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Current and Long-Term Effects of Delta Water Quality on Drinking Water Treatment Costs from Disinfection By-Product Formation

Wei-Hsiang Chen¹, Kristine Haunschild¹, Jay R. Lund^{1,2}, and William Fleenor¹

ABSTRACT

Sea level rise and the failure of subsided western islands are likely future conditions for the Sacramento-San Joaquin Delta. This study explores the current and long-term effects of changes in the Delta's water quality on drinking treatment costs for alternative disinfection and additional disinfection by-product (DBP) precursor removal. Current and likely future Delta water qualities were investigated for electrical conductivity and the concentrations of bromide, and organic carbon. With roughly 1.5 million acre-feet (af) per year of Delta water used for urban water supplies, the drinking water treatment cost differences of taking water from the south Delta and the Sacramento River upstream could amount to \$30 to \$90 million per year currently, and could rise to \$200 to \$1000 million per year in the future, with lower water quality and urban use of Delta waters rising to 2 million acre-feet annually. From these results, waters drawn directly from the Delta will likely become more difficult and expensive to treat, making the Delta less desirable as a conventional water source.

KEY WORDS

Drinking water quality, Sacramento-San Joaquin Delta, treatment cost, disinfection by-product, bromide, total organic carbon, sea level rise

INTRODUCTION

Many drinking water sources are being challenged by changes in climate and the environment. Estimating the water quality costs (and benefits) of such changes should be a part of policy and plan development. This study examines the likely water treatment cost effects of sea level rise and the failure of subsided islands in California's Sacramento-San Joaquin Delta, the single largest drinking water source for California, serving 23 million people. Contamination from natural and human sources, sea level rise, tightening drinking water standards, and public health concerns are expected to increase treatment costs and public health risks for water drawn from the Delta. One alternative is developing new source water with a better water quality, at some expense, but with a lower water treatment cost. Better understanding treatment costs for different water sources is therefore important for technical and economic decisions regarding drinking water management and the Delta.

This study compares current and likely future drinking water treatment costs from the southern

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Delta as compared with a location upstream on the Sacramento River. Sea level rise and flooding of the Delta's western islands were considered as the future likely conditions. Sea level at the Golden Gate Bridge has increased by 0.08 inches per year over the past century (Fleenor and others 2008). Most climate models have suggested an increase in the rate of sea level rise in the next century (Lund and others 2010). Sea level rise could be 8 to 16 inches and 28 to 39 inches by 2050 and 2100, respectively (CALFED 2007). Sea level rise would increase salinity in the Delta by either transporting higher-salinity water farther into the Delta directly due to the higher seawater levels and by increasing density-driven flows in deeper more strongly stratified flows (Fleenor and others 2008).

Delta islands have failed 166 times over the last 100 years (Fleenor and others 2008). As a consequence of continued sea level rises, periodic floods, deteriorating levees, and seismic activity, islands will continue to be flooded and may fail simultaneously. Some flooded islands may not be worth reclaiming due to the low economic value of activities on these islands (Lund and others 2007). The water quality effects of permanent failures as well as simultaneous earthquake-induced failure of many islands have been examined using hydrodynamic modeling (J. R. Benjamin & Associates 2005).

Under these likely future conditions, salinity-associated contaminants will become more significant for many Delta water exports. Salinity can increase taste problems, reduce water recycling capabilities, and raise costs to residential and industrial water users from corrosion. Higher seawater salinity is directly related to higher bromide and chloride concentrations, with bromides being of greatest concern for the formation of disinfection by-products (DBP) such as bromate and brominated forms of DBPs in drinking water treatment (Krasner and others 2006; Harader 2007). Higher salinity, even seasonally, can require water treatment plants to use other water sources or stored higher-quality waters to avoid additional treatment costs and potential public health risks posed by bromide in seawater (Chen and others 2008).

In this study we investigate electrical conductivity and bromide, two common salinity-associated

constituents, to reflect seawater intrusion into the Delta as well as wastewater discharges and agricultural runoff from upstream. It is likely that bromide varies most with Delta export location, operations, and likely future conditions. Other contaminants are also present in Delta water and possibly represent another public health threat by DBP formation, such as organic carbon (Krasner and others 1989) and pesticides and herbicides (Chen and Young 2008, 2009). Organic carbon, which is commonly measured and reported as total and dissolved organic carbon (TOC and DOC), is of concern in drinking water because of its reactions with chlorine or ozone to form several regulated DBPs, such as trihalomethanes (THMs) and haloacetic acids (HAAs) (Krasner and others 1989, 2006). Higher levels of organic carbon also increase the disinfectant levels required to achieve disinfection goals. In the Delta, organic carbon sources include algae, tributary-inputs, agricultural drainage, tidal marsh, wastewater discharge, and urban runoff (Jassby and Cloern 2000).

Many treatment technologies can be used to treat these contaminants. However, due to the complexity of constituent characteristics and treatment removal efficiencies under local water quality conditions, it is difficult to determine the best treatment technology combination for each Delta locations. Therefore, instead of explicitly calculating the costs for each Delta location, this cost analysis examines the general magnitudes of cost differences for various treatment technology combinations due to different water qualities at selected Delta locations. Reducing the possible health risks from the formation of DBP, notably bromate and brominated forms of DBPs, is the major driver for selecting treatment technologies in this cost-estimation exercise. This study focuses on bromide and organic carbon, which can react with bromide to form bromate during ozonation, as the primary DBP precursors, and only addresses disinfection processes and advanced treatment technologies for removing these DBP precursors.

Alternative disinfection technologies include ozonation and UV light irradiation. Ozone can replace chlorine and chloramines for primary disinfection, reducing the formation of THMs and HAAs. Ozonation disinfection is common for Delta waters,

and several plants are slated to employ this technology (CALFED 2005a). Ultraviolet light irradiation is an effective disinfectant that can physically inactivate microbes in water. Although not yet common for full-scale systems, UV disinfection is often recommended (CALFED 2005a; Darby 1995).

The advanced treatment technologies considered in this study include enhanced coagulation, microfiltration/ultrafiltration (MF/UF), nanofiltration (NF), and adsorption using granular activated carbon (GAC). To further reduce DBP formation, conventional water treatment plants that treat surface water commonly remove DBP precursors through enhanced coagulation (Lu and others 2007). Coagulation is common in most water treatment plants; if a water system removes a greater percentage of organic carbon, its coagulation is then considered enhanced. Microfiltration/ultrafiltration can be added to a base treatment process for additional particle and microbial removal, reducing the disinfectant doses and DBP formation (USEPA 2005). American Water Works Association (AWWA) published a study summarizing the reduction results of organic carbon and precursors of THMs and HAAs by MF/UF membrane systems (AWWA 2005). Although removal efficiencies may vary site by site, MF/UF is one technology for additional DBP precursor (organic carbon in this study) removal, particularly when combined with upstream coagulation, as assumed here. Granular activated carbon adsorption and NF remove natural organic matter (NOM), thereby reducing DBP formation (USEPA 2005). Other technologies to enhance organic matter and microbial removal (such as cartridge filtration and second-stage filtration) are not included since they are less common and unlikely to be used in the future Delta. Magnetic ion exchange (MIEX) resin is one of the few technologies available for bromide removal. Although it is still a developing technology, it could treat bromide in future Delta water (CALFED 2005a; Briggs and others 2008). More importantly MIEX is an option when ozonation is still used as the primary disinfection during high bromide occurrences. Although another strategy (i.e., UV) may be more feasible at high bromide levels, considering MIEX helps with comparison of management strategies.

The overall goal of this study is to compare alternative disinfection processes and advanced DBP precursor removal technologies to manage declining source water quality with respect to their estimated treatment costs between the through-Delta intakes in the southern Delta and an intake upstream on the Sacramento River.

METHODS

Current Drinking Water Quality

We examined the drinking water quality at three current Delta intakes—the CCWD Contra Costa Canal at Rock Slough (CONCOSPP1), the SWP-CVP South Delta pumps at Banks (BANKS), and the SWP North Bay Aqueduct at Barker Slough (BARKERNOBAY)—and two locations upstream of the Delta on the Sacramento (Hood) and the San Joaquin River at Vernalis (VERNAUS), as shown in Figure 1. The Banks Pumping Plant was chosen to represent water quality exported to the Bay Area and Southern California through the Central Valley Project (CVP) and the State Water Project (SWP). Water quality for the North Bay Aqueduct was assessed at the Barker Slough intake. The Contra Costa Canal intake is closest to San Francisco Bay.

Three water quality constituents including electrical conductivity, bromide, and organic carbon (TOC and DOC) were investigated by using the available water quality databases, the Municipal Water Quality Investigations Program (MWQI) and the Water Data Library on the Department of Water Resources (DWR) website (<http://wdl.water.ca.gov/wq-gst/>). Data from 2003 to 2007 were examined to represent current drinking water source quality conditions in the Delta and to estimate treatment costs for the selected Delta locations.

Future Delta Water Quality

Future water quality in the Delta over the coming 50 or more years is likely to be influenced by one to three feet of sea level rise and increased flooding of the Delta's western islands. Due to modeling limitations, island flooding is considered separately from sea level rise, even though they are likely to coincide,

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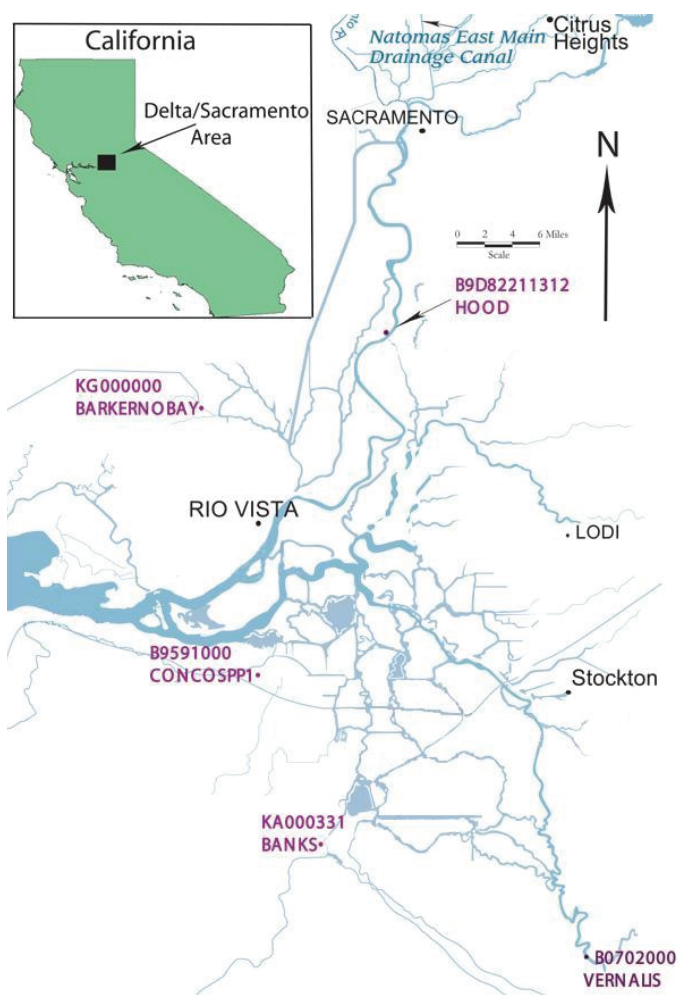


Figure 1 Principal water quality monitoring systems of the DWR in the Delta system considered in this study. Source: California Department of Water Resources.

so this study can only qualitatively assess their separate effects; their combined effects are likely to be greater. The focus of this future water quality assessment is on electrical conductivity, the water quality characteristic of primary interest to water users and most easily represented in Delta hydrodynamic models. More detailed modeling information appears in Fleenor and others (2008).

The tidally averaged Water Analysis Module (WAM) and the two-dimensional RMA Bay-Delta model were used to predict electrical conductivity change with sea level rise and permanently flooded islands,

respectively. Both models were developed by Resource Management Associates (RMA) Inc. for modeling used in the Delta Risk Management Strategy (DRMS) (DWR 2007). The simulation for sea level rise began from a comparison with the 1980 to 2000 base case. All islands are assumed to remain intact. The downstream electrical conductivity boundary condition at the northern San Francisco Bay is assumed to remain 50,000 $\mu\text{S}/\text{cm}$. The ocean boundary condition of the base case was raised by one or three feet to simulate sea level rise, and the initial water elevation throughout the model domain was increased comparably (Mount 2007).

The exercise for the western island failure relied on a simulation by RMA for the DRMS effort for April 12, 2002 to December 31, 2004. Five western islands were selected: Sherman (#52), Twitchell (#60), Bradford (#6), Brannan-Andrus (#7), and Jersey (#24), as shown in Figure 2. At the start of the simulation period, we assumed that these islands would first fill with water having the salinity of surrounding channels. The same inflows, outflows, and operations were used in all simulations, with the only difference being the permanently flooded islands.

We estimated future electrical conductivity by adding the possible electrical conductivity increase in the future—estimated by comparing present and future hydrodynamic model predictions, to the average electrical conductivity field data between 2003 and 2007. The estimated electrical conductivity was then employed in a regression model developed by the Metropolitan Water District of Southern California (MWDSC) (Hutton 2006), which correlates electrical conductivity with several other constituents at locations in the Delta, to estimate concentrations of bromide from hydrodynamic and salinity model results. Additional details are described in Chen and others (2008). The typically strong correlation between electrical conductivity and bromide allows this model to provide reasonable future water quality estimates for concentrations of bromide under the three sea level rise and island failure scenarios.

This analysis is preliminary and demonstrates the potential importance of water treatment costs for Delta decisions. The results presented here are not

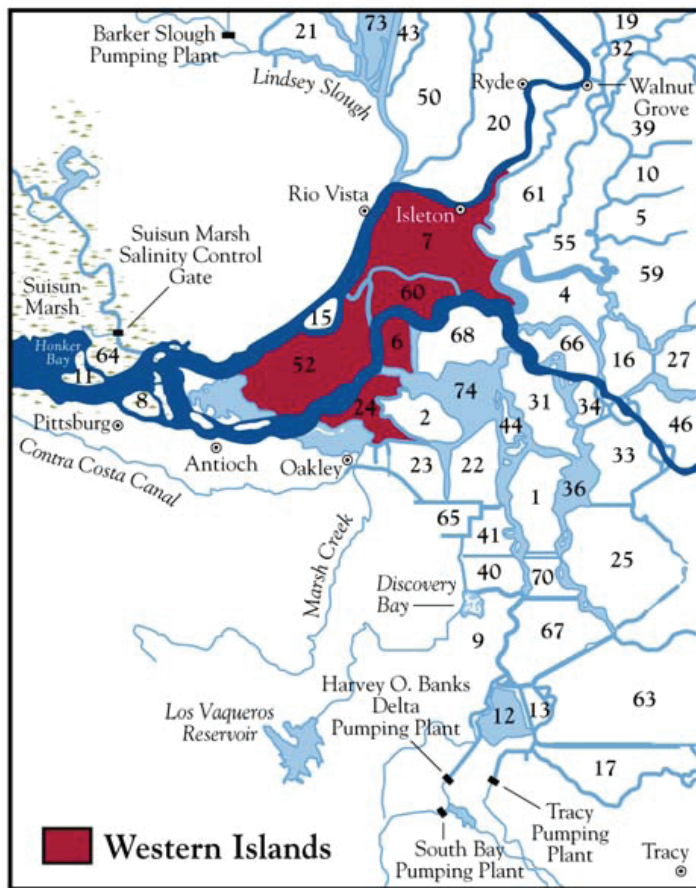


Figure 2 Scenario of the Delta’s western island flooding. Source: Fleenor and others (2008).

exhaustive, and only illustrate the general trends of changes, not the exact levels of change to be experienced in the future Delta. Two assumptions are involved. First, besides the Contra Costa Canal on Rock Slough, CCWD has other available intakes (Mallard Slough near Pittsburg, Contra Costa Canal at Old River) and one intake under construction on Victoria Canal, and uses the intake(s) with the best water quality for direct use. When no intake meets CCWD’s maximum water quality goal, water from Los Vaqueros Reservoir, which is filled using the intake with the better water quality between Old River and Victoria Canal, is used to blend. However, in this study we assumed that CCWD’s water comes exclusively from the Rock Slough intake at the Contra Costa Canal. Second, in the Delta, water quality standards require that salinity levels be met, and outflow is adjusted to meet the standards. However, this analysis did not consider that changes in upstream or in-

Delta operations might be used to meet water quality standards with sea level rise or island flooding.

Cost Estimation Concepts and Analysis

We developed treatment costs by modifying a base treatment plant, representing an existing treatment configuration, to add alternative disinfection and other technologies. Conventional surface water treatment employs coagulation, flocculation, clarification, filtration, and chlorine/chloramine application for disinfection and maintenance of a disinfection residual in the distribution system. We assumed that the technologies investigated here can be added directly to this base conventional plant without land and electricity limitations. Total costs for a plant with multiple treatment processes are assumed to be the simple sum of base plant costs and the costs of additional treatment. Capital and operations and maintenance (O&M) costs are considered. The capital cost includes construction such as excavation and site work, equipment, concrete and steel, labor, pipe and valves, electrical and instrumentation, and housing. These costs are expressed as annualized capital costs, assuming a 5% interest rate and 20 years of operation. O&M costs include building-related energy, process energy, maintenance materials, and labor. Annualized capital cost and annual O&M cost are summed to obtain the total annualized cost. Where the investigated treatment technology already exists in the base treatment plant, we do not consider the capital cost of the technology, so the total annualized cost equals the annual O&M cost of the technology.

By using the cost models and assumptions in published reports, we estimated preliminary costs for alternative disinfection processes including ozonation (USEPA 1999, 2005; Krasner and others 2007; Lu and others 2007), UV irradiation (Darby and others 1995; USEPA 2005; Briggs and others 2008), and advanced treatment technologies, including enhanced coagulation (USEPA 2005; Lu and others 2007), GAC adsorption, MF/UF, NF (USEPA 2005) and MIEX (Briggs and others 2008; CALFED 2005a). Some modifications were introduced, drawing on engineering judgment and practical experience from water agency experts. Costs were converted to 2007

dollars with the Building Cost Index and appropriate Producer Price Index developed by *Engineering News Record* and Bureau of Labor Statistics, respectively. Ranges of estimated costs for each treatment technology are established by considering different treatment goals for design flows generally ranging from 1 to 520 million gallons per day (mgd) based on the availability of cost information. These costs are then applied to estimate costs required for different treatment combinations, comprising alternative disinfection and various advanced treatment technologies. Although some published sources refer to field data for specific treatment plants (Krasner and others 2007; Lu and others 2007), many estimates rely on modeling studies and information from manufacturers. As a result, the estimated costs reported here may be very different from actual costs water agencies would incur from introducing these treatment technologies. More detailed analysis would be needed to develop more reliable estimates for individual locations.

RESULTS AND DISCUSSIONS

Current Delta Drinking Water Quality

We investigated recent patterns of electrical conductivity, bromide, and TOC and DOC for the selected Delta locations. As shown in [Figure 3](#), from 2003 to 2007 the highest electrical conductivity measurements were at the Contra Costa Canal intake, with annual peaks between 700 and 1200 $\mu\text{S cm}^{-1}$, and at San Joaquin River at Vernalis. The seasonal pattern at the Contra Costa Canal intake had high electrical conductivity typically from late summer to early winter. Lower electrical conductivity is found at the Barker Slough intake on the North Bay Aqueduct and at the South Delta pumps at Banks. Electrical conductivity at the North Bay Aqueduct increases from the late winter to late spring and fluctuates less at other times. Salinity at Banks is low during the late winter and early summer, when river flows are highest, and increases from August to December due to low river flows, agricultural drainage from the San Joaquin Valley and the Delta, and seawater intrusion. The lowest electrical conductivity is upstream on the Sacramento River at Hood. The San Joaquin River

at Vernalis has a high electrical conductivity from upstream agricultural drainage. Although the San Joaquin River is not a direct drinking water source, its poor water quality degrades water quality for several intakes (DWR 2004).

Seasonal variability of bromide concentration at the Delta locations from 2003 to 2007 appears in [Figure 4](#). Bromide concentrations at the Contra Costa Canal intake and South Delta pumps at Banks typically varied from 0.008 to 0.79 mg L^{-1} and between 0.05 and 0.41 mg L^{-1} , respectively. Bromide concentration at Barker Slough varies seasonally but never exceeded 0.09 mg L^{-1} . Monthly average bromide concentration at the Contra Costa Canal intake and South Delta pumps at Banks peaked from late summer to winter, while the opposite pattern occurred at Barker Slough intake. The strong correlation between the seasonal variability at the Delta locations except Vernalis indicates that bromide in the Delta mostly results from seawater intrusion. A maximum concentration of 0.48 mg L^{-1} from 2003 to 2007 was found at the San Joaquin River at Vernalis, which may contribute a high bromide load to the Delta from agricultural drainage. The bromide concentration in the Sacramento River at Hood never exceeded 0.02 mg L^{-1} .

TOC concentration can be influenced due to the highly turbid water carrying TOC during storm events, algal blooms, or interference of settled particles during measurement (CALFED 2005b). Therefore, DOC was considered a more accurate measure than TOC for the five locations shown in [Figure 5](#). The highest DOC concentrations were in the North Bay Aqueduct at Barker Slough, ranging from 2.6 to 16 mg L^{-1} C, with peaks typically from late winter to late spring. The DOC concentration at the Contra Costa Canal intake, the South Delta pumps at Banks, and the San Joaquin River at Vernalis varied from 2.1 to 6.5, 2.1 to 8.2, and 2.1 to 9 mg L^{-1} C, respectively, with peaks mostly from late winter to early spring. The Sacramento River has lower DOC concentrations than the other four sites, rarely exceeding 4.3 mg L^{-1} C. TOC and DOC usually has less annual variability than does salinity.

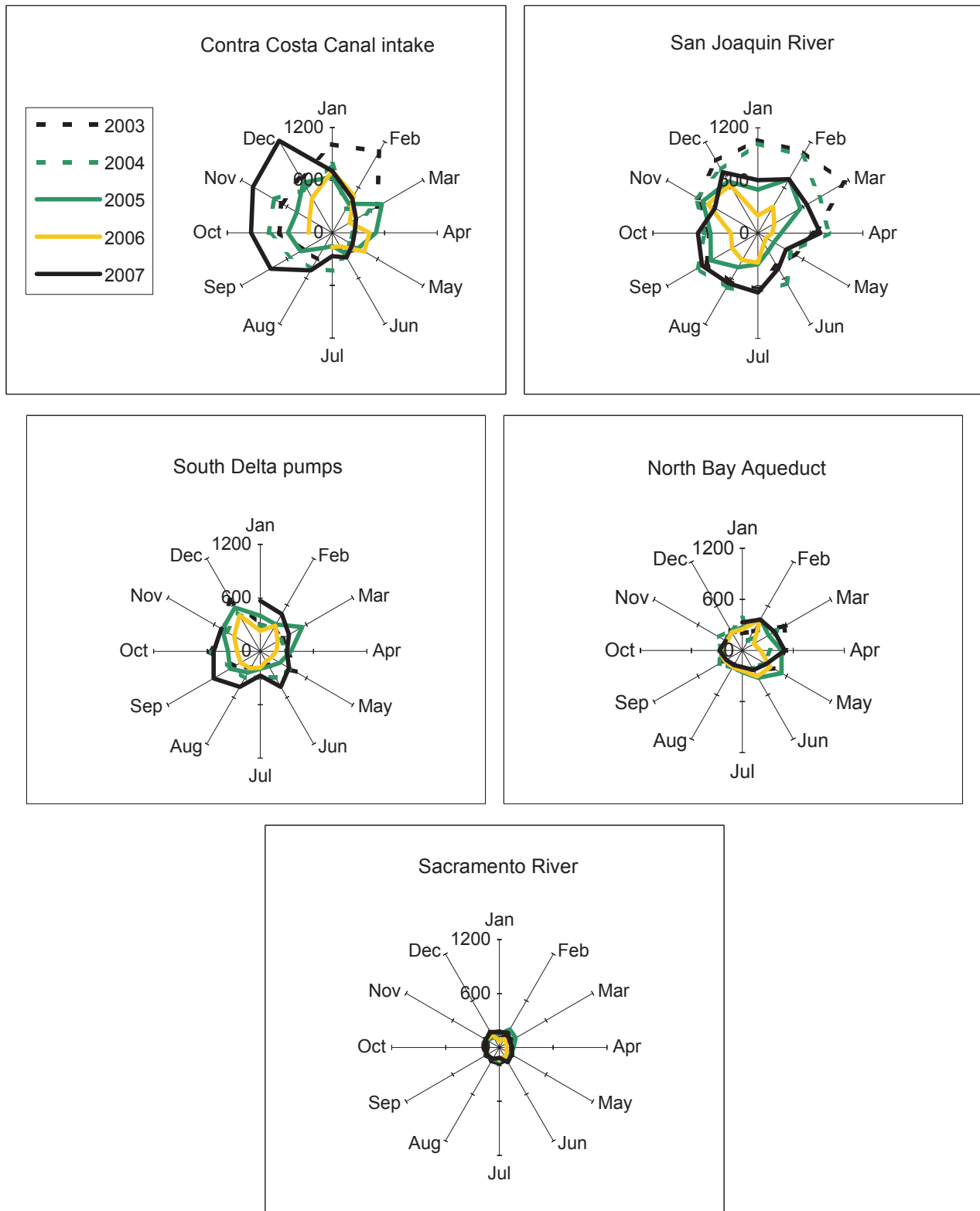


Figure 3 Seasonal variability of electrical conductivity concentration ($\mu\text{S cm}^{-1}$) detected at the selected Delta locations from 2003 to 2007. Source: California Department of Water Resources.

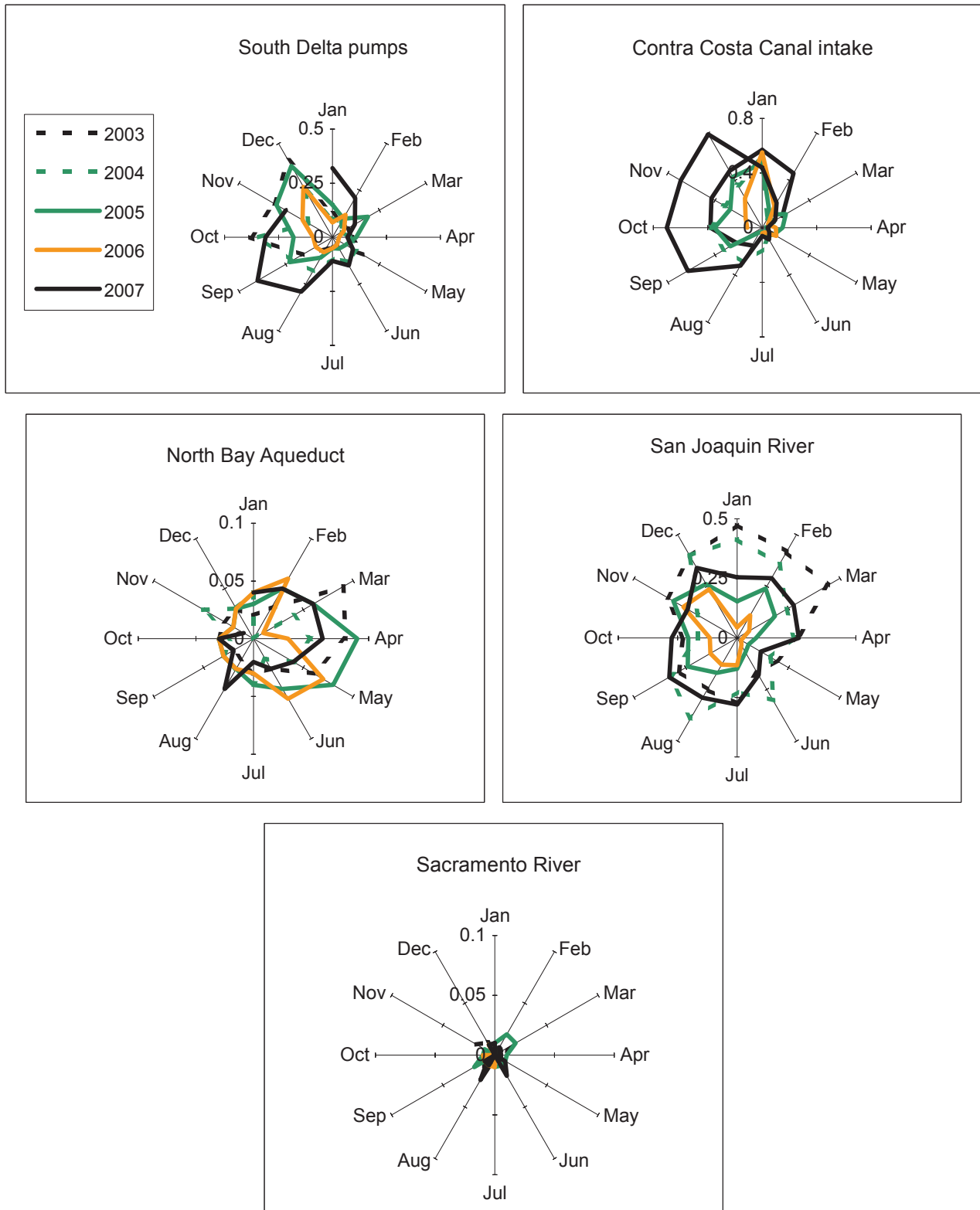


Figure 4 Seasonal variability of bromide concentration (mg L^{-1}) detected at the selected Delta locations from 2003 to 2007. Source: California Department of Water Resources.

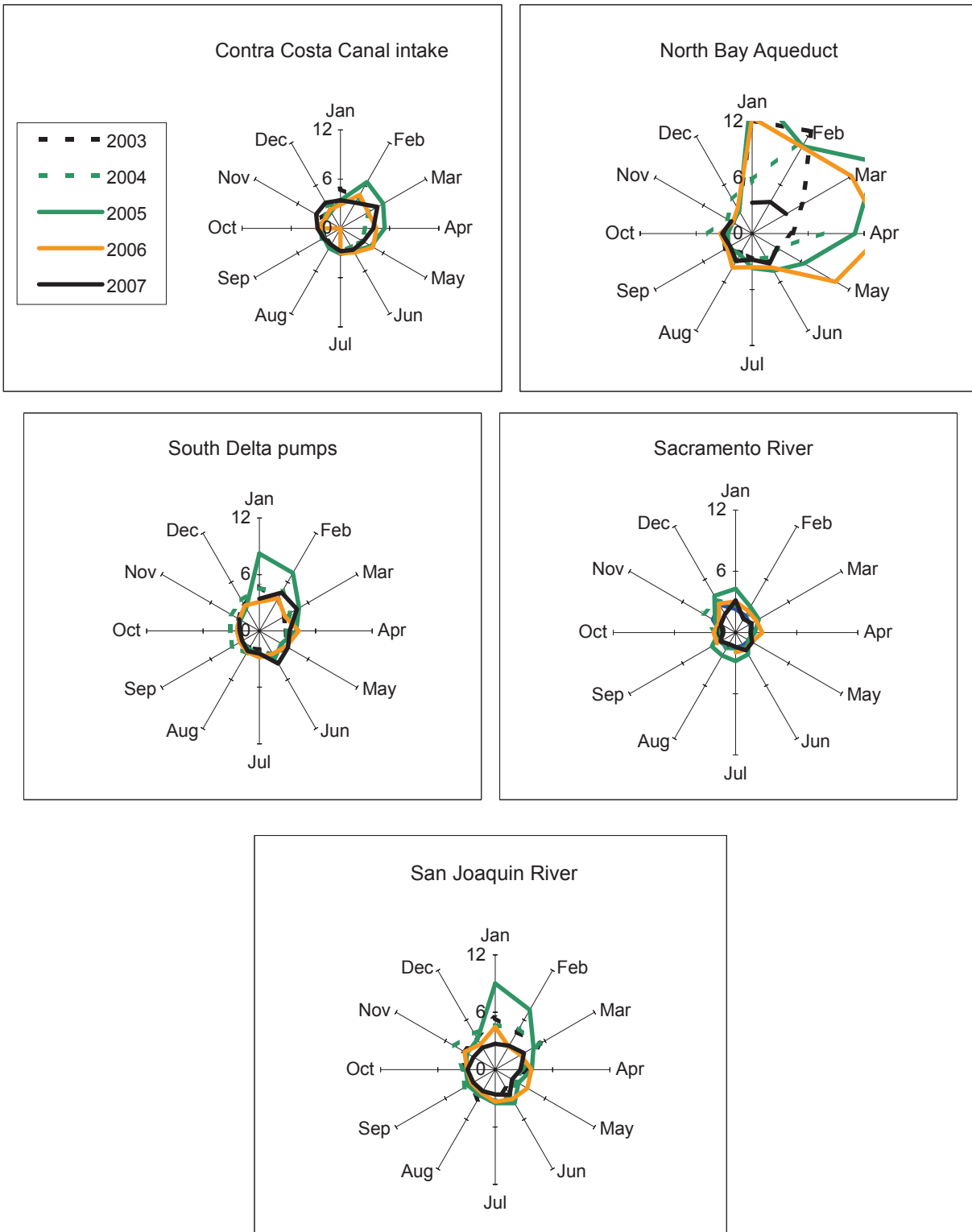


Figure 5 Seasonal variability of dissolved organic carbon concentration ($\text{mg L}^{-1} \text{C}$) at the selected Delta locations from 2003 to 2007. Source: California Department of Water Resources.

Future Water Quality

The future water quality scenarios are compared to current conditions (2003 to 2007) to show likely water quality differences for the future (Table 1). As a point of reference, the CALFED Record of Decision (ROD) concentrations, which are water quality targets for protecting public drinking water (CALFED 2000), are also given. The future DOC concentration was not predicted due to the lack of information required, but is assumed to be similar to the present because of its likely lower sensitivity to sea level rise and permanent island failure.

As shown in the table, water quality at the Contra Costa Canal intake is more significantly affected by any of the three future scenarios than the scenario at the South Delta pumps at Banks. Either one or three feet of sea level rise provide a worse water quality than the western islands flooding alone. The North Bay Aqueduct intake is omitted since the hydrodynamic modeling results were found to be unsuitable for this location (Fleenor and others 2008). Although these water quality predictions are rough, they are used to understand the general magnitudes of the future water quality differences in the Delta, and fur-

Table 1 Current and predicted future water quality conditions at different Delta intakes

Location	Time	Concentration of Constituents (Low, Average, High)			
		Conductance (EC, $\mu\text{S cm}^{-1}$)	Bromide (mg L^{-1})	TOC (mg L^{-1} C)	DOC (mg L^{-1} C)
Sacramento River ^a	Current (2003 – 2007) ^b	73, 155, 232	0, 0.01, 0.02	1.4, 2.4, 7.0	1.3, 2.0, 4.3
San Joaquin River ^a	Current (2003 – 2007) ^b	109, 636, 1143	0.02, 0.25, 0.48	2.7, 4.8, 10.7	2.1, 3.7, 9.0
North Bay Aqueduct	Current (2003 – 2007) ^b	136, 299, 572	N.D., 0.04, 0.09	2.7, 7.9, 52.5	2.4, 5.5, 15.9
South Delta pumps at Banks	Current (2003 – 2007) ^b	125, 355, 671,	0.03, 0.15, 0.41	1.9, 3.8, 5.7	2.0, 3.2, 8.2
	1 ft SLR ^c	126, 455, 1166	0.03, 0.16, 0.85	N.A.	N.A.
	3 ft SLR ^c	126, 741, 2120	0.03, 0.50, 1.64	N.A.	N.A.
	W Is. Fail ^c	210, 439, 729	0.06, 0.25, 0.49	N.A.	N.A.
Contra Costa Water District	Current (2003 – 2007) ^b	151, 497, 1212	0.03, 0.25, 0.79	2.2, 3.5, 6.3	2.1, 3.3, 6.5
	1 ft SLR ^c	151, 679, 2010	0.03, 0.45, 1.55	N.A.	N.A.
	3 ft SLR ^c	151, 1153, 3360	0.03, 0.84, 2.67	N.A.	N.A.
	W Is. Fail ^c	183, 607, 1064	0.04, 0.39, 0.77	N.A.	N.A.
Record of Decision (ROD) target concentration ^d		—	0.05	3	—

N.A. and N.D. represent modeling not available and not detected, respectively.

a For illustrative purposes. Not an urban intake site.

b Field Data (MWQI, Department of Water Resources)

c Future water quality data are estimated from hydrodynamic modeling (Fleenor et al, 2008) and water quality regression (Hutton, 2006) (1 ft SLR: 1 foot sea level rise; 3 ft SLR: 3 feet sea level rise; W Is. Fail: western islands failure)

d From the current Sacramento-San Joaquin River Bay Delta Water Quality Control Plan

ther, to estimate the appropriate treatment technologies at these Delta locations.

Cost Analyses for Treatment Technologies

Ozonation is one of the most common technologies for disinfection of Delta water. However, bromide can affect the efficiency and costs of ozonation for disinfection and oxidation by forming bromate when reacting with organic carbon during ozonation (Coffey and others 1998; Krasner and others 2007). Although established methods such as pH depression can control bromate formation during ozonation, they increase the ozone dosage required, decreasing treatment efficiency and increasing treatment costs due to the large amount of acid required to lower the water pH and the amount of base required to increase the pH after ozonation to prevent corrosion in the distribution system.

We estimated costs based on ozone dosages required to achieve two log *Cryptosporidium* inactivation. The median of all plant-mean ozone doses (3.91 mg L⁻¹)—the dose most common for all plants achieving the given inactivation and the dose most representative of daily plant flows—was used to calculate O&M costs. The median of the plant-maximum doses

(7.0 mg L⁻¹) is used to estimate capital costs because systems will be designed to meet a maximum dose under typical conditions (USEPA 2005). Capital costs include an ozone generation system, ozone contactor, off gas destruction, effluent ozone quench, chemical storage, and electrical and instrumentation. O&M costs include liquid oxygen, quenching agent (H₂O₂), parts replacement, performance monitoring, electricity, and labor. More details on methods and assumptions used for ozone cost estimation are available in USEPA (2005). Information on chemical costs for pH depression at various bromide levels (Krasner and others 2007; Lu and others 2007) is introduced to examine how bromide affects ozonation costs by considering the amount of acid (sulfuric acid) and base (sodium hydroxide) possibly needed to control the formation of bromate. Adjustment of pH is assumed to maintain ozonation pH at 6.1 to control bromate formation, while the pH of ozone contactor and treatment plant effluents are controlled at pH 7.0 and 8.4 to reduce corrosion in the downstream basins and distribution system, respectively.

The effects of bromide concentration on total annualized cost and annual O&M cost for three system sizes (1 to 7, 7 to 76, and 76 to 430 mgd) are shown in Figure 6. Bromide is considered in this

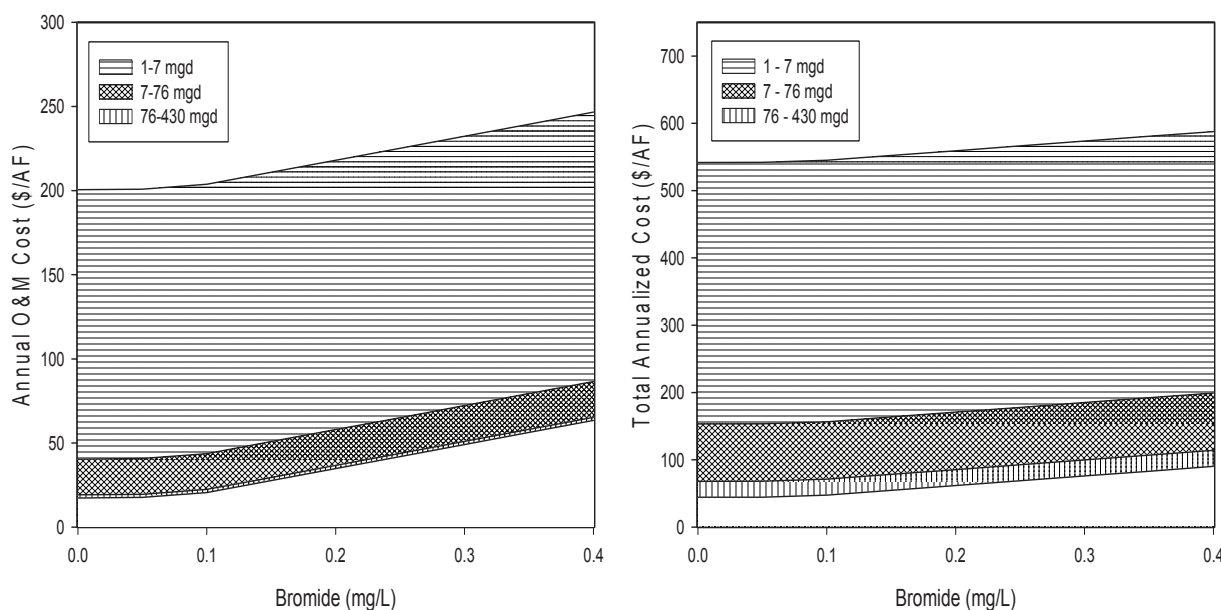


Figure 6 Bromide concentration effects on total annualized cost and annual O&M cost of ozonation for disinfection and oxidation in conventional water treatment

cost estimation for ozone. Substantial economies of scale occur for larger plants. Both total annualized cost and annual O&M cost per acre-foot increase as bromide concentration increases and system size decreases. These costs are based on bromide concentrations ranging from 0 to 0.4 mg L⁻¹, which is the bromide concentration range common in the Delta. The concentrations of TOC are assumed to be 3.5 and 4.1 mg L⁻¹ as C during wet years, and dry and critical years, respectively. TOC removal before ozonation is another option to control bromate formation by further reducing the organic carbon concentration, but we did not investigate the effect of TOC on ozonation cost (ozonation cost as a function of TOC concentration) because TOC can typically be removed by other treatment processes before ozonation in conventional water treatment.

Estimated total annualized and annual O&M costs of UV disinfection for three system sizes (1 to 7, 7 to 76, 76 to 520 mgd) appear in Table 2. Methods used for this estimation are found in USEPA (2005), with several important assumptions as follows. These costs are estimated by assuming a UV dose of 40 mJ cm⁻² with an uninterrupted power supply (UPS). Low and medium pressure lamps are assumed to be replaced annually and every six months, respectively. Although the effects of water quality changes on UV disinfection costs cannot be estimated directly, the comparison with ozone oxidation costs under current conditions suggests that this technology is potentially cost-effective for upgrading or replacing current disinfection and oxidation processes. However, UV disinfection uses large amounts of electricity and requires regular lamp cleaning (Briggs and others 2008; USEPA 2005), which can be expensive. Additional pumping to overcome head losses may be needed for some sites (USEPA 2005).

Coagulation already exists in most water treatment plants to remove organic matter, so only annual O&M costs are considered. The information used to estimate the O&M costs of enhanced coagulation is collected from Lu and others (2007). The costs include aluminum sulfate, polymer, and solid waste to be handled, and are developed for implementing enhanced coagulation with the TOC removal ratio of 1.0 every month (Lu and others 2007). Effects of TOC concentration on annual O&M cost for three system sizes (1 to 7, 7 to 76, and 76 to 430 mgd) are shown in Figure 7. TOC concentration is the only water quality parameter considered, and TOC is assumed to range from 0 to 5 mg L⁻¹ C in this cost estimate, since most TOC concentrations detected in the Delta from 2003 to 2007 are within this range. Additional costs not considered in the estimation may include dewatering and disposal of the sludge, and standby charges by the contractor.

Table 3 presents total annualized and O&M costs of GAC, MF/UF, and NF for various system sizes. Several assumptions for each technology are summarized as follows. For GAC, two empty bed contact times (EBCTs) and a range of reactivation frequencies (90, 240, and 360 days) are considered to account for variability in source water quality. For MF/UF and NF, costs are provided for a design feed water temperature of 10 °C, and other assumptions including pumping, land cost, backwash disposal, brine discharge, etc. follow the EPA's document. For the same system size, both total annualized and annual O&M costs are lowest for GAC, followed by MF/UF, and then NF, which is the most costly. We did not calculate the effects of water quality changes on costs due to the lack of information.

We estimated the annualized capital costs of a MIEX system for different system sizes, but did not esti-

Table 2 Total annualized and annual O&M costs of UV disinfection process for systems of different sizes

Size of System (mgd)	1 – 7	7 – 76	76 – 520
Total Annualized Cost (\$ af ⁻¹)	21 – 105	10 – 22	6 – 12
Annual O&M Cost (\$ af ⁻¹)	6 – 27	2 – 12	2 – 7

The costs were converted to 2007 dollars using deflators from *Engineering News Record* and the Bureau of Labor Statistics.

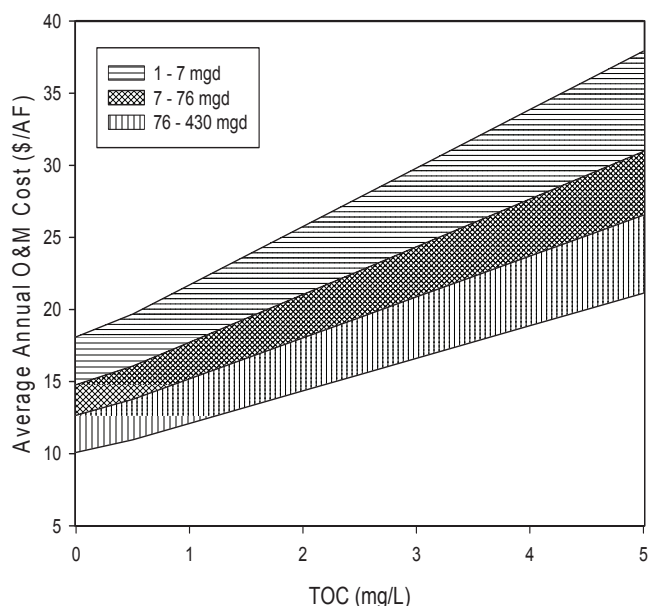


Figure 7 Effects of total organic carbon concentration on annual operation and maintenance cost of enhanced coagulation

mate annual O&M cost due to the lack of data. Based on the data from CALFED (2005), it is calculated that annualized capital cost ranges from \$53 to \$23 per acre-foot for system sizes between 10 and 150 mgd. However, using the data from Briggs and others (2008) we estimated the annualized capital cost and annual O&M cost to be \$105 and \$34 per af, respectively, for a system size of 100 mgd. Economy of scale is not observed between these two studies, perhaps due to site-specific operations or different safety factors.

Treatment Strategies for Various Water Quality Scenarios

DBP formation is a complex process involving several chemical constituents in the water source as well as various reactions with the disinfection process. Several treatment approaches often are available for reducing DBP precursors to prevent DBP formation, instead of changing the disinfection process. The least expensive approach to increased bromides in Delta source water is likely to be increased treatment to remove TOC (Krasner and others 2007; Lu and others 2007). Reducing TOC reduces the ozonation dose needed for disinfection and reduces the amount of carbon available, which both reduce DBP formation. For example, although GAC is not designed to remove bromide, it can reduce TOC enough to reduce ozone dosage, which in turn reduces bromate formation. These methods are not necessarily exhaustive, and other methods or variants might provide better treatment cost performance than predicted in this study.

Figure 8 summarizes possible treatments for various Delta TOC and bromide conditions. The concentration limits of TOC and bromide for various treatment strategies are developed by considering the current regulatory limit of 10 µg L⁻¹ for bromate (Krasner and others 2007) and using studies prepared by AwwaRF (now Water Research Foundation) (Briggs and others 2008) and MWDSC (Krasner and others 2007; Lu and others 2007), and information provided by the Santa Clara Valley Water District (SCVWD) and the Alameda County Water District. Ozonation is assumed as the base treatment technology for disin-

Table 3 Total annualized cost and O&M costs of selected technologies for DBP precursor removal

Treatment		System Size (mgd)		
		1 – 7	7 – 76	76 – 520
Granular Activated Carbon ^a	Total Annualized Cost (\$ af ⁻¹)	137 – 877	62 – 282	39 – 146
	Annual O&M Cost (\$ af ⁻¹)	44 – 568	21 – 126	18 – 74
Microfiltration/Ultrafiltration	Total annualized Cost (\$ af ⁻¹)	301 – 554	214 – 301	158 – 214
	Annual O&M Cost (\$ af ⁻¹)	113 – 207	91 – 113	82 – 91
Nanofiltration	Total Annualized Cost (\$ af ⁻¹)	464 – 584	364 – 464	293 – 364
	Annual O&M Cost (\$ af ⁻¹)	256 – 345	225 – 256	209 – 225

a. The maximum system size considered for granular activated carbon is 430 mgd instead of 520 mgd.

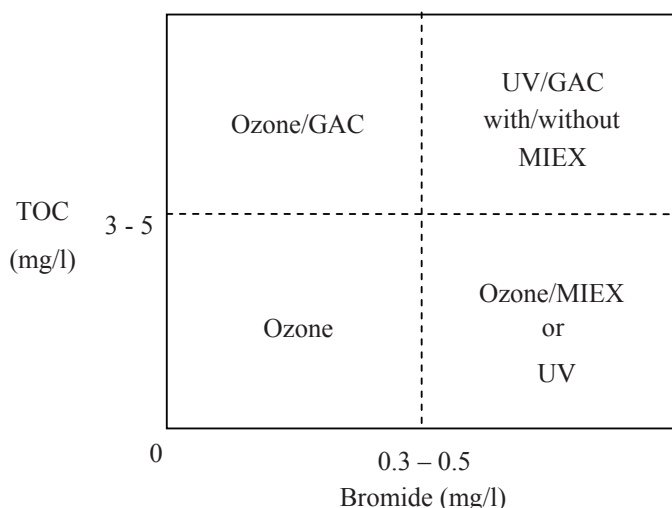


Figure 8 Treatments assumed for different Delta raw water qualities

fection and oxidation; it is used in many water treatment plants for Delta waters (Chen and others 2008). GAC and MIEX are considered for high concentrations of TOC and bromide, respectively. Besides ozone with GAC, enhanced coagulation with post-ozonation is also effective for high TOC and low bromide conditions (not shown in the figure). For medium bromide concentrations— 0.4 mg L^{-1} was examined in Briggs and others (2008)—MIEX following coagulation could improve bromide removal by removing competing anions (NOM and alkalinity) through coagulation. For high bromide concentrations (0.8 mg L^{-1} tested in the study) MIEX placed before ultrafiltration removed both bromide and TOC. Although likely an expensive process, MIEX seems capable of controlling NOM (and TOC) and low-affinity ions such as bromide (Briggs and others 2008). Changing from ozonation to UV light irradiation for disinfection is another alternative for high concentrations of bromide. Besides high turbidity and suspended solids, high organic carbon levels interfere with UV transmittance as well, reducing UV efficacy (USEPA 2005). However, for systems with high DOC levels, UV light irradiation is recommended to be applied after treatment processes that remove organic carbon, circumventing organic carbon interference (USEPA 2005).

Other technologies, such as NF and RO, also can help minimize TOC and bromide levels but may have

higher treatment costs, so only GAC and MIEX are considered. In some cases, GAC may be more expensive than MF/UF for DBP precursor removal, such as in California, since GAC may only last one to three months. When the bromide concentration is high, the treatment cost might be higher with the combination of ozone/MIEX than with UV (cost difference not shown in Figure 8).

Each ozone plant will have different ozone and/or bromide limits because of site-specific operations or different safety factors employed by the water agencies for water quality standards. For example, the MWDSC -operated Mills Water Treatment Plant by that uses ozonation for disinfection and oxidation can only handle bromide levels of up to 0.3 mg L^{-1} when treating Delta water with TOC levels less than 4 mg L^{-1} (Lu and others 2007). However, a pilot study conducted by the SCVWD in 2000 found that source water with bromide concentration as high as 0.6 mg L^{-1} can still meet a $8 \text{ } \mu\text{g L}^{-1}$ of bromate concentration goal when the ozone dose was 2 mg L^{-1} at pH 6.4 (Zhou 2008). For the CCWD, bromide is also not a problem when the TOC concentration is low (Briggs and others 2008). In addition, some plants have sufficient free chlorine or chloramines contact downstream of ozonation to achieve additional disinfection credit, which also may affect treatability limits for some treatment plants and locations.

Treatment Costs for Disinfection Alternatives at Delta Locations

To understand how water quality at different Delta locations affects treatment costs, we used cost information for unit treatment technologies to estimate the costs required to treat Delta water, as summarized in Table 4. We considered disinfection processes including chlorine, ozone, and UV and enhanced coagulation since the costs of these technologies depend on the concentrations of bromide and organic carbon. We estimated costs of ozone and enhanced coagulation using the average concentrations of bromide and TOC from 2003 to 2007 at the five intake locations examined above (Table 1). Since enhanced coagulation and ozonation are already used in most Delta treatment plants, we considered only annual O&M costs for these two technologies.

Table 4 Summary of estimated treatment costs of treating current Delta water

Plant and Intake Location	System Size (mgd)	Treatment	Estimated Costs (\$ af ⁻¹) ^a
Sacramento River ^b (Hood; Medium Plant)	7 – 76	Enhanced coagulation/Chlorine ^c	19 – 25
		Enhanced coagulation/Ozone ^d	37 – 62
		Enhanced coagulation/UV	28 – 45
Sacramento River ^b (Hood; Large Plant)	76 – 520	Enhanced coagulation/Chlorine ^c	18 – 22
		Enhanced coagulation/Ozone ^d	35 – 40
		Enhanced coagulation/UV	24 – 33
North Bay Aqueduct	7 – 76	Enhanced coagulation/Ozone ^d	54 – 81
		Enhanced coagulation/UV	44 – 65
Contra Costa Water District	7 – 76	Enhanced coagulation/Ozone ^d	66 – 91
		Enhanced coagulation/UV	32 – 50
South Bay (South Delta Export)	7 – 76	Enhanced coagulation/Ozone ^d	53 – 78
		Enhanced coagulation/UV	33 – 51
Southern California (South Delta Export)	76 – 520	Enhanced coagulation/Ozone ^d	46 – 53
		Enhanced coagulation/UV	25 – 35

a For illustrative purposes. Currently no urban intakes here.

b Enhanced coagulation/chorine is not possible for other plants. Only the base cost is listed based on the current drinking water treatment processes used at this location.

c Only annual O&M costs were used for enhanced coagulation and ozonation since these are already used in most Delta treatment plants; annualized total costs (annualized capital cost and annual O&M cost) were used for other treatment technologies.

d Costs of ozonation and enhanced coagulation were estimated using the average concentration of TOC and bromide at Delta intake locations from 2003 to 2007.

The Sacramento River location, where no urban intake currently exists, is used for illustrative purposes. Cost estimated for South Bay and Southern California plants assume that these plants export Delta water at Banks. Different water quality issues might occur for South Bay and Southern California water treatment plants, affecting the quality of their source waters taken from South Delta pumps, such as their blending of Delta, non-Delta, and stored water sources. True treatment costs of scenarios involving other source waters or technologies will likely differ from the estimates provided here. However, these estimates should provide insights into general or potential magnitudes of Delta water quality effects.

Recently, the CCWD built a new 40-mgd water treatment plant for a capital cost of approximately \$48 million, with full-capacity operating costs of roughly \$2 million per year (Briggs 2008). For a 5% interest

rate, the total annualized treatment cost is roughly \$100 per acre-foot. For the water treatment plant operated by the City of Sacramento that collects water from the Sacramento River, calculated operating costs were roughly \$300 per acre-foot (Peifer, City of Sacramento). Inconsistent cost accounting across agencies prevents cost comparisons among actual plants for our study. However, as compared to the costs from these full-scale plants, the relatively lower costs in Table 4, which address only coagulation and disinfection, indicate that the cost estimation in this study is probably not over-stated.

At locations with low bromide concentrations (the Sacramento River at Hood), ozonation and UV costs are similar. Ozonation cost increases significantly with bromide concentration, with UV disinfection combined with other treatments eventually having an apparently lower cost (the CCWD). Ultraviolet is

a potential disinfection alternative to ozonation if the source water quality degrades further, such as if bromide concentration increases due to seawater intrusion. However, providing a sufficient dose for targeted inactivation level (the efficacy of UV is significantly influenced by turbidity and suspended solids) and disinfectant residuals in the distribution system will affect the application of UV in a conventional drinking water plant. Since ozonation is used in many Delta water treatment plants, revising treatment operations also might help control treated water quality as in-Delta water quality degrades for urban uses.

Treatment Costs for Potential Future Water Quality

We examine the influence of future water quality changes on treatment cost differences among these Delta locations by estimating total costs for different combinations of treatment technologies for current and potential future water quality conditions at three in-Delta intakes, assuming ozonation and enhanced coagulation as the base case. We did not investigate UV costs because of the lack of information on the effects of water quality changes on UV costs. Our primary purpose in this study was to examine likely increases in treatment costs for potential future worsened water quality when ozonation, the major disinfection process in the Delta, is used for disinfection. This information is important so various management strategies—such as changing to a new source with a better water quality or replacing ozonation with UV disinfection—can be compared.

Assumptions regarding the system sizes and cost estimation are similar to those used for Table 4. Annualized costs are used for these treatment technologies, except enhanced coagulation and ozonation, two technologies already installed in Delta plants. Both TOC and bromide concentrations are considered in the cost estimation; however, only bromide concentrations are particularly indicated in the table, since it varies most among intake locations and future scenarios. The average annual concentrations of bromide at each Delta location from 2003 to 2007 and the model prediction for likely future water quality are then used to estimate the annual O&M costs

for enhanced coagulation and ozonation. Various changes in the Delta and upstream can increase TOC concentration. Since future water quality conditions do not include TOC predictions, we used the TOC concentration ranges from 2003 and 2007 to estimate treatment costs, assuming future TOC concentrations will not change significantly with seawater intrusion.

The future conditions assume seawater intrusion into the Delta from sea level rise or failure of western Delta islands (Table 1). The North Bay Aqueduct is excluded because salinity projections are unavailable for this site. We examine the Sacramento River location for current conditions only, given our assumption that upstream locations on this river will not have greater costs from seawater intrusion, although they, like some Delta locations, might have higher TOC concentrations. Because of increasing bromide concentration, MIEX was considered to treat Delta water, with an assumed total annualized cost ranging from \$50 to \$100 per acre-foot, as discussed above. As sea level rises and western islands fail, total costs to treat Delta water from the current CCWD intakes will be highest.

Given current treatment technologies, the estimates of future conditions and costs, and the available knowledge of treatment processes (e.g., treatability limit of treatment technologies discussed in Figure 8), the most likely treatment processes and costs are indicated in bold in Table 5. Granular activated carbon has been employed in some treatment plants in the CCWD and the South Bay, especially in larger plants (CALFED 2005a). Therefore, the most likely treatment costs of the CCWD and the South Bay plants under current conditions could be within the cost ranges estimated for the combination with GAC. However, other factors also can affect the choice of treatment technology, such as reliability and residuals disposal. In Table 5, GAC is primarily considered to prevent a possible high TOC concentration in the future because of its relatively low cost, assuming enhanced coagulation has been employed. When bromide concentration exceeds the range of 0.3 to 0.5 mg L⁻¹, the use of MF/UF with MIEX is recommended to remove bromide (see Figure 8).

With some combinations of treatment technologies possibly being economically infeasible or impractical

Table 5 Summary of estimated treatment costs for treating current and potential future Delta water by various treatment methods. (Most likely treatments are presented in boldface.)

Intake Location (Plant)	Condition	Bromide (mg L ⁻¹)	Estimated Costs (\$ af ⁻¹)				
			Enhanced Coagulation/Ozone ^{b,c}	In Combination with GAC ^c	In Combination with MF/UF ^c	In Combination with MIEX ^{c,d}	In Combination with NF ^c
Sacramento River (Medium Plant)	All	0.01	37 – 62	100 – 343	251 – 363	301 – 463	402 – 525
Sacramento River (Large Plant)	All	0.01	35 – 40	74 – 187	193 – 254	243 – 354	329 – 405
CCWD ^a	Current (2003 – 2007)	0.25	66 – 91	128 – 373	280 – 392	330 – 492	431 – 555
	1 ft SLR	0.45	91 – 127 ^d	153 – 409	305 – 428	355 – 528	455 – 591
	3 ft SLR	0.84	147 – 183 ^d	209 – 465 ^d	360 – 484 ^d	410 – 584	511 – 647
	W Is. fail	0.39	82 – 119 ^d	145 – 400	296 – 420	346 – 530	446 – 582
South Bay ^a (South Delta Export)	Current (2003 – 2007)	0.15	53 – 78	115 – 359	266 – 379	316 – 479	417 – 541
	1 ft SLR	0.26	63 – 100 ^d	126 – 381	277 – 401	327 – 501	428 – 563
	3 ft SLR	0.50	98 – 134 ^d	160 – 416	311 – 435	361 – 535	462 – 598
	W Is. Fail.	0.25	62 – 98 ^d	124 – 380	276 – 399	326 – 499	426 – 562
Southern California ^a (South Delta Export)	Current (2003 – 2007)	0.15	46 – 53	85 – 199	204 – 266	254 – 366	340 – 417
	1 ft SLR	0.26	61 – 78 ^d	124 – 360	275 – 379	325 – 479	426 – 542
	3 ft SLR	0.50	96 – 113 ^d	158 – 394	309 – 414	359 – 514	460 – 576
	W Is. Fail.	0.25	60 – 77 ^d	122 – 359	274 – 378	324 – 478	425 – 541

GAC = granular activated carbon; MF/UF = microfiltration/ultrafiltration; NF = nanofiltration; MIEX = magnetic ion exchange. CCWD = Contra Costa Water District; 1 and 3 ft SLR = 1 and 3 feet sea level rise; W Is. Fail. = western islands failure.

- a A medium treatment plant ranging from 7 to 76 mgd is assumed for the CCWD and the South Bay; a large plant ranging from 76 to 430 mgd is assumed for Southern California.
- b Costs of ozonation and enhanced coagulation were estimated using the average annual concentration of water constituents of interest from 2007 data and the model prediction.
- c Only annual O&M costs were used to represent the costs of ozonation. Total annualized costs (annualized capital cost and annual O&M cost) were used for the costs of other treatment technologies.
- d The combination of treatment technologies might not be practical for this water quality condition; ultraviolet or further combination with additional treatment technologies might be needed.

for some water quality conditions, UV or combinations of additional treatment technologies might be needed. Although costs for UV are not investigated in Table 5, UV costs probably will not increase greatly under the future conditions projected in this study because of the limited effect of bromide concentration on UV cost. Therefore, with the possibly significant increase of total treatment costs of using ozonation as the disinfection process, UV for disinfection and oxidation or other centralized or decentralized treatment and disinfection processes might be considered. In addition, the treatment cost estimates in Tables 4 and 5 do not show possible limitations on availability of land and electricity capacity at existing treatment plant sites. Using other source water with fewer contaminants and DBP precursors might help accommodate increasing Delta contaminants, at lower treatment costs.

CONCLUSIONS

The Delta is California’s single most important drinking water source, supplying water to more than two-thirds of California’s residents in the greater Bay Area and Southern California. Sea level rise or failure of the Delta’s western islands would likely increase the

costs of treating water from the south Delta intakes. Minimum increases of annualized treatment cost for simulated future conditions, with various treatment combinations are presented in Table 6 for two Delta intake locations (Contra Costa Canal intake and the South Delta pump at Banks) and for a hypothetical intake in the north Delta on the Sacramento River at Hood, with estimates for the two size categories used at the South Delta and Sacramento River plants. A 3-ft sea level rise has the greatest effect on Delta drinking water quality and associated treatment costs, with similar effects being observed under the scenarios of a 1-ft sea level rise and/or the flooding of western Delta islands. While Sacramento River intakes upstream of the Delta are largely unaffected by sea level rise or the failure of Delta islands, the Contra Costa Canal and Sacramento River intakes show the highest increases in annualized treatment costs. These cost estimates, although preliminary, illustrate the magnitude of likely cost differences for strategic planning purposes.

Overall, drinking water treatment costs for diversions upstream of the Delta on the Sacramento River are the lowest and least susceptible to increase due to sea level rise and Delta island failures. The drinking water

Table 6 Summary of estimated costs of alternative disinfection and selected treatment technologies for treating current and future Delta water

Plant and Intake Location	Annualized Treatment Cost ^a (\$ af ⁻¹)			
	Current (2003 to 2007)	1-ft Sea Level Rise	3-ft Sea Level Rise	W Is. Fail.
Sacramento River (Medium Plant)		37 – 62 ^c		
Sacramento River (Large Plant)		35 – 40 ^c		
CCWD ^b (Contra Costa Canal Intake)	66 – 91	153 – 409	410 – 584	145 – 400
South Bay ^b (South Delta Pumps)	53 – 78	126 – 381	160 – 416	124 – 380
Southern California ^b (South Delta Pumps)	46 – 53	124 – 360	158 – 394	122 – 359

CCWD = Contra Costa Water District; W Is. Fail. = western islands failure.

a Includes annual O&M costs of existing enhanced coagulation and ozonation processes and total annualized cost of selected additional advanced technologies including GAC, MF/UF, MIEX, and NF.

b A medium treatment plant (ranging from 7 to 76 mgd) is assumed for the CCWD and South Bay; a large plant (ranging from 76 to 430 mgd) is assumed for Southern California.

c Water quality in the Sacramento River is assumed constant over simulated conditions.

d Coagulation.

treatment cost difference of taking water from the South Delta, as opposed to from the Sacramento River in the north Delta, is currently about \$20 to \$60 per acre-foot, which is in line with the MWDSC's annualized cost estimates for ozonation (Harader 2007). This cost difference is likely to increase to \$100 to \$500 per acre-foot with sea level rise and failures of the western Delta's islands. With roughly 1.5 million acre-feet per year of Delta water currently used for urban water supplies (Lund and others 2010), these cost differences amount to \$30 to \$90 million per year currently and could increase to \$200 to \$1000 million per year in the future, if urban use of Delta waters rises to 2 million acre-feet annually.

The increasing likelihood of bromide in Delta waters affected by sea level rise and island failures also raises health risks from residual DBPs after treatment. Besides modifying operational strategies of existing treatment processes and adding new treatment technologies, other established methods such as using or blending with other source waters with less contamination may further change treatment costs but help reduce costs and health risks. Currently, both the CCWD and the North Bay Aqueduct plants switch to alternative water sources when water quality is poor and are also considering alternative Delta intake locations (Briggs and others 2008). More detailed information and studies from different aspects—including treatment technologies and costs, water resource policy and management strategies, and residual public health risk by potential DBPs—will be necessary to assess the best management options for drinking water sourced from the Delta.

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