costs of chromium treatment may encourage greater participation. Based on existing programs, it is reasonable to assume that the amount of conservation achieved by the District through a low-flow fixture and education program will be on the low end of the figures presented above. Based on water conservation programs among other municipalities, a 5% reduction in water usage is a reasonable estimate for conservation in ID1.

Because water conservation programs will reduce overall utility profits in addition to requiring a capital investment, their overall costs may be difficult to predict (Olmstead & Stavins 2009). While costs vary based on the degree of participation in the program, a conservative estimate puts the costs of such a program within the District at around $460,000 (Table 6.1) based on scaled down projects done by the City of Santa Maria, California. These values were used due to the similar demand composition to the District (City of Santa Maria UWMP 2007). Costs of similar programs across the country appear to be highly variable depending on outside factors such as the availability of state and federal grants and staff training requirements, so these figures are meant to be a preliminary estimate of possible costs only.

An additional difficulty with estimating the success of low flow conservation programs comes from the fact that it is difficult to predict how much water will be conserved after the implementation of the program. Unlike direct water treatment, there is no guarantee that investing in a water conservation plan will give the expected returns in terms of increased water supply.

Table 6.1: *Estimated total cost of water conservation measures based on information from 2005 Santa Maria Urban Water Management Plan. Prices were scaled according to the ratio of AF/year delivered to each district.*

	Santa Maria	Santa Ynez (residential only)
Estimated Total Water Delivered in 2010	19,100 AF	2,900 AF
	Actual Values	**Estimates**
Plumbing Retrofits	$600,000	$90,600
Water Audits and Leak Repair	$1.4 million	$211,400
Residential ULFT* Replacement	$1.1 million	$165,000

***Ultra Low Flush Toilet**

VI.a.ii Xeriscaping

Xeriscaping is a method of landscaping, using primarily native plants and grasses, that reduces outdoor commercial and residential water use. In arid regions, outdoor water use can account for 60% of total household use (Sovocool et al 2006). In the District, household water use accounts for about 50% of total demand, meaning outdoor use could account for up to 30% of overall demand. Few water conservation measures target water use for landscaping, which can account for a significant proportion of demand, and is a main driver of peak summer demand. Voluntary Xeriscape programs have been gaining popularity in the recent years as a means of reducing both overall and peak water demand, especially in arid and semi-arid climates (Sovocool et al 2006).

In southern Nevada, an incentive-based voluntary Xeriscape program was implemented in the early 2000s to investigate the magnitude of water use reduction that could be achieved (Sovocool et al 2006). The program provided 45 cents for every square foot of traditional turf landscape converted to xeriscaping, and compared water use to unconverted turf. Xeriscaping resulted in a decrease in outdoor water use of 76% and a decrease in total household water demand by 30% as compared with turf landscaping (Fig 6.2, Sovocool et al 2006). This also resulted in a dramatic decrease in the peak summer demands, effectively flattening the monthly demand curve for those participating.

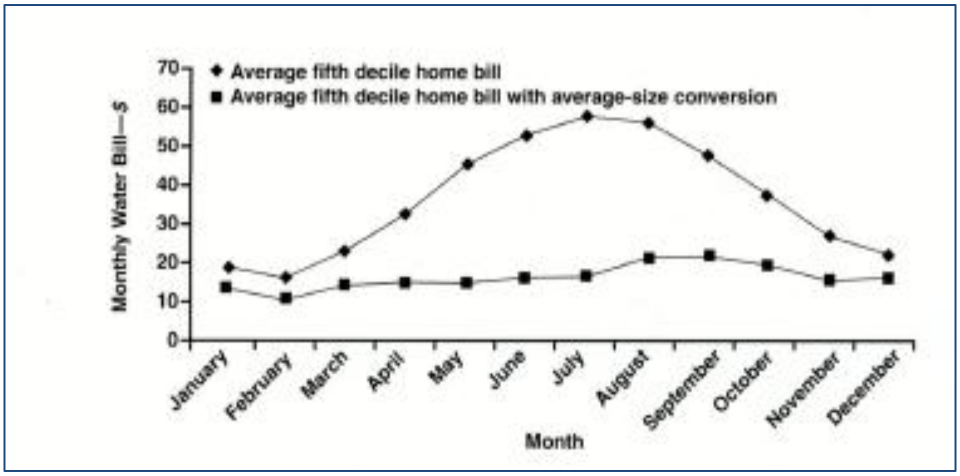


Figure 6.2 Modeled monthly water bill for a typical Las Vegas, NV area home and the same home with an average-sized conversion. Source: Sovocool et al 2006

Although the climate in Santa Ynez might not be quite as arid as that in Southern Nevada, we estimate at least a 20% reduction in household water use would likely occur with conversion to xeriscaping. Table 6.2 summarizes the percent reduction in overall demand that could be achieved in Santa Ynez for various percentages of Xeriscaping conversion (assuming household water use accounts for 50% of demand). Even with this conservative estimate of water savings, demand could be significantly reduced though implementation of a Xeriscape program. Additionally, demand would be reduced even more in peak summer months, resulting in a dramatic increase in system reliability in those months.

Table 6.2: Estimated reduction in water demand as a function of Xeriscape conversion for ID1

Percentage Conversion	10%	20%	30%	40%	50%	75%	100%
Percentage reduction in Demand	1%	2%	3%	4%	5%	8%	10%

Implementing a landscape conversion program to achieve 10% reduction in demand, would mean a majority of the residential customers would need to participate. This is not probably in the short-term, because of the voluntary nature of the program and the time-frame for implementation, but we have devised some cost estimates to show what it might cost. Using a previous study, which sought to estimate conservation limits statewide, we were able to find the average percentage of single-family residence land area within the District that is irrigated. This was broken down into small single-family residences (<1 acre) and what the study refers to as “ranchettes” (> 1 acre), each with a corresponding percentage of irrigated area, 36% and 10% respectively (Hanak and Davis, 2006). Using the Assessor’s Parcel Number (APN) layer from Santa Barbara County GIS, we selected only those parcels with the land use description “single family residential” shown in the figure below (Fig 6.3).

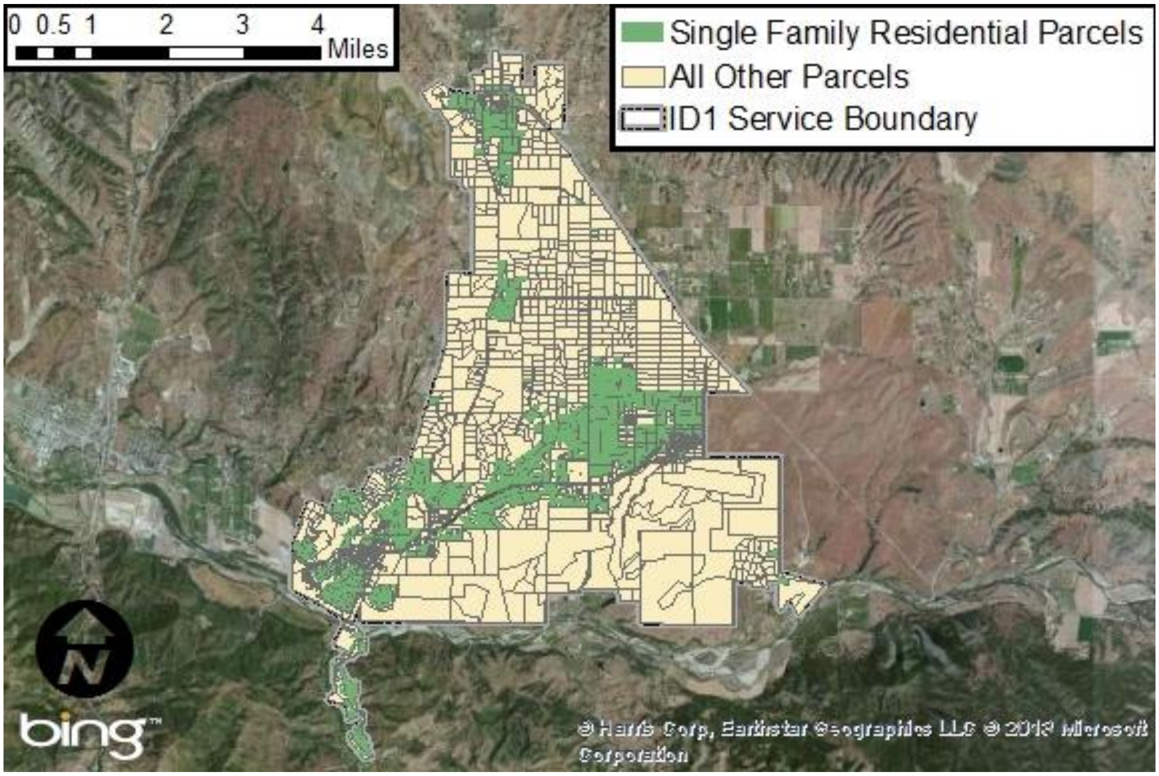


Figure 6.3 Map of single-family residential parcels in ID1. Source: Santa Barbara County GIS

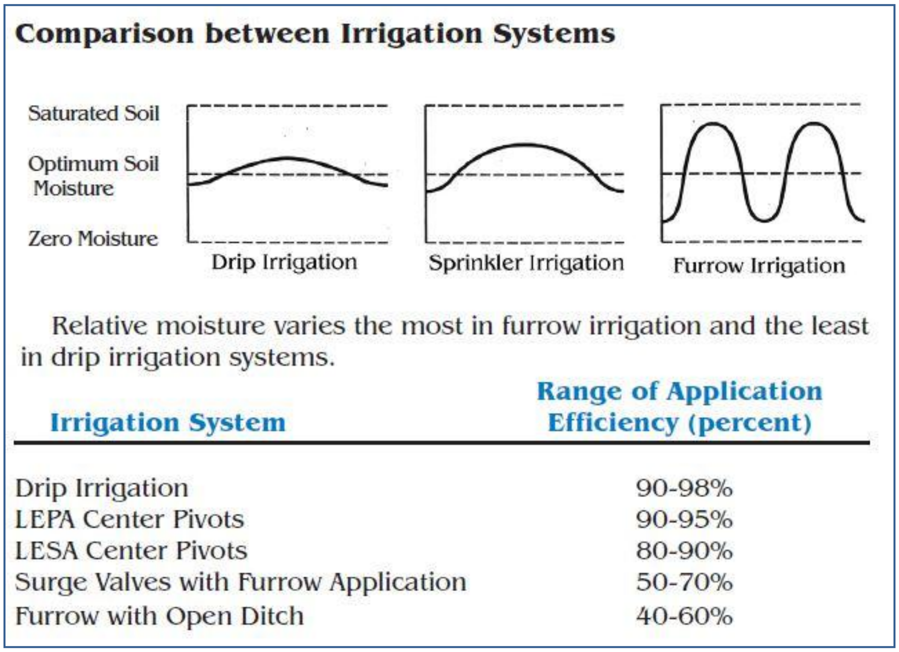
These parcels were split according to their area into their respective classes, and the amount of irrigated area was calculated for each. From this, we were able to calculate the cost of conversion, based on the incentive commonly found in the literature, of $0.45 per square foot. Incentive programs of this type also commonly have a maximum incentive that can be achieved, so we capped the incentive for any single parcel at $900 (Sovocool et al. 2006). The costs of incentivizing the conversion of the single-family residences is estimated to be $350,000 and the cost for ranchettes is estimated to be about $2,100,000, for a total estimated cost of approximately $2,500,000.

A number of things could improve this analysis, such as better data on the percentage of irrigated residential land, as well as estimations for irrigated land area in commercial and industrial uses. Additionally, the reduction in demand we are using is the same over all months, but it is clear that the percent reduction in demand would be higher in the summer months (Sovocool et al. 2006). We would like to account for this, but we did not have data on the monthly breakdown of the percentage of demand representing agricultural as opposed to residential. Nevertheless, since demand will decrease more in the summer months, the time that is most difficult to meet demand, it is likely that even partial conversion of residential landscaping to Xeriscaping would result in substantial increases in minimum monthly reliability.

VI.a.iii Agricultural Water Conservation

With 50% of water demand in the District coming from agriculture, a program that assists farmers with water conservation measures could yield more efficient water usage and significant water savings.

Water use on farms is directly related to production and yield, and it is, therefore, important to implement water conservation strategies that do not decrease yield (California Department of Water Resources, 2013). Irrigation scheduling, irrigation systems, and field preparation are the main components of a proper agricultural water conservation strategy. Irrigation scheduling is based on soil moisture, weather, soil capacity, and crop type. Irrigation systems, like drip irrigation, are designed to achieve the appropriate soil moisture for each crop and reduce the effects of evaporation and wind-drift (Fig 6.4). Field preparation employs systems such as laser leveling, furrow diking, conservation tillage and tailwater reuse (Texas Water Development Board, n.d.).



Relative moisture varies the most in furrow irrigation and the least in drip irrigation systems.

Irrigation System	Range of Application Efficiency (percent)
Drip Irrigation	90-98%
LEPA Center Pivots	90-95%
LESA Center Pivots	80-90%
Surge Valves with Furrow Application	50-70%
Furrow with Open Ditch	40-60%

Figure 6.4 Soil moisture comparisons of various irrigation systems. Source: Texas Water Development Board, n.d.

VI.a.iv Block Rate Structure

Currently, ID1 employs a uniform rate structure for water delivery such that the price of water per gallon used is the same across all usage levels, resulting in a devaluation of water. This happens because the cheaper sources of water are supplied first; and as demand increases, more sources of water are needed, which may be more expensive for the supplier to purchase, but are delivered at the same unit price to customer. On average, households in the United States only pay 0.5-0.6% of their total income for water and sewer bills (Mehan and Kline 2012). The need to treat water for contaminants like Cr(VI) further raises the cost per unit of water from that source. Therefore, when demand is high the District may be losing money by selling more expensive water at lower rates.

Studies suggest that the implementation of a block rate structure can serve as an incentive to conserve water by lowering demand (EPA 2000). Block rate structures are set up such that a water customer pays a base rate for a reasonable amount of water, with each additional unit of water sold rising in price.

Some studies suggest that for each 10% increase in the price of water, residential demand can be reduced by 3-4% (Olmstead & Stavins 2009). It is commonly believed that water demand is inelastic; however with increased prices water use becomes more elastic (Olmstead & Stavins 2009). Furthermore, the elasticity of water purchasing is greater with an increasing block rate structure than with linear uniform prices (Mehan and Kline 2012).

A poorly designed block rate structure may cause revenue loss. Methods for assuring adequate revenue can be the block rate prices on the upper end and estimations of water use (EPA, 2000). Estimates on likely revenue loss need to be compared to the future block rate pricing with careful consideration not to focus on the short-term revenue effects (Mehan and Kline 2012). This was achieved in the Coachella Valley Water District to within 1% of estimations (S. Bigley, Personal Communication 2013).

Another incentive that can add revenue and promote conservation is the installation of a landscape budget. A landscape budget can be created for each property using Geographic Information System (GIS) software or field methods based on the size of the property and current landscape conditions. With estimates of how much water a property should be using, penalties can be added to the bill. If a customer goes over their allotted water budget fees per gallon or unit of water over may be assessed. This landscape budget pricing may only have to be implemented in the peak summer demand season (EPA 2000).

VI.b Purchase Water

The SWP has multiple methods for purchasing water, including Article 21 water and Turnback Pool water. As indicated above, Article 21 water is allocated to SWP contractors who request it based on additional unused water that is held in SWP storage facilities during wet periods, the availability of which is highly dependent on climate and is subject to significant variability within a single calendar year. Additionally, the SWP Reliability Report indicates that amounts of Article 21 water that will be available in each month are expected to decrease significantly under climate change scenarios (State of California 2012). The amount of water that any SWP purchaser is able to obtain through the Turnback Pool is dependent on the amount offered by other purchasers, as well as that particular purchaser's total size (Brown et al 2012). Compared to many other SWP purchasers, ID1 is small in size and thus would probably not be able to rely on the Turnback Pool for large amounts of water even in comparatively wet years.

VI.c Divert and Repair Well Field

As noted, ID1 has licenses for alluvial well production along the Santa Ynez River that specify diversion and withdrawal rights for a 6.0 CFS well field and a 4.0 CFS well field. The 4.0 CFS well field is not currently in operation due to a broken pipeline. Making the repairs necessary to bring their 4.0 CFS well field online is a priority management action, but one that has also proven problematic. The repair requires accessing the channel, which in turn requires timing the work during low flow conditions within the channel. The Department of Fish and Wildlife imposes strict limits on activity within the channel and forbids work during the typical low-flow months. A series of wet years, weather, and conservation releases for the Southern California Steelhead habitat have combined to prevent conditions that would allow the repair. Although the District requires favorable conditions to restore production in the 4.0 CFS field, an option is to temporarily divert the Santa Ynez River (SYRWCD ID1, Personal Communication 2012).

VI.d Blending

Blending could potentially be a more economical management strategy for Cr(VI) than treatment at ID1; however, this solution is not without costs and is subject to certain constraints. Blending water sources has been used nationwide to meet water quality standards and improve the reliability of water supply systems. A closer look at this option reveals that it should be evaluated as a management strategy on a case-by-case basis. At the 34th Annual Old Water Industry Operations Workshop in 2009, Dewis *et al.* presented an evaluation of methodologies for blending water (Appendix #). Impacts associated with the introduction of a new water source can be costly and substantially change water quality. These impacts need to be predicted and evaluated prior to implementation of this strategy (Dewis et al 2009). Depending on the origin and water quality of sources being combined, the following problems may arise and have been found to be problematic in systems throughout the United States (Dewis et al 2009, Lovins et al 2005):

- Lack of consistency in water quality
- Loss of disinfectant residual
- Bacterial regrowth
- Reduced clarity caused by sediment re-suspension
- Release of metal corrosion products from pipe materials
- Disinfection byproduct formation
- Taste and odors from chemical and biological reactions
- Change in speciation of contaminants

Blending water sources to meet water quality standards is complicated and requires careful planning. Prior to action, the water distributor needs to establish desirable risk levels, analyze reliability, and consider the cost of sampling and maintenance. These factors differ by location, water quality, and regulations. General guidelines on blending water sources to address radionuclides are provided by the EPA. The Agency suggests using a margin of safety (MOS) below the pertinent standard, such as 80% of the MCL (US EPA 2013). Some states have their own regulations concerning blending sources that must be consulted (US EPA 2013). In California though, blending is legal and has been used to address nitrate and arsenic contamination (Harter and Lund 2012). An important factor to consider is the potential long-term cost of blending water sources; although this option may be inexpensive initially, in the long run, costs may intensify due to strict monitoring, inconsistent water quality, and infrastructure improvements (Lovins et al 2005). In addition, the cost of compliance with local and federal standards may change over time with new legislation and changing water parameters.

The District is not likely to encounter all the problems experienced in other locations because different sources of water are already distributed in the same pipes and have been shown to have compatible chemistry. However, there is a small probability that mixing sources of water may alter the chemical state of chromium present in the water (i.e. Cr(III) → Cr(VI)) and should be evaluated prior to designing a blending program for the District. In addition, decreased reliability may occur with blending because the well water needs to be mixed prior to delivery.

While there may be potential problems with utilizing blending to meet the new MCL at ID1, it has the potential to be an inexpensive alternative to Cr(VI) treatment. For this reason, we have conducted an analysis of a hypothetical blending operation that utilizes one of the existing Zone 3 reservoirs. For this analysis, we selected four wells closest to the reservoir 5, 7, 24, and 25. We made a conservative estimate that twice the highest observed Cr (VI) concentration in any of these upland wells could be present in each well. We used this value because the Cr concentrations in ID1's upland wells have not always tested consistently, and this seems to be an adequate buffer against future unexpected increases in concentrations.

Assuming the Zone 3 reservoir, which has a volume of 9.97 acre-feet (3.25 million gallons), is used for blending, about 2.35 AF of well water with a Cr(VI) concentration of 34 ppb or less, must be blended with 7.62 AF of water containing no measurable Cr(VI) to achieve a hypothetical MCL of 10 ppb with a margin of safety. Based on EPA MOS recommendations, the acceptable level was determined to be 80% of the hypothetical MCL, or 8 ppb. To achieve this, the District would need connect all four upland wells to the Zone 3 reservoir through separate piping and pump 2.35 AF or less into the reservoir. Then, using the existing infrastructure, the reservoir would be filled with SWP and river well water.

Assuming that this amount of water can be reliably obtained and that all four wells are pumping, it will take about two days of straight pumping to fill a reservoir of this size. This amount of time limits the reliability of the system, because water cannot be supplied from these sources until it is mixed properly. Additional precautions must be implemented to ensure sufficient turnover time of water, and water quality may be impacted if water sits for extended periods of time. The cost to connect the upland wells to the reservoir is approximated to be about $950,000 based on the historical costs of pipe installation.

Unfortunately, this strategy requires a lot of maintenance and does not produce a large volume of additional water, so it is not one the district is likely to pursue. However, blending can be implemented in several other ways that may have lower maintenance and higher returns. One such way is blending two upland wells together, though this is only applicable if the MCL is set high enough. Additionally, this strategy could be used in conjunction with the cluster system treatment for Cr(VI) in a process called "side-stream blending". This would allow the District to have a smaller treatment system and still supply the same amount of water as a larger system.

VI.e Treating Nitrates

Addressing nitrate contamination in ID1 wells that are currently deemed inoperable due to nitrate concentrations that exceed the MCL could provide the District with an additional source of water during times of peak demand.

Nitrate is an odorless, colorless, and tasteless form of naturally-occurring nitrogen present in the environment. It is a stable and highly soluble ion with a low potential for co-precipitation or adsorption.

Common sources of nitrate include microbial decomposition of organic material, natural and synthetic fertilizers, animal feedlots, municipal waste, lightning, and atmospheric deposition (Self and Waskom 2008). Moderate concentrations of nitrate are benign to humans; however, contamination of drinking water is an evolving health concern (Gulis et al 2002). Acute exposure to nitrates has been linked to methemoglobinemia in infants ("blue-baby syndrome"). Further, chronic exposure to elevated concentrations of nitrate can lead to various blood disorders, gastrointestinal problems, diabetes, and has been linked to lymphoma and colorectal cancer (Kostraba et al 1992; Gulis et al 2002).

Currently blending is the most cost-effective option for the management of nitrates in drinking water; however, the feasibility of this option is anticipated to decrease as groundwater plumes of nitrate grow and as other contaminants are more strictly regulated (Harter and Lund 2012). Despite these options, many small districts are unable to comply with the standard because of the associated costs (Harter and Lund 2012).

VI.f Well Capacity Improvements

Some of the ID1 wells do not have high levels of chromium or nitrate, but have experienced a reduction in efficiency due to age. Many older wells lose their capacity due to blockages, known as incrustations, deposited on the screens or within the pores of the gravel and rock lining the walls of the well. These incrustations can be removed by a variety of mechanical and chemical methods. The mechanical method involves either manually scraping off the affected areas or, more commonly, pumping water under high pressure into the well. This high-pressure water fractures the incrustations, allowing for larger pore spaces in the surrounding gravel of the well and the wire mesh liner that encloses the well. The second method of well rehabilitation, known as acid washing, involves the use of chemicals to dissolve the solid encrustations by altering the pH and redox conditions of the well. Despite permitting requirements of acid washing due to possible safety and environmental implications (Houben and Treskatis 2007), ID1 managers prefer the method due to historical contracts with trusted and reliable individuals.

VI.g Zone testing

One treatment method that has been suggested for the District is based on preventing the geological sources of chromium from releasing Cr(VI) to the water table in the first place. A method known as "zone testing" would be used to distinguish Cr(VI) concentrations at different water table depths in the well. If a specific geological layer was found to be primarily contributing to Cr(VI) concentrations in the water, a seal could be installed on the inside of the well at that depth. This would prevent further addition of the chromium while leaving the well operational. Zone testing can cost between $10,000 and $20,000 per well. Depending on the depth of the source layer, installing the barriers on the inside of the well may cost up to $200,000 per well. This method would be particularly cost effective as no ongoing maintenance would be necessary for operation, as was the case for all other treatments considered. Zone testing is becoming a more common practice to produce depth-dependent water quality data when initially preparing to drill a well (Gossell et al 1999). While this test is often formed on newly drilled wells, several companies are also able to perform retroactive tests on existing wells (BESST Inc. 2012).

After communication with external advisors, we have hypothesized that the Cr(VI) is most likely originating from older water that is entering the well at the deepest points in the aquifer. If this is the case, there is a chance that additional wells may start to show positive Cr(VI) levels over time, making it beneficial to immediately map out the geological profile of each well to identify a definite geologic source.

Zone testing for nitrates may also be useful in determining the level of the water table from which nitrates are infiltrating. If the nitrate source is primarily from the upper levels of the well, it may be possible to use some sealing technique to prevent further infiltration.

VII Reliability Optimization Model

A key objective of any water purveyor is to provide highly-reliable, clean water to its customers at a reasonable cost. To the Santa Ynez River Water Conservation District, Improvement District No. 1 (ID1 or "District"), this means developing a water supply management strategy that meets drinking water standards in light of the anticipated MCL for hexavalent chromium (Cr(VI)). System reliability can be measured in a number of ways and is defined here as the ability for ID1 to meet the water demand of its customers, while maintaining a consistent store of water above some threshold of redundancy in supply.

As noted above, the reliability of a water supply-system is a function of water use (demand) and the ability to meet that demand immediately when it is needed. The nature of water delivery that differentiates it from many commodities is that managers do not know ahead of time with very much precision what demand they will need to meet. This uncertainty creates the need for capacity in the water supply portfolio to handle extreme conditions of water demand. This buffer, or supply redundancy, determines whether this is the case and the degree to which the system can reliably deliver water. In order to measure the overall consistency of water delivery for ID1 under various possible scenarios, our group created a Microsoft Excel-based mathematical model that measures monthly system reliability as a function of capacity and demand.

$$R_j = \frac{\sum_{i=1} C_i}{\bar{D}_j}$$

Where,

$R =$ maximum reliability
$C =$ capacity of source
$D =$ mean monthly demand
$j =$ month
$i =$ source

System resilience, which represents the system's ability to recover from outside shocks, can be another important objective to a water supply district. Outside factors, like changes in Cr(VI) and nitrate levels or system leaks, as well as changes in regulatory pressures, can all affect system resilience.

VII.a Metrics of Reliability

VII.a.i Capacity

Capacity is the maximum quantity of water that could *potentially* be delivered in a certain period of time, given current states of the system. The model's starting point includes only the capacity that exists within the current supply portfolio, meaning that it excludes possible capacity resulting from any management actions outside the operation of the system at its maximum yield. This maximum capacity for a given month is a derived measure which sums all sources of water available for that month, *given* the requirement that supplies must be *allocated* over a future period, and so cannot be brought to bear all at once in a given month. Different techniques were used to gauge this quantity for each source below.

- ***River Well*** production over a year is limited both by operational conditions and the District's licensing by the California State Water Resources Control Board (SWRCB). Monthly capacity was modeled as the legal monthly limit, subject to the yearly constraints mentioned above. This implies that ID1 has flexibility in the timing of river well production so that realized monthly capacity is determined after optimization.

- ***State Water & Cachuma Exchange*** is a yearly entitlement. It includes 2,651 acre-feet of Lake Cachuma water that is exchanged for water from the State Water Project (SWP). State water is determined each year by the California Department of Water Resources (DWR) according to snowpack runoff availability and equals a percentage of the yearly contract of 700 acre-feet. Monthly capacity for this source is constrained by these yearly amounts only. A very low allocation of state water could prevent an exchange and lead to a shortfall in the Cachuma entitlement. ID1 managers estimate this event would occur with an allocation below 22.5% (SYRWCD ID1, Personal Communication 2012). There are legal and practical ramifications of this outcome that aren't fully understood.

- ***Upland Wells*** have maximum yields that are governed largely by hydrological conditions and prior use, and must be estimated. Additionally, yields fluctuate over time. To estimate maximum monthly capacity for each well, the supply data for fiscal years 1998 through 2012 were used to sample observed maximum monthly production. These values were scaled down from the year in which they were observed by 1% per year to account for efficiency loss over time. During the drought of the late 1980s – early 1990s, the upland basin produced a maximum of 5,294 acre-feet; however, we have modeled the upland wells more conservatively by adjusting for age and potentially large draw-down for over more than six months. Draw-down was modeled using a third order polynomial equation that resulted in a 10% reduction in capacity every six months the well is in use. We did not model recovery, so a well's capacity was determined according to the month that it was last in use even if it had been turned off during interim months.

VII.a.ii Demand

Water demand was simply determined using ID1's records of actual water delivery (in AF) from 1998 through September 2012. Mean historic monthly demand values and deviations from these means for that time period were used for modeling purposes and for a measure of expected demand. Logically, demand trends and seasonality indicate that water usage is highest in the summer months (Table #, Fig #). Notably, although demand is at its peak in these months, and water supplies are often pressured, the coefficient of variation shows the least uncertainty as a percentage of mean demand for June – September.

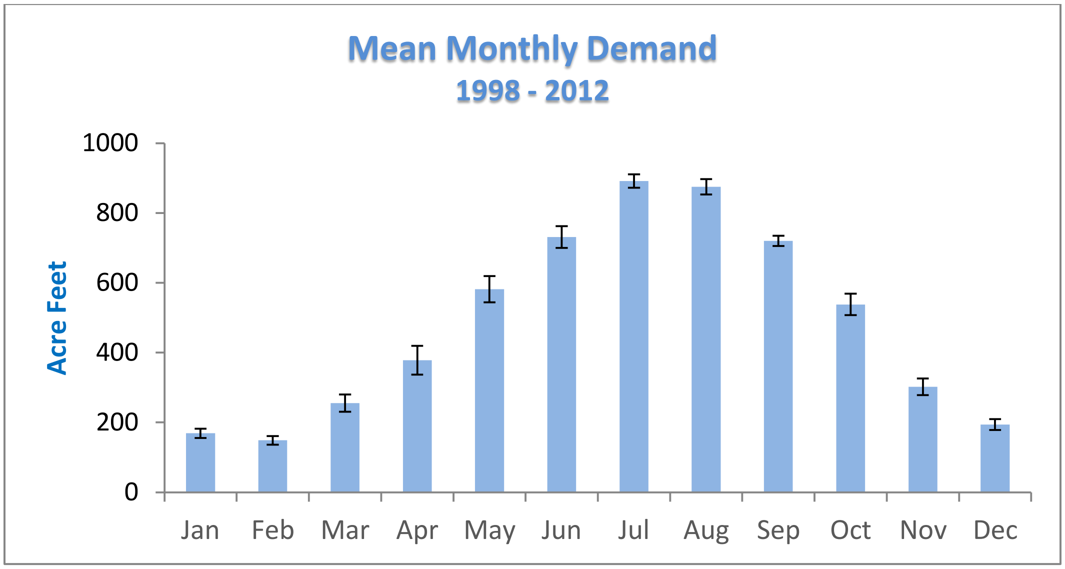


Figure 7.1 Mean historic monthly water demand (in acre-feet) in ID1 from the period January 1998 – September 2012.

VII.b Modeling Reliability

The objective of the quantitative model is to facilitate analysis of reliability for various scenarios that ID1 could potentially experience. First, it was necessary to define a specific metric of reliability as an objective of District managers and model the input variables that determine it. Because ID1 managers are decision makers who seek maximum reliability of their system as one goal and have various resources and strategies at their disposal, an optimization component is needed so that pre-analysis, or base-line reliability, is as realistic as possible. With an objective function, and this optimization component in place, the modeled scenarios could then be analyzed numerically in terms of reliability of the system. Finally, with the behavior of reliability estimated, capacity needs can be identified that inform the scope and timing of management actions to enhance reliability.

Various measures of reliability were proposed as objective functions. The most straightforward was simply the redundancy factor, as acre-feet in capacity per acre-feet of expected demand per month; which is the number of times that demand can be met (Fig 7.2). If this measure is 1, deliveries are just equal to the expected demand, and if it is less than 1, there is a short-fall. A second metric was derived similarly as capacity divided by expected demand, but with the mean plus one standard deviation, or the 84th percentile of demand, used instead of the mean to account for fluctuation. This measure leads to the counter-intuitive result of higher reliability in the driest months of summer. As noted, reliability was calculated by optimizing it given the constraints for each source.

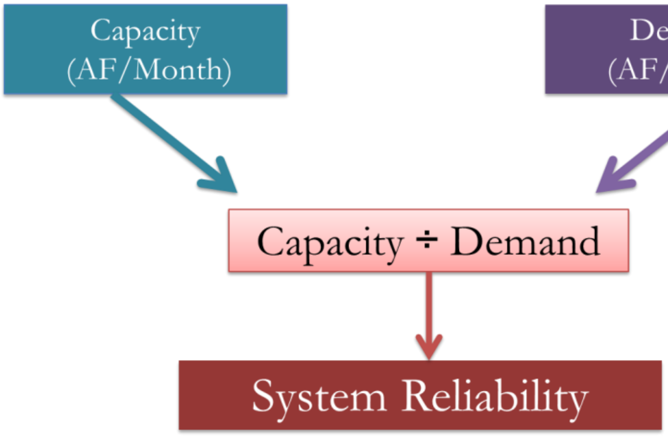


Figure 7.2 Conceptual model representing System Reliability as a function of total system capacity divided by average historic demand

The Microsoft Excel Solver tool was used to optimize reliability (Appendix C). Specifically, Solver was used to allocate water supplies so as to maximize the minimum monthly value of reliability over the course of one year. The cells in red are variables in the computation.

VII.c Scenarios

VII.c.i Climate Scenarios Used in the Model

In the model, changes in climate were accounted for by changes in the allocation of the District's total SWP entitlement. The SWP deliveries that correspond to each scenario in the model are shown below in Table 7.1. Because the District does not experience a reduction in the Cachuma Exchange water until SWP allocations drop below 25%, reductions in all scenarios except dry and very dry were only reflected in the 700 AF/year that the District directly contracts from the DWR.

Table 7.1: *Climate scenarios modeled and corresponding allocated percentages of State Water Project entitlement.*

Model Climate Scenario	Allocated % of State Water Entitlement
Very Wet	100%
Wet	80%
Average	60%
Dry	24%
Very Dry	11%

These amounts were chosen based both on historic deliveries and projections done by the DWR when determining the future reliability of the SWP (Brown et al 2012; State of California 2012). In the latest Reliability Report published in 2012, the DWR estimates that future demand for SWP will stay consistent with current levels, which have peaked at about 4,133 thousand acre feet per year (tAF/year). Historic data indicates that over the course of the SWP, average annual deliveries equal about 60% of allocation, which was then chosen for our own average scenarios. DWR models for future reliability categorize the low range of deliveries (chosen to represent the dry scenario) to start at around 1,000 tAF/year, which corresponds to an allocation to all SWP contractors of about 24% (State of California 2012).

For modeling purposes, the very dry scenario was meant to reflect an intense drought event, rather than a year of low precipitation. For reasons mentioned above, deliveries during the 2007-2009 drought may not be an accurate reflection of what might be expected in such an event. Additionally, the model is meant to be as conservative as possible to give a sense of what planning would be required in a worst-case scenario. To determine what SWP allocation could be expected in this case, we once again used data from the Reliability Report. As part of the report, the DWR ran models using historic drought conditions with additional information reflecting both land use changes and the impacts of climate change. Climate change scenarios also reflect the environmental demands on SWP water sources for local fisheries as defined by the National Marine Fisheries Service (NMFS). From this information, the DWR then estimated average delivery for single and multiple year drought scenarios (Table 7.2) (State of California 2012).

Table 7.2: *Estimated average SWP deliveries under different drought scenarios (corresponding SWP allocation). All values in tAF/year.*

Long-Term Average	Single Dry Year	2 Year Drought	4 Year Drought	6 Year Drought
2,466 (60%)	**443 (11%)**	**1,457 (35%)**	**1,401 (34%)**	**1,227 (30%)**

This suggests that a single dry year event has the potential to stress available resources the most, and because of this, the estimate of an 11% allocation was chosen for the “Very Dry” Scenario.

As part of these scenario models, the DWR generates a corresponding probability for ranges of allocations occurring. In this report, DWR estimates that there is only a 7% chance of a delivery of less than 24% (1000 tAF/year) occurring. Allocations between 24 and 50% have a 17% chance, with the remaining 50% probability for deliveries of over half of the SWP’s total possible allocation (State of California 2012).

Less information is available for years with an allocation of above the average of 60%, though a general trend of decreased likelihood as the total allocation approaches 100% may be observed (State of California 2012). For this reason, the SWP allocations chosen for the Wet and Very Wet scenarios were based on even percentage increases from the average level. Because these percentages represent very small increases in the amount of water available to the district above the average scenario, they were included only for the potential planning needs of the district and were not significantly analyzed for this report.

VII.c.ii Cr(VI) Maximum Contaminant Level

We accounted for potential future Cr(VI) regulations by examining the effect of four different potential MCLs on ID1 water supplies ranging from the current total chromium MCL to the recent PHG: 50 ppb, 20 ppb, 10ppb, and 0.02 ppb. Numerous factors impact the speciation of chromium in water, meaning there is no guarantee that current Cr(VI) concentrations will remain stable. Because of this, we chose to use recorded total chromium measurements as our determining factor for whether or not a well is allowed to be in use. If a well has a total chromium concentration either above the scenario MCL or within 1 ppb below the scenario MCL, that particular scenario does not use any water from that well.

The major factor we considered in choosing the range of hypothetical Cr(VI) MCLs is the recent setting of the arsenic MCL to 10 ppb, despite a PHG of 4.0 parts per trillion (California DPH 2008; Fan and Alexeeff 2004). The Cr(VI) occurrence data in California, and accompanied costs of treatment, suggests that an MCL of less than 10 ppb is unrealistic (WRF Cr(VI) Workshop, Personal Communication 2013), due to the greater increase of occurrences below 20 ppb within the state (Seidel 2013). With this in mind, we chose to model hypothetical MCLs representing a range from the PHG to the current total chromium MCL: 0.02, 10, 20, and 50 ppb.

VII.d Management Actions

In order to address the shortfall in system reliability under each climate conditions and Cr(VI) MCL, we chose to focus on several of the previously mentioned management actions that the District is likely to employ. With the high cost of Cr(VI) treatment, we chose purchasing SWP water, repairing the broken alluvial well field, and conservation as the measures to implement before resorting to treatment. These particular options were chosen due to ID1 managers' preference and the limitations of the other management options. If system reliability fell below a certain threshold, the management actions were applied in the model in a step-wise manner, beginning with the most feasible and relatively economical short-term solution and ending with the most cost-intensive long-term solution (Fig 7.3).

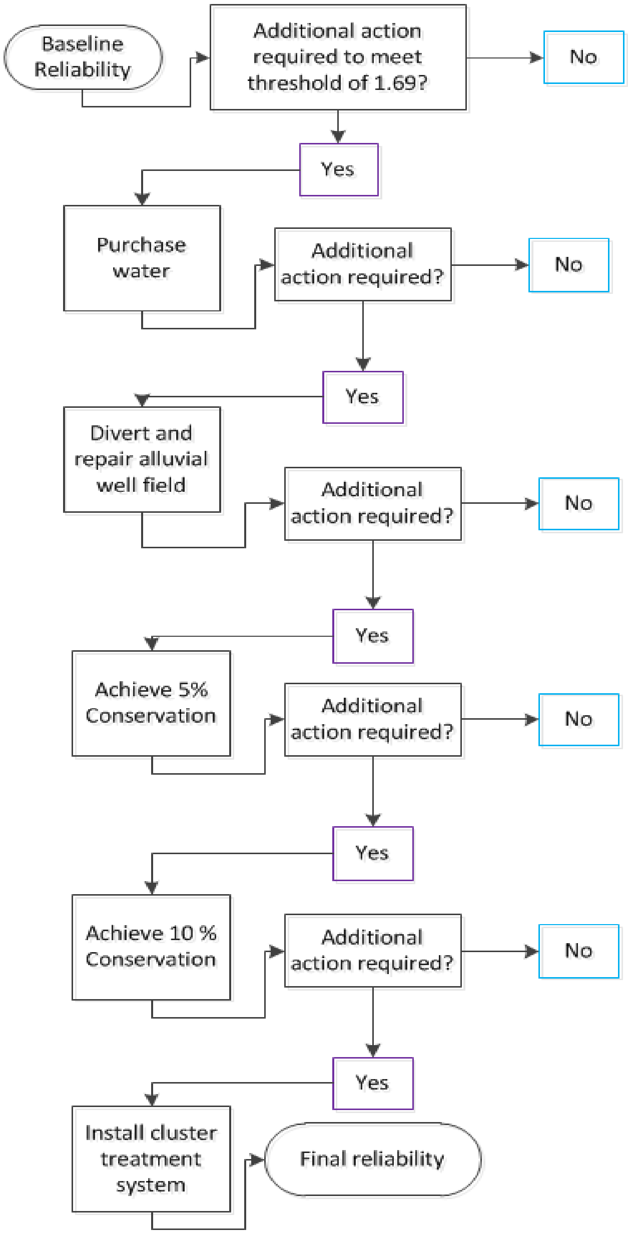


Figure 7.3 Decision tree representing management actions applied to increase reliability as a result of the supply shortfall associated with varying climate conditions and Cr(VI) MCLs.

VII.d.i Water Purchase

Due to the relatively inexpensive nature of water purchasing, we implemented this measure first to increase total reliability. As previously mentioned, the SWP has multiple methods for purchasing water, including Article 21 water and Turnback Pool water. The water included in our model was assumed to come from the Turnback Pool, based on consistent availability and documented historic use by the District.

Based on water purchased by different SWP participants in past years with a variety of hydrological conditions, the amounts shown in Table 7.3 were chosen for the total amount that could be purchased in the corresponding model climate scenario. Note that though very little water will be available under the very dry climate scenario, the effects of drought may not occur evenly across the State. Locations experiencing a lesser impact may still make additional water available through the Turnback Pools.

Table 7.3: *Amount of water that the model is allowed to purchase for each corresponding climate scenario under the water purchase management action.*

Model Climate Scenario	Purchase Available (AF) from the State Water Project
Average	**500**
Dry	**250**
Very Dry	**100**

Water purchased from the first of the two Turnback Pools is sold at 50% of the total SWP Delta water rate ($12.75/AF), while water from the second Pool is sold at 25% ($6.37/AF). For the sake of making a conservative cost estimate, we assumed that all water would be purchased from the first more expensive Pool. While Turnback Pool water is not made available until March, the model is allowed to allocate water across all twelve months to give a better annual estimate of reliability. Also, because the model is intended as a planning tool only, the source of water purchase can be changed in the future according to the discretion of District managers (Brown et al 2012).

VII.d.ii River Well Repair

As noted, ID1 has licenses for alluvial well production along the Santa Ynez River that specify diversion and withdrawal rights for two well fields, one of which is not operational due to a broken pipe connecting the wells to the system. The combined licenses allow for 3,308.9 AF per year and repairing the broken 4.0 CFS well field could provide about an additional 1000 AF . The amount of production from the 6.0 CFS field alone is less than the 3,308.9 AF, and less than its individual limit of 3,291.3 AF because of operational constraints. This would be a significant undertaking, with a preliminary estimated cost of $75,000 in addition to permitting, with extensive engagement of regulators and stakeholders (SYRWCD ID1, Personal Communication 2012).

VII.d.iii Conservation

We selected two scenarios to reflect the changes in demand that can result from implementing different conservation measures at the District. We choose two values – 5 and 10 percent – to reflect what can reasonably be achieved with two conservation strategies: low-flow fixtures and Xeriscaping. ID1 supplies 50% of its water to residential customers and very little conservation is currently practiced, providing a tremendous opportunity for water savings.

The installation of low-flow fixtures can save a significant portion of household water, up to 20% (Inman & Jeffrey 2006). The initial investment for implementing this type of conservation is very low, many low-flow appliances are already offered by the District, and an educational pamphlet, motivated by the Cr(VI) MCL would be easy and cheap to produce, and effective. Research on water conservation programs implemented by other municipalities suggests a 5% reducing in usage to be a reasonable estimate for such conservation measures (Appendix A).

The single largest source of household water use, especially in summer months, is landscaping. Xeriscaping can significantly reduce the amount of water needed for landscaping, resulting in decreases of up to 30% of total yearly household demand, and in summer in particular (Sovocool et al 2006). Assuming 10% reduction in water use is certainly feasible in ID1, although it will be significantly more expensive than installing low-flow fixtures, as an incentive program will likely be necessary (more information on Xeriscaping can be found in Appendix A).

VII.d.iv Cr(VI) Cluster Treatment System

The final and most expensive management action is the installation of a centralized treatment facility utilizing RCF, with a capacity of 2,600 gpm, based on the four chosen wells. This facility may be located at well 5 since there is ample flat space owned by the District. This location is also near three other Cr(VI) affected wells within the Los Olivos area. The close proximity to other wells that may need treatment makes this option more viable. Results

VII.e Reliability Results

After running all scenarios under the baseline chromium MCL (50 ppb), we decided that the reliability under a very dry climate represents the minimum acceptable level of reliability that would not warrant extraordinary actions in the District's judgment, and therefore our logical baseline. By this reasoning, the reliability under these circumstances represents the lowest the District would be willing to meet without pursuing options to increase this reliability. The reliability value under very dry conditions and the current total chromium MCL is 1.69. Table D1 in Appendix D shows the reliabilities for each climate and regulatory MCL scenario with management options applied sequentially until the minimum reliability is reached, or all options are exhausted.

VII.e.i Average Climate

Under an average climate (i.e. 60% allocation of State Water Project entitlement) with current chromium regulation no further treatment is required, as the reliability threshold is based on the more water-limited very dry climate under the same regulatory scenario. An average climate with 20 ppb MCL achieves the threshold after water purchase and alluvial well repair, while the 10 ppb MCL takes all available options before it reaches the threshold (Fig 7.4). The reason for this large difference between MCLs is that the initial threshold was determined when all the upland wells were able to operate, and under the 10 ppb MCL, only one well is able to operate. Under a 20 ppb MCL, four of the highest producing wells are still on, so the difference in water availability between 10 and 20 ppb scenarios is very large. Finally, under an average climate and with 0.02 ppb MCL the available options are not enough to raise reliability above the threshold and it stands at 1.46 after all have been applied (Fig 7.4). While the 0.02 ppb MCL does not meet the threshold reliability, it still is able to supply water for the District under an average demand year (1.00 reliability). Reliability breaks the 1.00 reliability mark after water purchase and divert and repair (Fig 7.4).

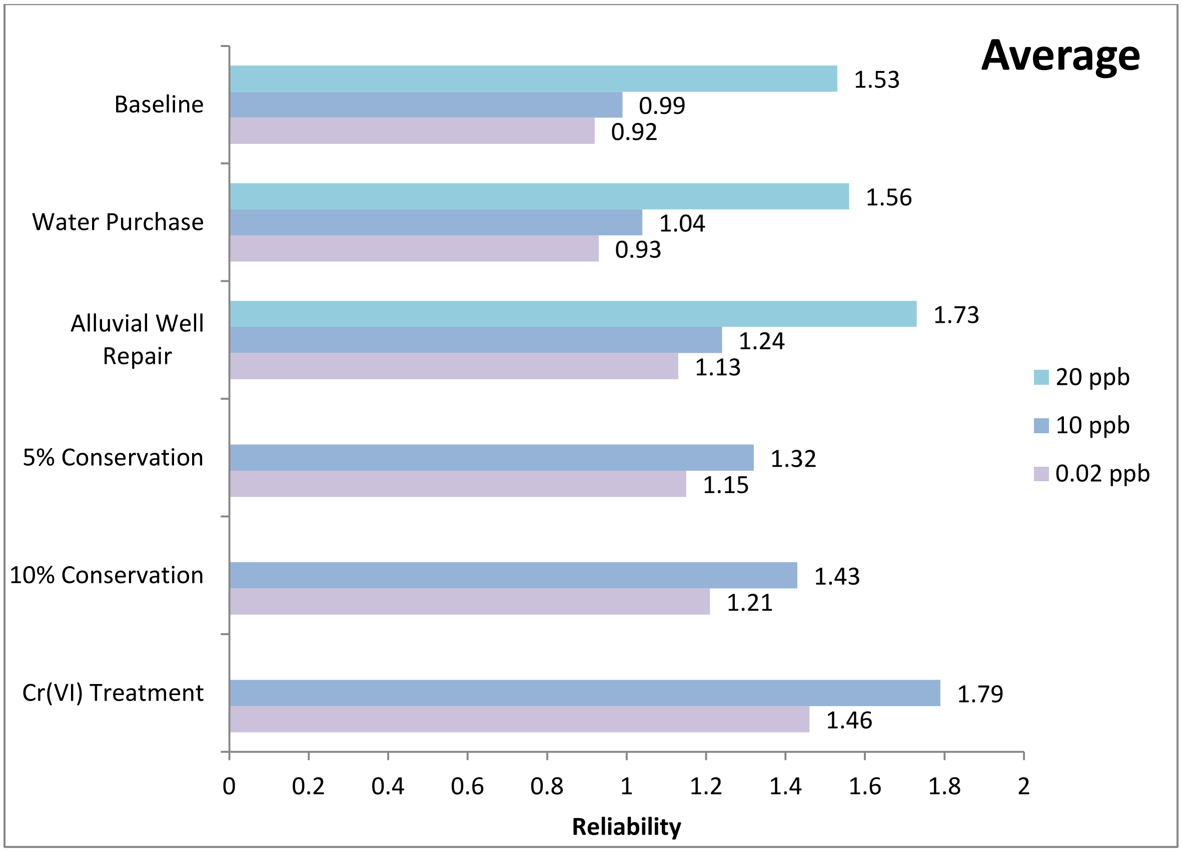


Figure 7.4 Model results under average climate conditions (i.e. 60% allocation of State Water Project entitlement).

VII.e.ii Dry Climate

For the dry climate simulation (i.e. 24% allocation of State Water Project entitlement), only the baseline and 20 ppb MCL are able to achieve the threshold level (Fig 7.5). Under the 20 ppb MCL, it takes water purchase, alluvial well , and 5% and 10% conservation to get above the threshold, leaving the reliability at 1.79. Both 10 and 0.02 ppb MCL scenarios are unable to meet the reliability threshold after utilizing all available options, standing at reliabilities of 1.65 and 1.54 respectively. However, these MCL scenarios do meet the average demand for the District. The 10 ppb MCL scenario just meets demand after water purchase and alluvial well repair, while the 0.02 ppb MCL also requires 5% conservation.

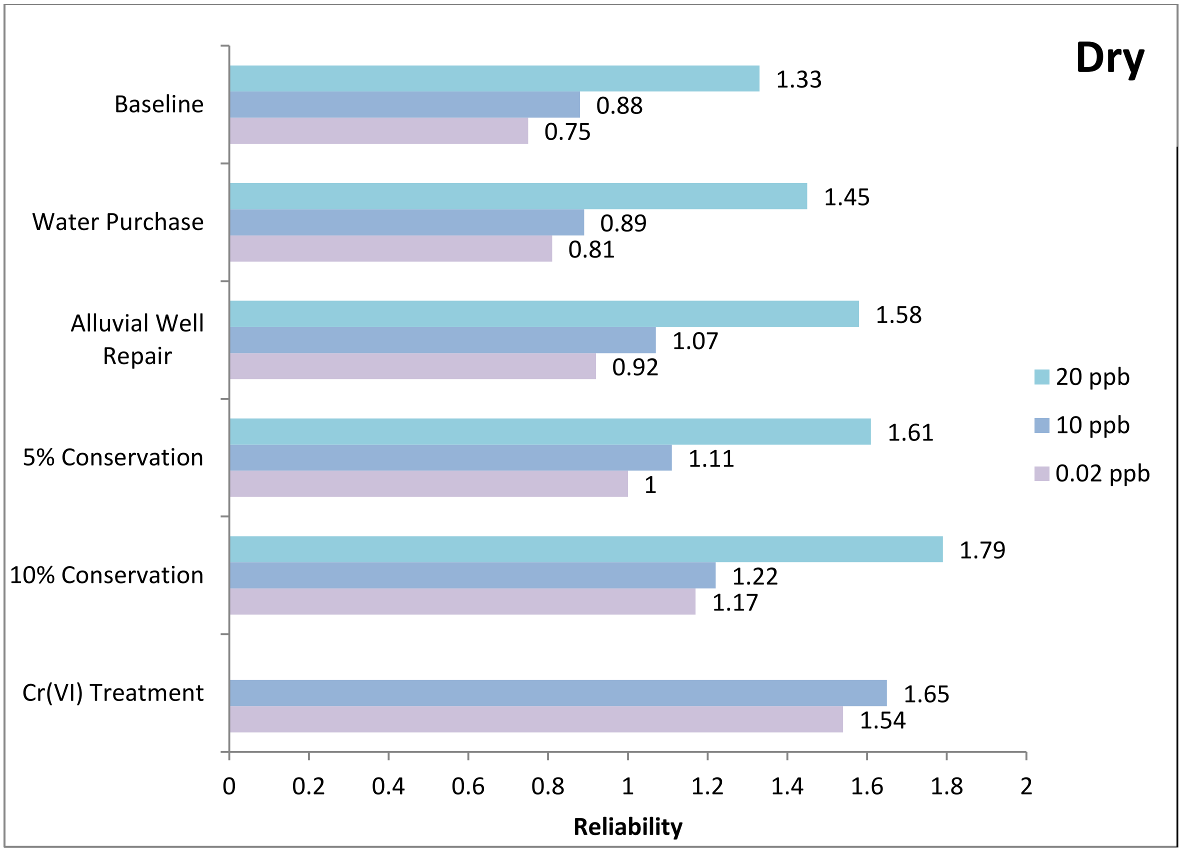


Figure 7.5 Model results under dry climate conditions (i.e. 24% allocation of State Water Project entitlement).

VII.e.iii Very Dry Climate

Under the very dry climate simulations (i.e. 11% allocation of State Water Project entitlement), none of the MCL scenarios are able to meet the reliability threshold set by the very dry baseline case (Fig 7.6). After all available options are used, the reliabilities stand as 1.53 for the 20 ppb MCL, 1.39 for the 10 ppb MCL, and 1.31 for the 0.02 ppb MCL. While these scenarios don't meet the 1.69 threshold, they do all meet the average demand of the District. The 20 ppb MCL scenario meets average demand without requiring any further management action, starting with a reliability measure of 1.13. Both 10 and 0.02 ppb MCLs take all available options before they break the 1.00 barrier, ending with 1.39 and 1.31 reliabilities, respectively.

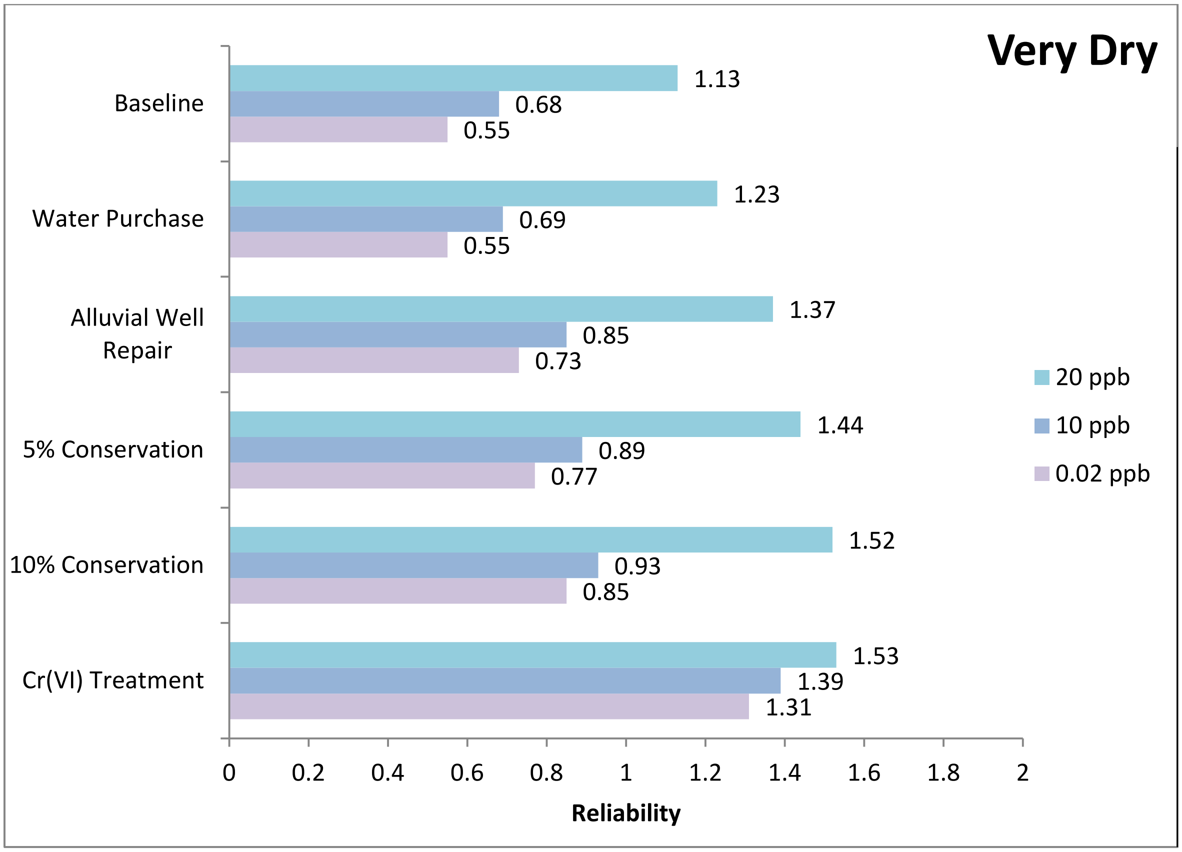


Figure 7.5 Model results under very dry climate conditions (i.e. 11% allocation of State Water Project entitlement).

VII.f Shortfall

Six of the original 12 scenarios were unable to meet the reliability threshold of 1.69 set by the very dry baseline condition. For these six scenarios, a shortfall measure was calculated for each month to determine how much extra water would be needed to get those months up to the threshold value (Table 7.4). Unsurprisingly, the largest shortfalls are observed in the late spring to late summer (May-September). The largest monthly shortfall occurs under the very dry 0.02 ppb MCL scenario, amounting to 302 AF (Table 7.4). Based on this, the reliability threshold can be met if District managers can find a way, beyond the options set forward, to ensure an extra 300 AF/month is available at any given time.

***Table 7.4**: Monthly shortfall in acre-feet for "Climate + MCL" scenarios not meeting reliability threshold after all management options were applied*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average + 0.02	35.0	18.8	50.8	77.9	119.7	150.2	184.2	180.3	149.0	94.5	0.0	0.0
Dry + 0.02	0.0	11.3	18.3	50.0	76.9	96.8	118.0	115.8	95.3	70.4	0.0	0.0
Dry + 10	4.9	4.4	3.0	12.6	19.5	24.5	29.9	29.4	24.2	18.0	0.0	0.0
Very Dry + 0.02	0.0	0.0	86.5	127.3	197.1	246.7	302.0	296.6	243.7	173.9	0.0	0.0
Very Dry + 10	1.7	0.0	53.6	92.2	154.9	194.9	237.6	233.2	191.9	128.5	0.0	0.0
Very Dry + 20	0.0	0.0	0.0	0.0	79.4	102.0	124.4	122.1	100.4	72.7	0.0	0.0

VII.g Scenario-Specific Monthly Reliabilities

The final minimum reliability measures are shown in Table D1 in Appendix D, but the goal of our optimization was to maximize the minimum monthly reliability, so some months will be over this minimum value. Figure 7.6 illustrates this for the average climate 50 ppb MCL baseline scenario.

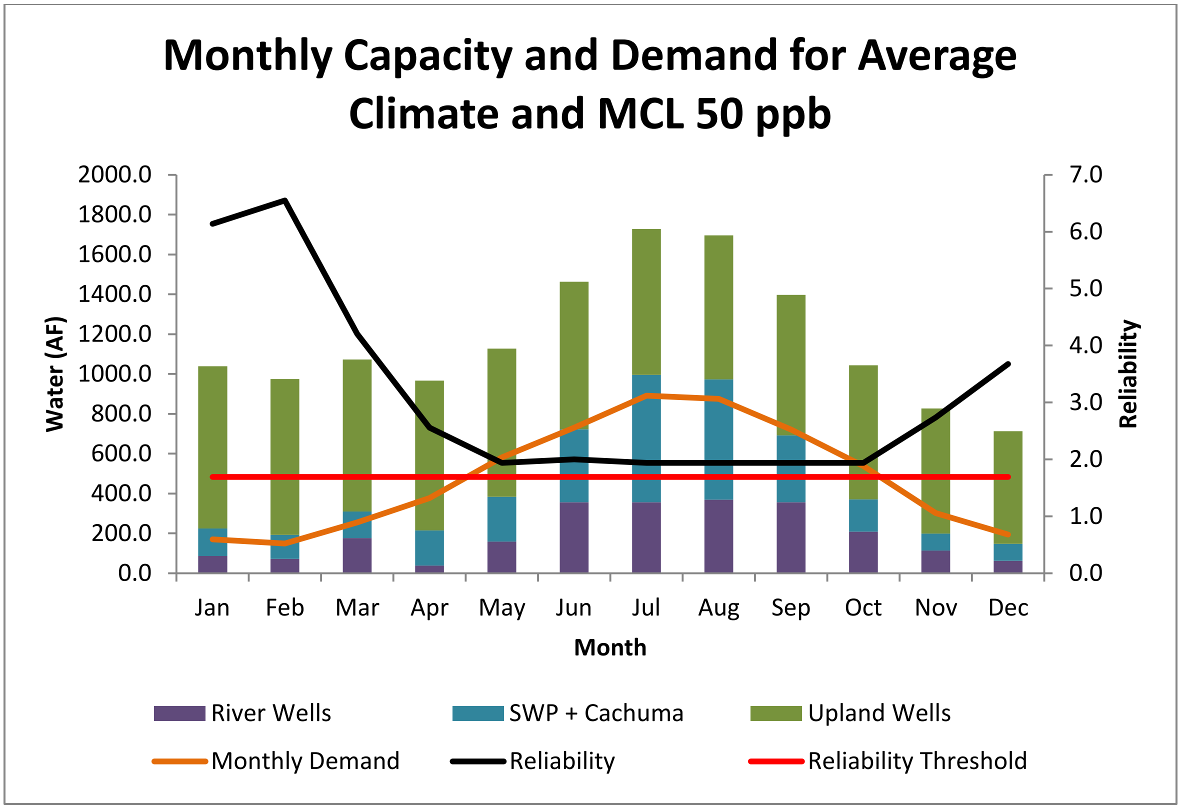


Figure 7.6 Monthly breakdown of supply, demand, and reliability for the baseline scenario (Climate = average; MCL = 50 ppb). The red line indicates the threshold reliability of 1.7 and the black line follows monthly reliability values. The red, green, and blue bars indicate the amounts of each water source that are available in each month, and the orange line tracks monthly demand.

Figure 7.6 indicated that the reliability is much higher in the winter and spring months because of the low average demand when compared to the summer months. It is important to note that reliability cannot be increased in the summer months by allocating more of the water from the winter months to the summer because there are monthly constraints on well pumping, for both the upland and river wells.

Figure 7.7 shows the worst-case scenario, very dry climate and an MCL of 0.02 ppb, with all available management options utilized. Under this scenario, there is an additional supply source, water purchase, shown by the light blue portions on top of many of the monthly supply bars. In this case, even with all the management options, the District is not able to meet the minimum reliability for all months, though the winter months do meet this threshold.

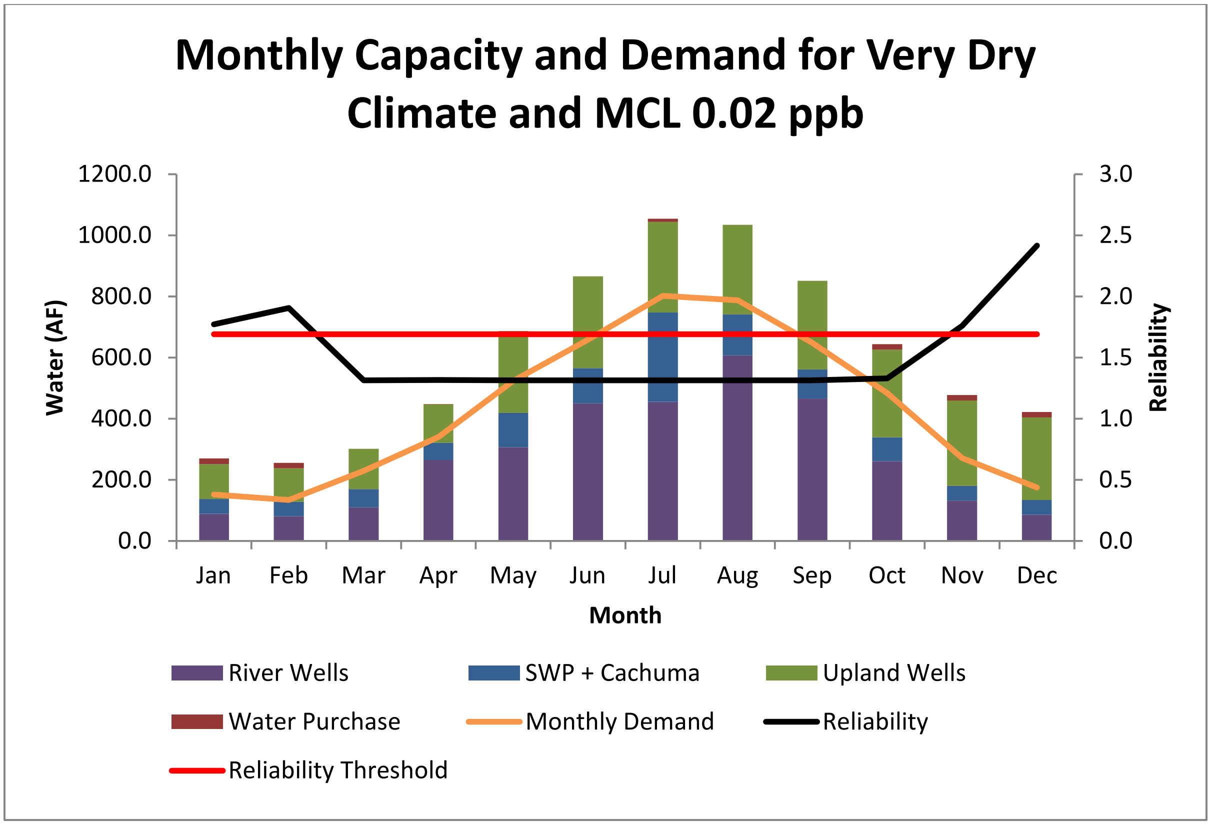


Figure 7.7 Monthly breakdown of supply, demand and reliability for the worst case scenario. The red line indicates the threshold reliability of 1.7 and the black line follows monthly reliability values. The red, green, and blue bars indicate the amounts of each water source that are available in each month, and the orange line tracks monthly demand.

VII.h Other Reliability Measures

In our analysis we used average demand over the period January 1998 – September 2012 as our target for reliability; however the demand fluctuates, especially in non-peak months. For this reason, we developed two other measures of reliability which incorporate these variations. The first measure is monthly capacity divided by average monthly demand, plus one standard deviation; and the second is monthly capacity divided by average monthly demand, plus two standard deviations. Reliabilities for these measures were calculated for each scenario and management option, but we only optimized for the average monthly demand reliability. These measures allow this model to investigate worst-case scenarios, where demand is high and supply is limited, but we did not choose to run optimization for these reliability measures as we did not think they are an accurate depiction of potential demand scenarios. Demand will deviate from the average demand numbers we used, but it is not likely to increase significantly for more than a few months, let alone an entire year.

VII.i Reliability Discussion

These model runs capture the static reliability of ID1's supply system under various scenarios fairly well. Unfortunately, supply and demand at ID1 are not static even on the one-year time scale for which we ran our results. Unexpected events can change both supply and demand more quickly than this one-year timeframe, thus our model would fail to capture these potential changes and the results displayed previously might misrepresent the actual reliability of the system. For this reason, we investigated the effects of unexpected events to more accurately capture the overall reliability of the system.

VIII Modeling Resilience

Results of the previous model simulations indicate that many of the climate and Cr(VI) MCL scenarios still do not meet the desired threshold, even after all the management options have been applied. Furthermore, shocks to the system, like a natural disaster, can make even the 1.7 threshold meaningless. This leads into the discussion of resilience, since using a static system and preparing redundant water sources is both infeasible for small districts and may not be able to withstand major system upsets.

Designing systems to be more resilient, so that they are adaptive to changing conditions even if they have a lower instantaneous reliability, is a more viable option than solely focusing on maximizing reliability. This is even more important in light of various factors that may further stress water supply systems throughout California, like climate change, population growth, land use changes, and regulatory pressures.

VIII.a Natural Disaster Scenario: Flood

In order to model how the system may be expected to respond to a single-occurrence disaster event, we simulated a flood disaster that would eliminate the alluvial well field source. There have been several minor and five major flood events in the past century, though the section of the Santa Ynez River that flows adjacent to the District is not currently considered at high risk for flooding. As the seasonality of precipitation shifts with changing climate conditions, higher spring temperatures and more intense runoff may lead to an increase in flooding throughout the Santa Ynez River Basin (California State WRCB, 2011; UWMP, 2000). Severe storms throughout the last 20 years have left various wells within the 6.0 and 4.0 cfs well fields non-operational, and a flood in 2000 diverted the natural course of the Santa Ynez River enough to completely take the 4.0 cfs well field offline (UWMP 2000).

As previously noted, when the level of water in the Santa Ynez River comes within 150 feet of the existing river wells, the water these wells provide becomes classified as surface water and is subject to treatment restrictions that the District is unable to meet with the current treatment system. If the water rises to the level of the wells themselves, as was the case in the flood of 2000, the wells may be damaged to the point of requiring repair to remain operational. Repair of the well field is an intensive enough operation that it may take over a year to put these sources back online. For this reason, in the model, the flood scenario cuts off the use of the river wells entirely for the duration of the year in order to reflect the most restrictive scenario. We assumed that flood events would occur only during a very wet climate scenario.

VIII.a.i Flood Scenario Results

Because our model only predicts planning on an annual basis, we ran the flooding scenarios as if a flood event had taken the alluvial well field offline late in the previous year. This would mean that the District would need to plan for the coming year without this particular water supply. Two different flood scenarios were compared for each previously examined climate (Average, Dry, and Very Dry) and MCL (20 ppb, 10 ppb, and 0.02 ppb) (Fig 8.1).

The first scenario assumed that all of the management options from the decision tree, with the exception of repairing the alluvial well field, had been implemented prior to the flood. The point of this modeling was to determine the performance of the system without the alluvial supply source. Additionally, an extreme flood event may change the cost and amount of effort required to put well fields back into the system, making the early placement of this action on the tree less realistic. The second scenario assumed that the District had not yet undertaken any of the management options from the decision tree.

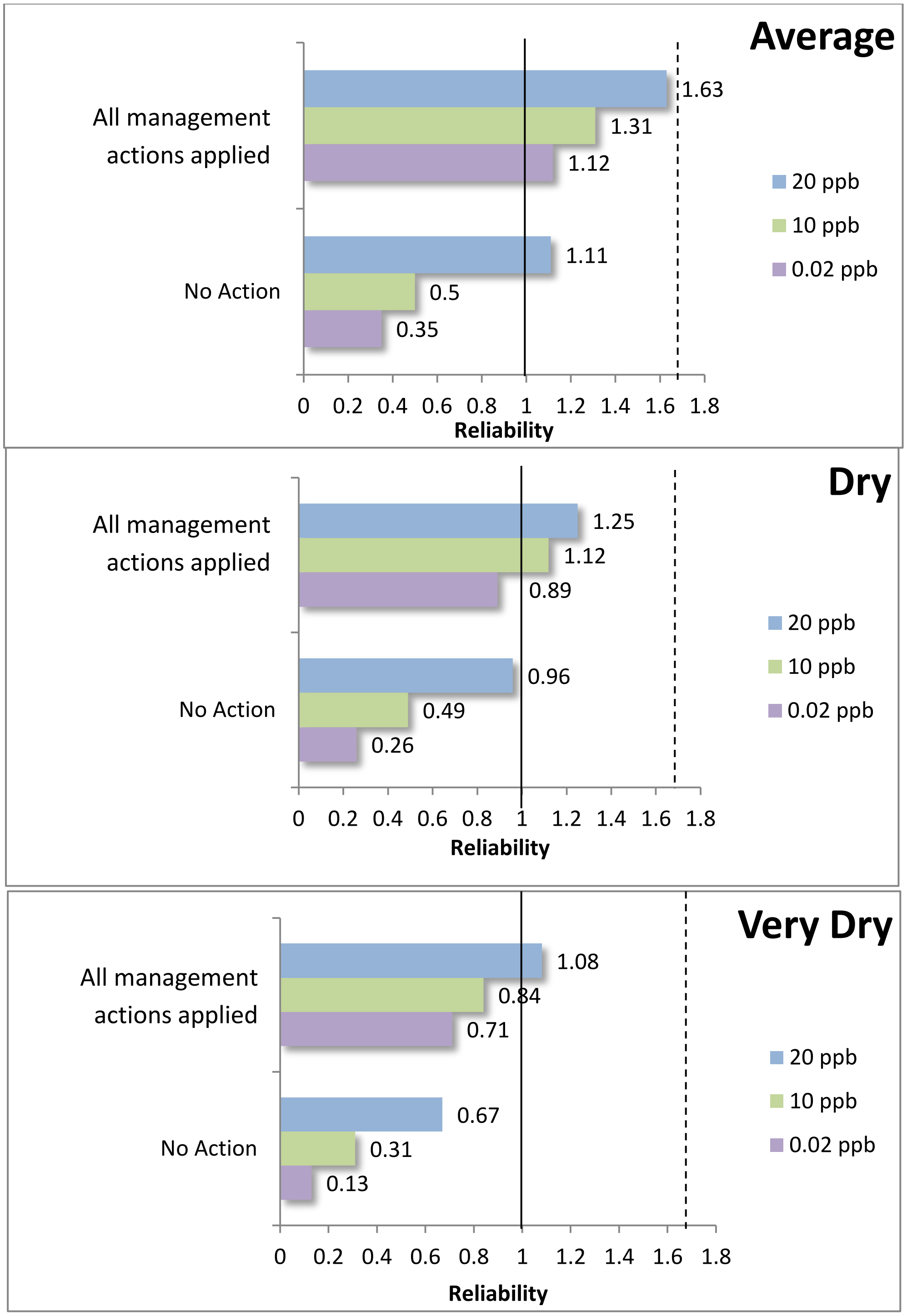


Figure 8.1 System reliability after flooding scenario 1 (all management actions applied) and scenario 2 (no action taken). The solid line at a reliability of 1 indicates that demand can be exactly met. The dashed line at 1.69 indicates that the previously determined demand threshold can be met.

While none of the flood scenarios can meet the 1.7 reliability threshold, several are able to at least meet demand with a reliability over 1.0. Not surprisingly, we see an improvement in overall reliability between when the cluster system has been installed and when it has not across all three MCLs. This is because the cluster system allows for the use of upland wells that would otherwise be eliminated under the more restrictive MCLs. This improvement in reliability represents the greater resilience of the system if the decision tree is implemented.

It is unlikely that it would take the District an entire year to repair the damaged well fields, but using the model in this way does expose some of the issues that a system with low resilience faces. Previous analysis showed that in a year with a Dry climate and an MCL of 20 ppb, the system had a baseline reliability of 1.33. In this case, though the system does not meet our predetermined reliability threshold, it is able to completely meet demand. If a flood were to hit in this scenario before any management actions are taken, reliability drops to 0.96 and demand is not met. While the system previously appeared at least reliable enough to answer to historic demand, it was not resilient enough to stand up to the pressure applied by the flood.

A resilient system is able to respond to upsets in either supply or demand, such as losing the entire alluvial well field, with little disruption to delivery. The same Dry year with an MCL of 20 ppb increases to a baseline reliability of 1.65 and maintains a reliability of 1.25, even after a flood, if all of the management options from the decision tree have been applied. In this case, the cluster system allows the upland wells to be used as backup after the alluvial wells are temporarily eliminated. This is a realistic expectation for the District to have, as the upland wells have done just this in the past when the District has been unable to rely on other supply sources, such as during the 1987-1992 drought (UWMP 2000).

When looking at water supplies, it is crucial that a system be reliable enough to meet the demands of its consumers; however, an optimized supply system will be managed for resilience as well as reliability. The flood scenario shows that the cluster system both increases overall reliability and makes the system better prepared to handle threats to the non-upland well water supply sources. Part of a resilient system's value comes from the fact that it could pay off at any time due to the unpredictability of certain system threats. Several other factors that may affect the resilience of the District's system are discussed below.

VIII.b Other Possible System Upsets

VIII.b.i Future regulations

There are currently 86 drinking water contaminants (18 inorganic, 60 organic, and 6 radionuclides)with MCLs regulated under Title 22 of the California Code of Regulations, including four disinfection byproducts, that require periodic testing and compliance through treatment (CDPH 2008). Even fewer contaminants are regulated by the US EPA. Given that there are over 70,000 known commercial chemicals in existence – from industrial chemicals, to pharmaceuticals, to personal care products – it is fair to assume that there will only be more contaminants for which MCLs will be developed. In fact, some currently-unregulated chemicals have already gained attention as "emerging pollutants" for their potential to cause adverse human health effects via environmental contamination. Although industrial activities are limited in the District, therefore limiting possible drinking water contamination from industrial sources, it is important to consider the implications of investing in major infrastructure to address *one* drinking water contaminant in light of probable future drinking water standards.

Additionally, a basic inefficiency inherent in almost all water supply systems is that only one set of pipes is available to convey all sources. The result is treatment to the same water quality standard of water destined for drinking from the tap as that for agricultural and residential irrigation. There is a possibility that future regulations will shift towards point-of-use treatment, thus requiring ID1 to install new infrastructure and develop new maintenance procedures.

VIII.b.ii Earthquakes

California's unique geologic location on multiple moving tectonic plates causes a considerable amount of people and infrastructure to be vulnerable to earthquakes. Since 1971, earthquakes have produced over $56 billion in damage for California alone (State of California 2003). The potential of future quakes can be predicted based on the location and movement of plates. Earthquakes pose a threat to water reliability because much of the state is dependent on imported and surface water, which will likely be impacted by an earthquake. An earthquake could damage significant portions of the State Water Project and limit distribution of water for extended periods of time. It is important for ID1 managers to understand the implications of not receiving SWP water and to develop a plan accordingly.

VIII.b.iii Population and land use change

Population growth can influence water use and water quality, but effective management and water use efficiency improvements can decrease the negative effects population growth may have on water sources. The population of the District is concentrated in the two main cites, Santa Ynez and Los Olivos. In 2010 the average household income in the district was estimated to be between $84,000 and $375,000. The 2000 population in Santa Barbara County was roughly 399,000 and is predicted to increase 30% by 2030 (Santa Barbara County Associations of Governments 2002). The population was anticipated to grow the fastest from 2000 to 2010 and is estimated to slow down from 2010 to 2030 (Table 8.1). Thus, population growth is not anticipated to significantly alter residential water demand in the District in the foreseeable future.

Table 8.1 Estimated population changes in select areas of ID1. Source: US Census Bureau, 2011.

Area	2000	2010	Change (2000-2010)	2020	Change (2010-2020)	2030	Change (2020-2030)	Total Change (2000-2030)
Santa Ynez – Uninc	12,700	15,000	18.1%	15,100	0.7%	15,200	0.7%	20%
City of Solvang	5,300	6,300	18.9%	6,300	0%	6,300	0%	19%

The District is dominated by agricultural land and residential land uses which represent total water demand. Within Santa Barbara County, pastureland for grazing covers approximately 1.3 million acres and Cultivated Crop land occupy 710,142 acres (Santa Barbara County 2010 Agricultural Production

Report). Agriculture in Santa Barbara County is estimated to generate upwards of 1 billion dollars annually and be dominated by strawberries, broccoli, grains, grapes and lettuce. Strawberries and grapes are two crops known to require significant applications of fertilizer and pesticides, insecticides and herbicides, which have the potential to impact water quality as non-point sources pollution (USDA, 2010). Nitrate contamination of groundwater is a concern for the district and elevated concentrations are present in some wells. Future shifts in crop choice and watering methods could alter water demand and impact the reliability and resilience of the system.

VIII.b.iv Climate change

The State of California has experienced many droughts over its history, and, in light of predicted climate change, managing the future water supply of the state will only become more difficult. Climate change predictions estimate an increase in average temperatures of 1.3 - 4.0° C by mid-century, possibly leading to a decrease in the winter snowpack, one of the largest reservoirs of state water during the high-demand summer months (CA DWR 2012). Climate change is likely to decrease the actual supply of state water, putting stress on local wells, which represent the remaining water supply. During peak summer months, ID1 runs all operable wells, including the few that have periodically high Cr(VI) levels (SYRWCD ID1 Personal Communication, 2012).

IX Conclusion and Future Considerations

IX.a Conclusions of Model Results

Our analysis of ID1's water supply system in light of the anticipated Cr(VI) MCL has identified how future regulation changes can affect system reliability and resilience. Anticipating specific future regulations can be difficult, but, through proper planning, necessary steps can be taken to identify the potential vulnerabilities within the system. Use of the water supply optimization model can reveal shortcomings in system reliability under various potential scenarios, which can then be used to gauge the system resilience in the long term.

As expected, the drier climate conditions and more restrictive MCLs led to lower system reliability and required the most treatment. While we were unable to bring the reliability of every scenario we examined up to the predetermined threshold of 1.69, our process revealed that implementing measures from our decision tree always at least allows the system to reach a reliability of 1. Implementing these management actions to at least meet demand would allow ID1 some time to adjust to a potential future of increasingly restricted water supplies in California. Importantly, all the management actions have significant associated costs, as well as increased operation and maintenance requirements which also would need to be considered.

After examining our data, we recognized some additional benefits of treating Cr(VI) that were not captured when using reliability as the sole metric for determining the viability of a system. High values for reliability do not guarantee that a water supply system will be able to respond to all outside threats and similarly, there can still be value in a system even if it has a relatively low level of reliability. When faced with a natural disaster, such as the flood that we modeled, even systems with a low reliability were better able to withstand the shock if our management actions from the decision tree had already been applied. Capturing this sense of resilience is another important aspect of a water manager's portfolio.

While this water supply optimization model has been specifically designed for ID1, other water suppliers may use the methodology to conduct their own studies of reliability and resilience. The concept of being able to measure these factors for a water district should be shared with other water suppliers in order to better assess options with a quantitative and qualitative viewpoint.

IX.b Broader Implications of this Project

IX.b.i The Importance of Adaptive Management

Many external pressures influence both water supply and demand, especially in the state of California. These include, but are not limited to, strict water quality standards for many contaminants, land-use change, population growth, and climate change. In the future, all of these pressures are likely to increase stress on California water supplies, both by increasing demand as well as reducing supply. Traditionally, most water suppliers have managed their water in a very static way, preparing supplies and deliveries based on historic demand. In an average year, at any given time, more water is available than is delivered, so as to ensure supply can be increased in the case of unexpected circumstances. In water constrained years (i.e. drought), this additional water is not always going to be sufficient. The drought of the late 1980s through early 1990s led suppliers to employ such extreme measures as water rationing and forced conservation (Hannigan and Davis, 2000). Though this drought led to better management of the SWP, the next intense drought event of the late 2000s still impacted local water supplies, especially in rural communities (Cody et al, 2009). In light of the external pressures mentioned previously, it is likely that the next major drought will have an even greater impact on water supplies, particularly for smaller water purveyors, like ID1. To avoid such a scenario, adaptive management options are being pursued by researchers and water managers alike (Medellin-Azuara et al., 2006; Metropolitan Water District, 2010). These options can help to manage all sources of water – from the SWP to local groundwater basins – more effectively. Adaptive management, in this context, refers to managing a system in such a way that threats to reliability are quickly and accurately identified and addressed, or increasing the resilience of the system. To accomplish this, an array of high quality data is required, including meteorology, natural disasters, system infrastructure, customer demographics, and current economic and regulatory conditions. Not all systems need to have all of these data, or have significant spatial and temporal resolution for it, but the more that is available, the more resilient the system can potentially be. This information in itself can add resilience to the system, by providing advance notice of potential shortages or problems. It can also inform the supplier as to which strategies to pursue in order to mitigate the most likely adverse events, thus increasing the resilience of the system. In the case of the District, additional data could easily be procured for the purpose of analyzing the probabilities of unforeseen events, such as droughts or floods, and a plan developed that would increase reliability in the most probable events first.

IX.b.ii Balance between centralized and decentralized systems

The results of our analysis indicate the significance of the upland wells in providing a buffer against water supply shortfalls of all kinds including drought, fluctuations in demand, and adverse operating conditions. Given the regulatory uncertainty of water use entitlements, and the vulnerability of supply infrastructure, the importance of groundwater cannot be overstated for small water districts without surface water treatment plants. This speaks to the need to protect the water quality of this source and the merit of at least seriously considering capital investments for well water treatment techniques such as our modeled clustered-well system.

Like many rural districts, ID1 faces significant challenges every time there is a new water quality regulation due to the fact that it does not have a centralized treatment system. This is one of the reasons that small rural districts are typically identified by the DWR as the highest risk areas in water shortages. While a more centralized system would benefit ID1 with regards to treatment, it also has the potential to decrease overall resilience. Having a system that is decoupled and more decentralized is not always a disadvantage.

This project shows the importance of striking a balance between a centralized and decentralized system as well as the importance of an adaptive management policy. The clustered-well treatment system has the benefit of centralizing the system to some degree while still maintaining the overall flexibility offered by decentralization. Developing a cost-effective solution for managing water supply problems is often challenging as municipalities do not want to over or under invest. Based on this analysis, we believe a combination of smaller more decentralized projects and a focus on demand-side management should help water agencies such as ID1 respond more effectively to a variety of impending challenges to water supplies.

IX.b.iii Demand Side Responses to Supply Restrictions

As the population of California grows and factors such as land use change and climate change stress the availability of natural resources, it is reasonable to expect that water availability may begin to decline in the future. Up to this point, the first response to supply threats has often been to engineer new solutions either by constructing massive water transport projects such as the SWP or by investing in costly and complex treatment measures. While the uncertainty for actions like this to succeed in providing the necessary water is low, they do not represent a sustainable long term method for creating solutions.

To this end, investments in technology and efficiency and smart adaptive management strategies should be considered by decision makers during budgeting and rate setting. Longer term water-saving infrastructure investment should also be considered by city planners and development agencies. This includes, but is not limited to, systems for artificial groundwater recharge, grey water systems, and recycling of municipal wastewater treatment plant discharge.

An infrastructure improvement, such as a centralized treatment system for Cr(VI), may be the most viable option for this threat to ID1’s water supplies, but this may not always be the case. Although we recognize that targeting demand-side programs may not typically be a water manager’s primary goal, we believe a long term investment in what are typically referred to as soft path solutions should also be considered. For the District, this would mean additional studies on the potential gains of such programs, and the logistics of managing them.

While we only chose to model two potential demand-side management actions, 5% and 10% conservation, such approaches are likely to become the commonplace method of addressing supply challenges in the future. The observed ability of a method like Xeriscaping to cut down peak summer demand can help address the root cause of diminished reliability rather than simply addressing one of its symptoms. Additional conservation measures discussed but not modeled, such as the implementation of a block rate structure and changes in agricultural practices, have the potential to manage demand efficiently even in areas where water is scare. Part of ensuring the success of such programs is making sure that the public is educated about the behavioral changes required and understands its role in the water management process.

Appendix A: Conservation Case Studies

Albuquerque, New Mexico

The City of Albuquerque serves a population of almost half a million and delivers approximately 114,000 acre feet (AF) per year of potable water. With the release of a USGS report identifying that groundwater withdrawals exceeded two times the sustainable yield, the city adopted the Long-Range Water Conservation Strategy Resolution. As part of this resolution, the city applied a surcharge of $1.07 per 100 cubic feet (ccf) when customers exceeded 200% of their winter average. Over half of the surcharge went back to the city to fund the water conservation program. The remaining surcharge funds were to be used in the form of rebates and other incentives for customers. Additionally, education programs, such as water usage information on water bills and cooperative programs with school and community organizations, were instigated. The city also implemented landscape and outdoor water use regulations, in addition to rebates for the use of the xeriscaping at 25 cents per square foot of landscape converted up to $500.

Through the use of conservation, the City of Albuquerque was able to slow the drawdown of its groundwater supplies and be better prepared for future growth. Furthermore, the city reduced per capita water use by 45 gallons per capita per day. With the use of a tiered rate structure and the landscaping program, the city reduced peak demand by 14% in 2001 from the high point in 1990. This program is an example of how ID1 can reduce demand for water through a conservation program using a tiered rate structure and a landscape rebate program (EPA 2002).

Cary, North Carolina

With an almost doubling of population during the 1990s, the town of Cary realized that conservation would be necessary. Water supplies for the city became stressed during the summer months and expansions to the water treatment plant were scheduled in the next thirty years. In order to meet growing demand, the town implemented a conservation program. One part of the program included public outreach, in which the city ran public education campaigns, such as “Beat the Peak”, to help reduce peak summer demand. Cary also offers public workshops on water-efficient landscaping and gardening. Residential audits were also conducted for customers, giving customers a free assessment of water use, leak detection, and offering low flow plumbing devices. Cary also instigated a tiered rate structure that consists of three rate payer divisions: low use, average use, and high use. Additional conservation measures included a landscape water budget for large public and private irrigation users identifying appropriate watering needs and the use of reclaimed water for irrigation and non-potable uses (EPA 2002).

The city is expecting to reduce water supply by 16% and delayed two planned expansions of the city’s water plant. Through the use of reclaimed water, the city is expecting a cut in peak demand of 8%. While the town of Cary is able to implement measures that ID1 may not, such as city ordinances to enforce conservation methods, there are still viable options that can be applied to ID1. (EPA 2002).

Goleta, California

The Goleta Valley Water District serves approximately 75,000 customers, with Lake Cachuma, the State Water Project, and groundwater wells serving as its main supplies. During the 1970s, predictions of water shortages prompted the City of Goleta to begin a water conservation program. The program cost approximately $1.5 million and mainly emphasized plumping retrofits. Other methods, which could be applied to ID1, include free onsite water surveys, public education, and changes in a metering and rate structure. Through the use of these measures the per capita residential water use dropped by 50% in a one year period from 1989 to 1990 in Goleta (EPA 2002).

Houston, Texas

With a population of 1.7 million, Houston is not comparable to ID1's customer population. However, the city has initiated some conservation measures that may be applied to ID1. Houston's conservation program has four elements: education, in-house, contract customers, and conservation planning. The education program consists of outreach initiatives and plumping retrofits of old homes. The in-house element focuses on city infrastructure for irritation and leak detection improvements. The contracted customers program changes the billings and also adds penalties for excessive water use during peak demand times. The conservation program was setup to evaluate various conservation measures and to acquire grant funding.

Houston's increasing block rate structure, with two tiers for single family residences, may be applied to ID1. The billing program includes a minimum charge to cover a set base amount of water, then consumption between 5,000 and 12,000 gallons a month is billed an additional $2.36 per 1,000 gallons of water. For water use that is over 12,000 gallons a month, the rate increases to $4.30 per 1,000 gallons. With a range of prices based on usage and additional fines for excessive water use, ID1 could help incentivize water conservation with its residential customers (EPA 2002).

Irvine Ranch Water District, California

The Irvine Ranch Water District (IRWD) serves the City of Irvine and surrounding communities in Orange County, California. With services for almost sixty thousand costumers, a drought in the early 1990s and increasing wholesale water charges, IRWD chose to implement several conservation approaches.

One of IRWD's conservation methods is a multiple-tiered rate structure. This rate structure applies individualized rates for accounts based on landscape square footage, number of residents, special residential needs, and daily evapotranspiration rates. Water billings are based on precipitation, and customer's rates are adjusted based on estimated needs. If water use is greater than estimated needs, penalties are added and increase as water use goes up. If leaks or excessive water use is fixed or adjusted, then the penalties may be removed. Additionally customers are charged a flat water-service fee based on water meter size. This is to ensure that IRWD has stable revenues despite fluctuating water sales (EPA 2002).

With the implementation of this rate structure, IRWD has been able to decrease its water use from 1991 to 1992 by 19%. It was estimated that through this rate structure additional conservation efforts became more in-demand. Other conservation efforts included irrigation workshops, water audits, and fixture rebates. The use of an appropriate rate structure for ID1 could reduce demand and increase awareness for other water conservation methods.

Seattle, Washington

With a service population of 1.3 million people, Seattle Public Utilities has invested in innovative solutions to water supply problems. Despite the consistent wet winters, Seattle experiences hot dry summers and does not have large reservoirs for carryover storage. Along with plumping fixtures and operational improvements, the city has implemented a block rate structure during the peak season for its residential customers. The city also promotes commercial water conservation by offering free audits of irrigation practices and financial assistance for upgrading irrigation systems (EPA 2002).

Seattle was able to achieve a reduction of 20% in per capita demand and a water savings of 5 million gallons per day due to the seasonal rate changes (EPA 2002). With the high amount of residential per capita use and higher demand for water during the summer months, an increasing rate structure could assist ID1 in lowering the peak demand. Furthermore, given that approximately 50% of ID1's demand is agricultural, free evaluations and additional funding for irrigation systems could drastically reduce demand during the peak growing season.

Sonoma County Water Agency

The Sonoma County Water Agency has developed conservation measures specific to vintner agriculture. These practices can be applied to ID1 in an effort to promote water conservation among the large number of wineries in the area. These recommendations include improved drip systems, modified irrigation schedule, use of multiple methods to monitor plant status, and a change in cooling practices.

An improved irrigation system includes the installation of two low-flow drip emitters per vine, rated at 0.5 gallon per hour (GPH), evenly spaced. This configuration helps save water, if the low flow emitters are not already in place, and also increase available water to the root zones (SBWCA 2011).

Analyzing the soil profile of the vineyard can be helpful in determining irrigation needs. A soil profile can change within a vineyard block or between blocks. A backhoe pit can be used to analyze the soil profile. Installation of soil moisture devices to the depth of the root zone can allow for irrigation to be delivered only when needed (SBWCA 2011).

Further water savings may be achieved by waiting as long as possible into the growing season before irrigating. Determining when to irrigate can be based on when the shoot tip of the plants slow or stop growing. Once the tips stop growing, however, the vines will develop deep root systems to reach water and nutrients deeper in the soil profile. Benefits aside from water savings could be improved wine quality and a reduction in canopy maintenance (SBWCA 2011).

In order to achieve a complete plant water assessment, multiple methods of monitoring should be used. Through gaining a more accurate evaluation of plant water status, more accurate irrigation techniques can be applied. Monitoring of plant water status should be done by two or three methods. One method includes use of a porometer to measure the water that is lost from a leaf's stomata (SBWCA 2011).

A change in cooling practices can also yield water savings. By changing a system from overhead sprinklers to misters, vineyards will still allow for cooling of the vines and save money through water reduction (SBWCA 2011).

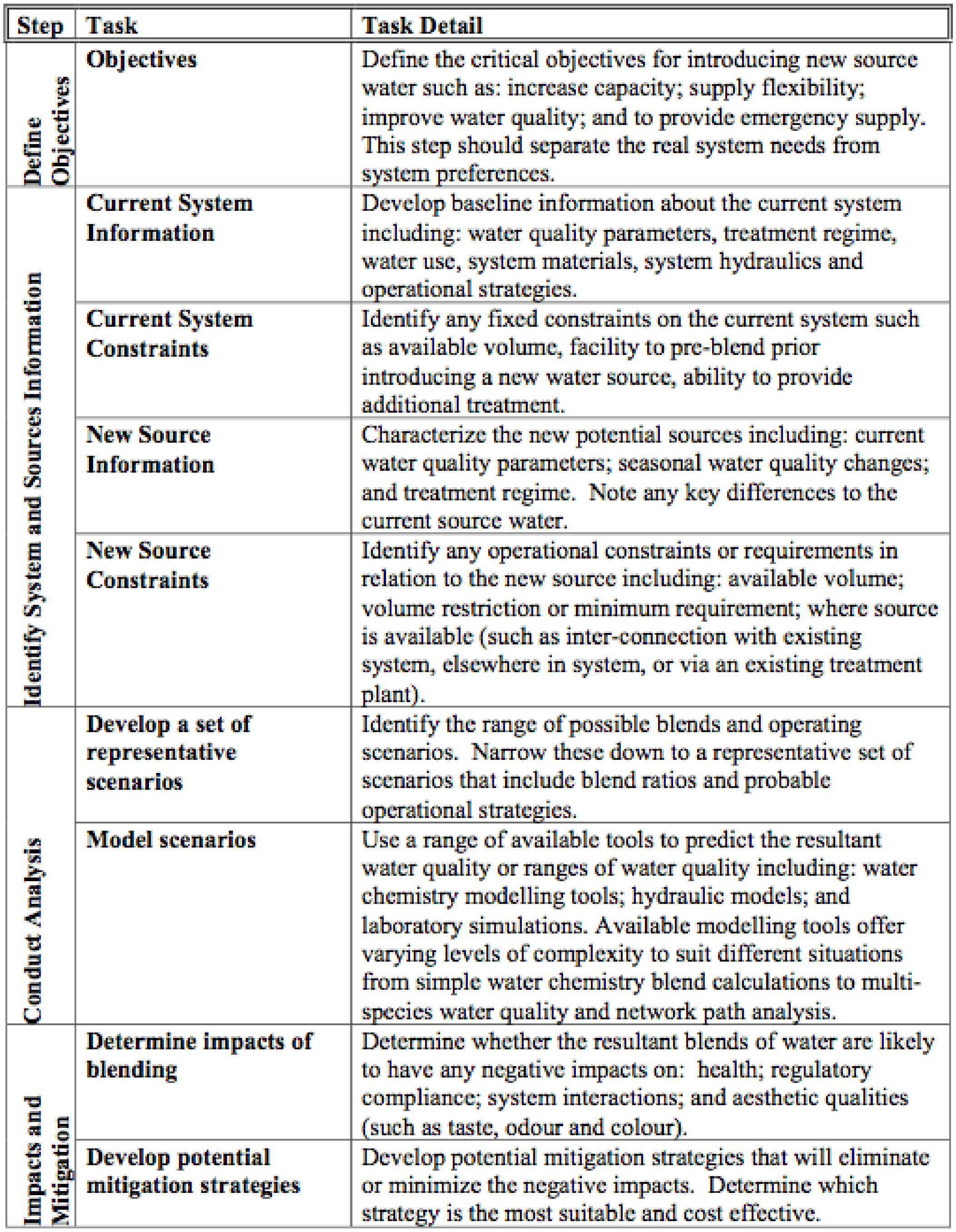
A combination of these practices can help reduce the agricultural water consumption in ID1. With approximately 50% of the water deliveries going to agricultural customers and a majority of those practices being in viticulture, there is potential for dramatic water savings. Furthermore, vintners that reduce water consumption will also reduce cost of water use and if using a private well, savings from electrical use for operating the pump.

Tucson and Phoenix – Water Conservation Comparison

Tucson and Phoenix are two cities in the desert of Arizona, yet they both have different takes on water conservation. Since the 1970s, Tucson has implemented a water conservation program which included a block rate structure and education campaigns. This program was able to achieve a 20% reduction in per capita water use from the mid-1970s to 2002 lowering per capita use to 160 gallons a day. In contrast the City of Phoenix per capita water usage in 2002 was 226 gallons a day. Furthermore, residents in Tucson are more in the mind-set that they are living in a desert and need to conserve water. This has led to homeowners conserving water through the use of desert landscaping, with one landscaping company in Tucson installing 90% of landscapes using drought tolerant plants. This type of landscape allows for a green look without high water bills (Copenhaver 2003).

The change in water consumption between the two cities can be related to the pricing structure of water for the two cities. Since the drought of the early 1990s, the two cities have made changes to their rate structures. Tucson instigated a block rate pricing structure, while Phoenix maintained a flat rate structure, though at a higher rate. Tucson’s block rate structure allows households that use less than 10,000 gallons per month to pay less for water than households in Phoenix. This was achieved using the block rate pricing structure by charging more for greater water users, to balance the loss in revenue, from those who conserve water (Turner, 2008).

Appendix B: Blending

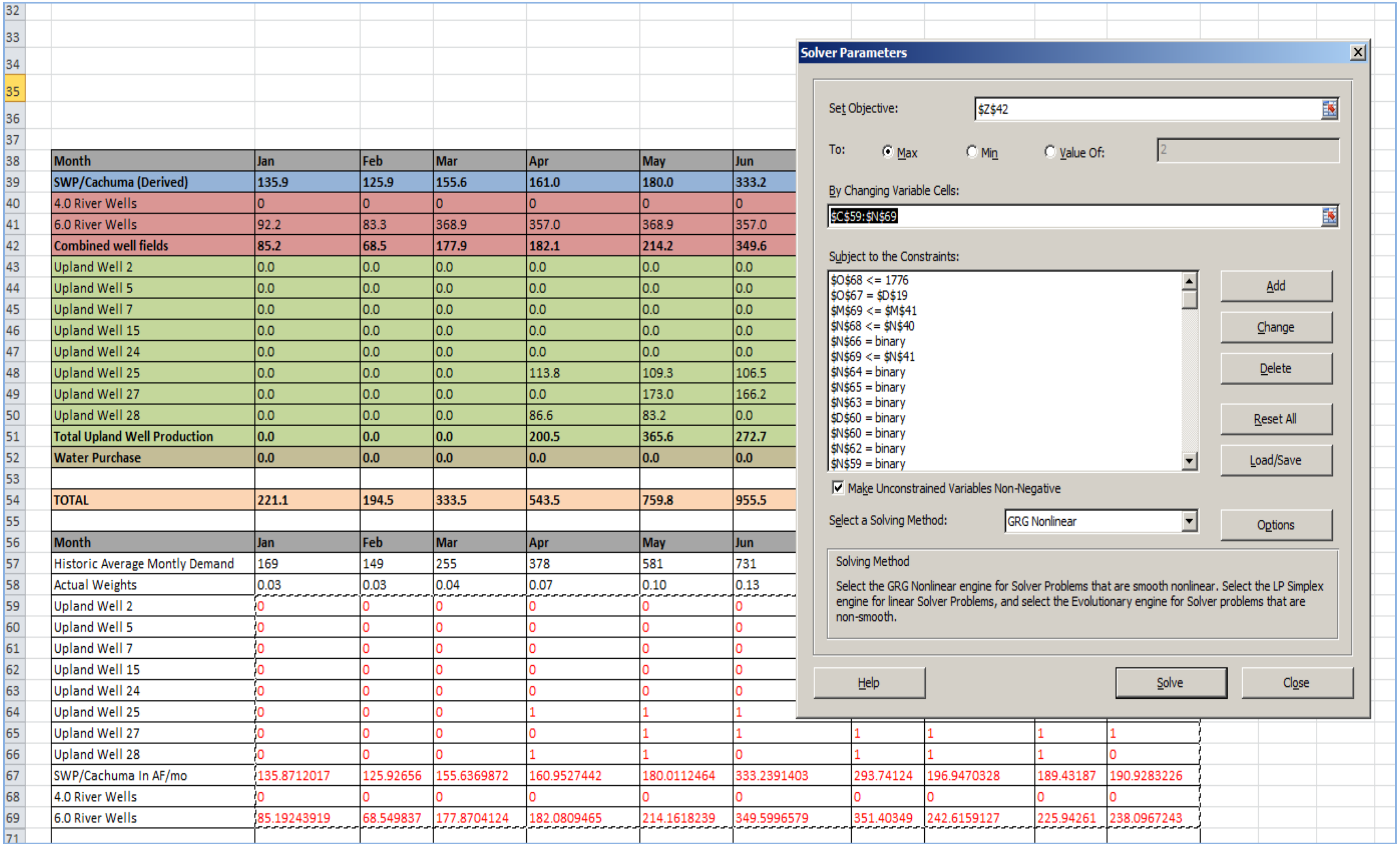


Step	Task	Task Detail
Define Objectives	**Objectives**	Define the critical objectives for introducing new source water such as: increase capacity; supply flexibility; improve water quality; and to provide emergency supply. This step should separate the real system needs from system preferences.
Identify System and Sources Information	**Current System Information**	Develop baseline information about the current system including: water quality parameters, treatment regime, water use, system materials, system hydraulics and operational strategies.
	Current System Constraints	Identify any fixed constraints on the current system such as available volume, facility to pre-blend prior introducing a new water source, ability to provide additional treatment.
	New Source Information	Characterize the new potential sources including: current water quality parameters; seasonal water quality changes; and treatment regime. Note any key differences to the current source water.
	New Source Constraints	Identify any operational constraints or requirements in relation to the new source including: available volume; volume restriction or minimum requirement; where source is available (such as inter-connection with existing system, elsewhere in system, or via an existing treatment plant).
Conduct Analysis	**Develop a set of representative scenarios**	Identify the range of possible blends and operating scenarios. Narrow these down to a representative set of scenarios that include blend ratios and probable operational strategies.
	Model scenarios	Use a range of available tools to predict the resultant water quality or ranges of water quality including: water chemistry modelling tools; hydraulic models; and laboratory simulations. Available modelling tools offer varying levels of complexity to suit different situations from simple water chemistry blend calculations to multi-species water quality and network path analysis.
Impacts and Mitigation	**Determine impacts of blending**	Determine whether the resultant blends of water are likely to have any negative impacts on: health; regulatory compliance; system interactions; and aesthetic qualities (such as taste, odour and colour).
	Develop potential mitigation strategies	Develop potential mitigation strategies that will eliminate or minimize the negative impacts. Determine which strategy is the most suitable and cost effective.

Source: Dewis et al 2009

Appendix C: Optimization Routine

The Microsoft Excel Solver tool was used to optimize reliability. Specifically, Solver was used to allocate water supplies so as to maximize the minimum monthly value of reliability over the course of one year. The cells in red are variables in the computation.



	Month	Jan	Feb	Mar	Apr	May	Jun
38	**Month**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
39	**SWP/Cachuma (Derived)**	**135.9**	**125.9**	**155.6**	**161.0**	**180.0**	**333.2**
40	4.0 River Wells	0	0	0	0	0	0
41	6.0 River Wells	92.2	83.3	368.9	357.0	368.9	357.0
42	**Combined well fields**	**85.2**	**68.5**	**177.9**	**182.1**	**214.2**	**349.6**
43	Upland Well 2	0.0	0.0	0.0	0.0	0.0	0.0
44	Upland Well 5	0.0	0.0	0.0	0.0	0.0	0.0
45	Upland Well 7	0.0	0.0	0.0	0.0	0.0	0.0
46	Upland Well 15	0.0	0.0	0.0	0.0	0.0	0.0
47	Upland Well 24	0.0	0.0	0.0	0.0	0.0	0.0
48	Upland Well 25	0.0	0.0	0.0	113.8	109.3	106.5
49	Upland Well 27	0.0	0.0	0.0	0.0	173.0	166.2
50	Upland Well 28	0.0	0.0	0.0	86.6	83.2	0.0
51	**Total Upland Well Production**	**0.0**	**0.0**	**0.0**	**200.5**	**365.6**	**272.7**
52	**Water Purchase**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
53							
54	**TOTAL**	**221.1**	**194.5**	**333.5**	**543.5**	**759.8**	**955.5**

	Month	Jan	Feb	Mar	Apr	May	Jun				
56	**Month**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**				
57	Historic Average Montly Demand	169	149	255	378	581	731				
58	Actual Weights	0.03	0.03	0.04	0.07	0.10	0.13				
59	Upland Well 2	0	0	0	0	0	0				
60	Upland Well 5	0	0	0	0	0	0				
61	Upland Well 7	0	0	0	0	0	0				
62	Upland Well 15	0	0	0	0	0	0				
63	Upland Well 24	0	0	0	0	0	0				
64	Upland Well 25	0	0	0	1	1	1				
65	Upland Well 27	0	0	0	0	1	1	1	1	1	1
66	Upland Well 28	0	0	0	1	1	0	1	1	1	0
67	SWP/Cachuma In AF/mo	135.8712017	125.92656	155.6369872	160.9527442	180.0112464	333.2391403	293.74124	196.9470328	189.43187	190.9283226
68	4.0 River Wells	0	0	0	0	0	0	0	0	0	0
69	6.0 River Wells	85.19243919	68.549837	177.8704124	182.0809465	214.1618239	349.5996579	351.40349	242.6159127	225.94261	238.0967243

Solver Parameters

Set Objective: $Z$42

To: ● Max ○ Min ○ Value Of: 2

By Changing Variable Cells: $C$59:$N$69

Subject to the Constraints:

$O$68 <= 1776
$O$67 = $D$19
$M$69 <= $M$41
$N$68 <= $N$40
$N$66 = binary
$N$69 <= $N$41
$N$64 = binary
$N$65 = binary
$N$63 = binary
$D$60 = binary
$N$60 = binary
$N$62 = binary
$N$59 = binary

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Appendix D: Reliability & Resilience Results

Table D1: *Reliabilities for all climate and Cr(VI) maximum contaminant level (MCL) scenarios based on applied management actions. Each action was applied sequentially if threshold reliability of 1.7 was not met. average climate = 60% of SWP allotment delivered; dry = 24%; very dry = 11%.*

	Model Runs (Climate MCL [ppb])			
	Average 50	Average 20	Average 10	Average 0.02
Reliability	1.94	1.53	0.99	0.92
Water Purchase Required?	NO	YES	YES	YES
Reliability 2		1.56	1.04	0.93
Alluvial Well Repair Required?		YES	YES	YES
Reliability 3		1.73	1.24	1.13
5% Conservation Required?		NO	YES	YES
Reliability 4			1.32	1.15
10 % Conservation Required?			YES	YES
Reliability 5			1.43	1.21
Cr Cluster Treatment Required?			YES	YES
Reliability 6			1.79	1.46
Further Action Required?			NO	YES
	Dry 50	Dry 20	Dry 10	Dry 0.02
Reliability	1.92	1.33	0.88	0.75
Water Purchase Required?	NO	YES	YES	YES
Reliability 2		1.45	0.89	0.81
Alluvial Well Repair Required?		YES	YES	YES
Reliability 3		1.58	1.07	0.92
5% Conservation Required?		YES	YES	YES
Reliability 4		1.61	1.11	1
10 % Conservation Required?		YES	YES	YES
Reliability 5		1.79	1.22	1.17
Cr Cluster Treatment Required?		NO	YES	YES
Reliability 6			1.65	1.54
Further Action Required?			YES	YES
	Very Dry 50	Very Dry 20	Very Dry 10	Very Dry 0.02
Reliability	1.69	1.13	0.68	0.55
Water Purchase Required?	NO	YES	YES	YES
Reliability 2		1.23	0.69	0.55
Alluvial Well Repair Required?		YES	YES	YES
Reliability 3		1.37	0.85	0.73
5% Conservation Required?		YES	YES	YES
Reliability 4		1.44	0.89	0.77

10 % Conservation Required?		**YES**	**YES**	**YES**
Reliability 5		1.52	0.93	0.85
Cr Cluster Treatment Required?		**YES**	**YES**	**YES**
Reliability 6		1.53	1.39	1.31
Further Action Required?		**YES**	**YES**	**YES**

Table D2: System reliability after flooding scenarios 1 and 2.

Climate	MCL (ppb)	Reliability - Scenario 1	Reliability - Scenario 2
		No Action	Through Cluster System
Average	20 ppb	1.11	1.63
Average	10 ppb	0.5	1.31
Average	0.02 ppb	0.35	1.12
Dry	20 ppb	0.96	1.25
Dry	10 ppb	0.49	1.12
Dry	0.02 ppb	0.26	0.89
Very Dry	20 ppb	0.67	1.08
Very Dry	10 ppb	0.31	0.84

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