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

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Abstract

This study explores the current and long-term effects of Delta export water quality on drinking water treatment cost and residual public health risk from disinfection byproduct (DBP) formation. Appropriate treatment options and strategies were discussed based on water quality constituents of concern. The costs of selected treatment technologies were estimated and applied for current and future conditions for different export locations with projections of future water quality. Overall, drinking water treatment costs would be lower for Sacramento River water. With roughly 1.5 million acre-foot (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 possibly rise to $200 to $1000 million per year in the future, with lower water quality and use of the Delta likely to rise to 2 million af annually. Currently DBPs are manageable with Delta supplies within treatment standards, while sea level rise and western island failures would make treatment of Delta water for urban use more difficult and expensive. Bromide from seawater, combined with total organic carbon is a particularly problematic precursor of DBPs. With sea level rise and western island failures, waters drawn directly from the Delta will likely become increasingly risky to public health and less desirable as a conventional water source.

Introduction

The Sacramento-San Joaquin Delta system is the single largest drinking water source for California, serving 23 million Californians, or more than two-thirds of households in the state. 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.

This paper describes the current and likely future state of drinking water from the southern Delta as compared with locations upstream on the Sacramento River, summarizing a lengthier report (Chen et al. 2008). Sea level rise and failure of Delta's western islands were considered as future likely conditions. The Sacramento River's water quality would be available to urban agencies if a peripheral canal replaced current through-Delta pumping. This study compared various advanced drinking water treatment technologies to manage declining source water quality with respect to their estimated drinking water treatment costs and potential disinfection byproduct (DBP) formation between the through-Delta intakes and an intake upstream on the Sacramento River.

Water quality in and near Delta

Delta water is collected and treated for urban users from several South Delta intakes on Rock Slough and Old River serving Contra Costa Water District (CCWD), the State Water Project (SWP) and main federal Central Valley Project (CVP) Banks and Jones pumping plants, and a northern Delta intake on Barker Slough feeding the SWP's North Bay Aqueduct. This study examines the drinking water qualities at three current Delta intakes (the CCWD Contra Costa Canal at Rock Slough, the SWP-CVP South Delta pumps at Banks, and the SWP North Bay Aqueduct at Barker Slough), and two locations upstream of the Delta on the Sacramento (at Hood) and the San Joaquin River (at Vernalis). Banks pumping plant was chosen to represent water quality exported to the Bay Area and Southern California through the CVP and 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. These data are used to understand current drinking water quality conditions in the Delta and to estimate water treatment costs for these locations.

Water quality constituents of interest

Delta water quality varies considerably by location and constituent of interest. The historical pattern of five major water quality constituents is described here for the selected locations. The constituents include electrical conductivity (EC), bromide, total and dissolved organic carbon (TOC and DOC), and pesticides and herbicides. Table 1 summarizes the main water quality concerns for each constituent.

Table 1. Drinking water constituents of interest

Constituent	Concern
Electrical Conductivity	Salinity
Bromide	DBP precursor, salinity
Total/Dissolved Organic Carbon	DBP precursor
Pesticide/ Herbicide	DBP potential precursor, risks to environmental and public health

Salinity can reflect seawater intrusion into the Delta as well as wastewater discharges and agricultural runoff from upstream that together are the major sources of bromides and salinity in the Delta. TOC and DOC from drainage waters are significant precursors of DBPs during disinfection. Pesticides and herbicides can pose risks to the environment and public health, and are potential precursors for certain DBPs (Chen and Young 2008).

The main sources used for water quality data at the five locations are 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/). These sources provide data from 2003 to 2007 (Chen et al. 2008).

Electrical conductivity (salinity)

Salinity in the Delta is commonly measured using EC, with bromide as an important salt constituent. Salinity can contribute taste problems, affect water recycling capabilities, and raise costs to residential and industrial water users from corrosion. Over the five-year 2003 to 2007 period, the highest EC measurements were at the Contra Costa Canal intake, with annual peaks between 700 and 1200 $\mu S\ cm^{-1}$, and at San Joaquin River at Vernalis. A seasonal pattern occurred at the Contra Costa Canal intake with high EC concentrations typically from late summer to early winter. Higher salinity is directly related to higher bromide and chloride concentrations, with bromides being of greatest concern for DBP formation in drinking water treatment (Harder 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 the seawater. CCWD constructed the Los Vaqueros storage facility primarily for storing high quality water to blend with Delta water when salinity is high.

Lower EC is found at the Barker Slough intake on the North Bay Aqueduct and at the South Delta pumps at Banks. EC levels at the North Bay Aqueduct increase from the late winter to late spring and have less fluctuation at other times. Salinity at Banks is low during the late winter and early summer when river flows are highest, and increase from August to December due to low river flows, agricultural drainage from the San Joaquin Valley and the Delta, and seawater intrusion. The lowest EC is upstream on the Sacramento River at Hood. The San Joaquin River at Vernalis has a high EC 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. The U.S. District Court (Wanger) decision in 2007 to restrict Delta pumping (at Banks and Jones pumping plants) increased the influence of San Joaquin River salinity at Banks pumping plant. In addition, when San Joaquin River flow exceeds about 3400 cubic foot per second, water at Jones pumping plant mostly from the San Joaquin River (DWR 2004).

Bromide

Bromide is a drinking water concern due to formation of bromate, a DBP and probable carcinogen, by reacting with ozone to produce potent brominated forms of DBPs during disinfection (Krasner et al. 2006). Because bromides in the Delta mostly result from seawater intrusion (except at Vernalis), they are typically correlated with EC. The CALFED Record of Decision (ROD) has a bromide target concentration of 50 $\mu g\ l^{-1}$ for public drinking water health protection (CALFED 2000).

As shown in Figure 1, bromide concentrations at the Contra Costa Canal intake and South Delta pumps at Banks typically varied from 8 to 790 ($\mu g\ l^{-1}$) and between 50 and 410 μg

l^{-1}, respectively. Bromide concentration at Barker Slough varies seasonally but was always below 90 μg l^{-1} from 2003-2007 (Figure 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 San Joaquin River at Vernalis may contribute high bromide load to the Delta from agricultural drainage, with a maximum concentration of 480 μg l^{-1} from 2003 to 2007. Peak bromide concentrations occurred in fall to early spring of most years. Bromide concentration in the Sacramento River at Hood never exceeded 20 μg l^{-1}.

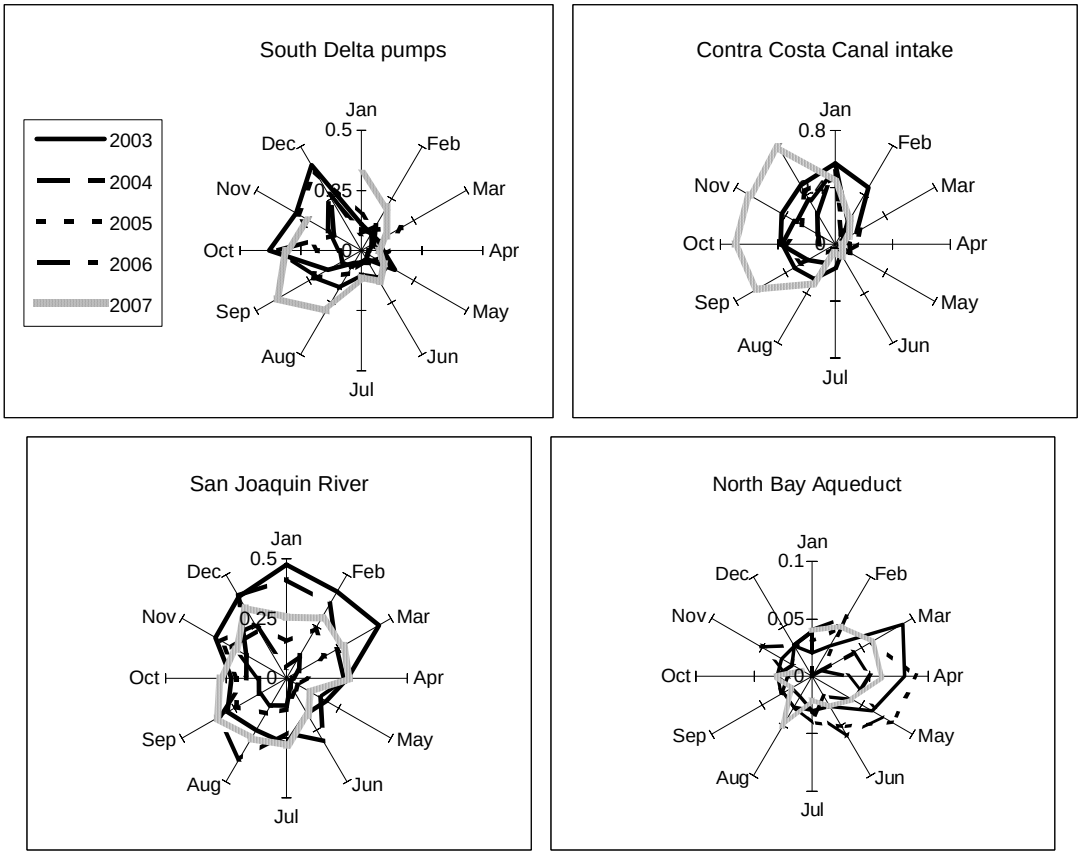

Figure 1. Seasonal variability of bromide concentration (mg l^{-1}) detected at the South Delta pumps at Banks, Contra Costa Canal intake, and the San Joaquin River at Vernalis (2003 - 2007) The bromide concentration data shown in the figure were collected from the California Department of Water Resources..

Total and dissolved organic carbon

Organic carbon in source water is a drinking water concern due to its potential for reacting with both chlorine and ozone during disinfection to form disinfection byproducts (DBP), such as trihalomethanes (THMs) and haloacetic acids (HAAs). Higher levels of TOC also increase 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). Organic carbon is commonly measured and reported as TOC and DOC. The fraction of DOC in TOC varies; at high concentrations of TOC, the

DOC/TOC ratio generally ranges from 0.8 to 1.0 (CALFED 2005). For some observations, the ratio was surprisingly low, possibly results from highly turbid water carrying TOC during storm events, algal blooms, or measurement error (interference of settled particles of organic matter on the analyzer during measurement). Therefore, DOC was considered a more accurate measure than TOC and is primarily discussed in this study. CALFED established a ROD target concentration of 3.0 mg l^{-1} of carbon (C) for TOC at Delta intakes (CALFED 2004).

The DOC data for the five locations are shown in Figure 2. 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. 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 have less annual variability than does salinity.

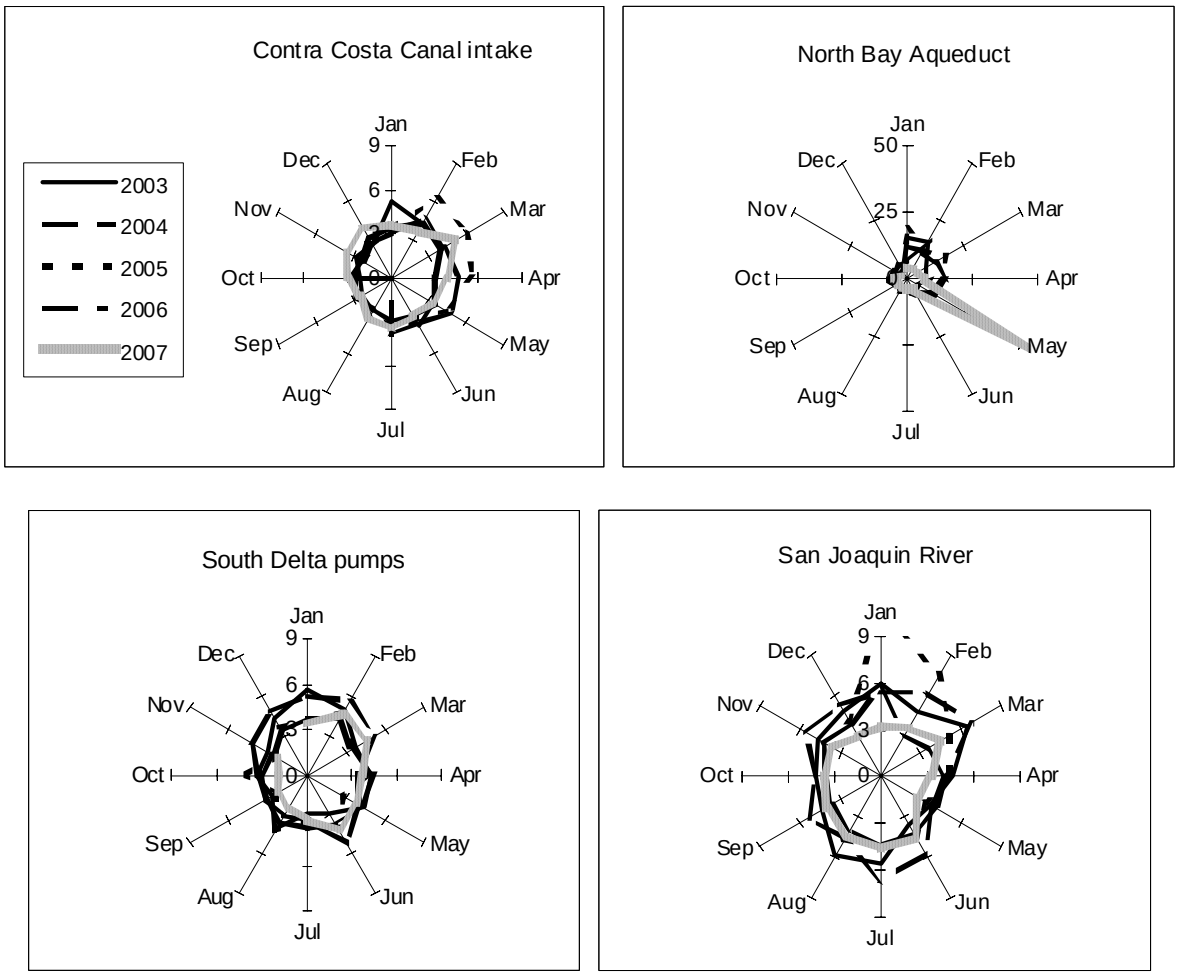

Figure 2. Seasonal variability of dissolved organic carbon concentration (mg l^{-1} C) detected at the selected Delta monitoring stations (2003 - 2007). The dissolved organic carbon concentration data shown in the figure were collected from the California Department of Water Resources.

Pesticides and herbicides

Pesticides and herbicides in the Delta are primarily from agricultural uses and partly from urban applications. They most commonly cause problems of taste and odor. However, pesticides and herbicides also can pose possible health risks in drinking water due to the contamination of source water, and the potential of forming DBPs during water treatment processes, although these risks remain unclear (Chen and Young 2008; Lubick 2008).

Pesticide and herbicide concentration data are available only for two of these five stations in MWQI data, BARKENOBAY and BANKS stations for the Barker Slough at North Bay Aqueduct and South Delta pumps at Banks, respectively, so the DPR's Surface Water Database also was used. The DPR surface water quality data were gathered weekly. Since the DPR station locations differ from those of MWQI, data from the closest DPR station were used. Pesticide and herbicide data are available from 1992 to 2006 for the locations at the South Delta pumps at Banks, North Bay Aqueduct at Barker Slough, San Joaquin River at Vernalis, and Sacramento River at Freeport, which is approximately six miles upstream of the location at Hood; no information was found at locations near the Contra Costa Canal intake.

In the DWR monitoring data, ten and eight pesticides and herbicides selected by DWR were detected with more than 19 and 22 detections at the North Bay Aqueduct at Barker Slough and South Delta pumps at Banks, respectively, from 2003 to 2007. Unexpectedly, no pesticides and herbicides selected by DPR were detected at these two locations in the DPR's report. From 2003 to 2006, DPR's report shows eleven pesticides and herbicides detected in the San Joaquin River at Vernalis, with more than 67 detections in all. In the Sacramento River at Freeport pesticide and herbicide detections were considerably lower: six pesticides and herbicides were found with more than 22 detections. No pesticide and herbicide monitoring information are available at these two locations in the MWQI data. Given these monitoring results, pesticides and herbicides may not be major drinking water concerns in the Delta. Various pesticides and herbicides detected at four Delta locations are detailed in Chen et al. (Chen et al. 2008).

Prediction of future water quality

Likely future water quality in the Delta was predicted with respect to EC by using hydrodynamic modeling developed in Fleenor et al. (Fleenor et al. 2008). The scenarios consider three long-term conditions, over the coming 50 or more years: 1 foot of sea level rise, 3 feet of sea level rise, and the failure of the Delta's western islands. The predicted EC was estimated by adding the possible increase of EC in the future from the hydrodynamic modeling predictions to the average EC field data between 2003 and 2007. The estimated EC were then employed in a regression model developed by MWDSC (Hutton 2006), which correlates EC with other selected constituents at locations in the Delta, to estimate concentrations of other constituents of interest from hydrodynamic salinity model results, which typically include only EC. Additional details regarding this future water quality prediction are described in Chen et al. (2008). The typically strong correlation among EC and bromide allow this model to provide reasonable future water quality with respect to the concentrations of bromide and chloride under the three hypothetical future scenarios.

The future water quality scenarios are compared to current conditions (from 2003 to 2007) in Table 2 to show likely water quality differences for the future. As a point of reference, the table also provides water quality targets from the CALFED ROD. Because the hydrodynamic modeling results are not yet suitable for the North Bay Aqueduct intake this location is omitted. The other water quality constituents including TOC and DOC, nutrients, and pesticides and

herbicides were not predicted due to lack of the associated information required. Although the predictions for EC and bromide are rough, they are the best available indicators for these future conditions. Other water quality constituents, TOC, DOC, and nutrients, were not predicted due to the lack of information regarding these constituents and their likely lesser long-tem sensitivity to sea level rise and permanent island failure.

This analysis is preliminary and for illustrative purposes due to two assumptions involved in Table 2. 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 diversions 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 it is 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 meeting salinity levels, and outflow is adjusted to meet the standards. However, this analysis did not consider changes in upstream or in-Delta operations to meet water quality with sea level rise.

Table 2. Current (2007) and predicted future water quality conditions at different Delta intakes

Location	Time	Concentration of constituents (Low, Average, High)			
		Conductance (EC, µS 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 fail).
d. From the current Sacramento-San Joaquin River Bay Delta Water Quality Control Plan

Disinfection byproducts

Most Delta drinking water quality problems result from DBPs produced by the constituents discussed above. Disinfectants, including chlorine, chloramines, ozone, UV, and other technologies, are typically used to prevent microbial contamination in drinking water. However, numerous studies confirm that hundreds of DBPs can be formed by disinfectants reacting with various water quality constituents, particularly bromide and organic carbon (Boorman et al. 1999; Arbuckle et al. 2002; Krasner et al. 2006).

Only a small fraction of DBPs have been individually understood and quantified, with still fewer monitored or regulated by U.S. Environmental Protection Agency (EPA) (Krasner et al. 2006). The EPA promulgated the Stage 1 Disinfectants and Disinfection Byproducts Rule (Stage 1 D/DBP Rule) in 1998. Water systems are complying with this rule since January 2002. This rule established maximum contaminant levels of 80 $\mu g\ l^{-1}$ for total trihalomethanes (TTHMs) and 60 $\mu g\ l^{-1}$ for five HAAs (two major classes of halogenated DBPs), 10 $\mu g\ l^{-1}$ for bromate (a typical byproduct of ozonation), and 1 $\mu g\ l^{-1}$ for chlorite. EPA also suggested best available technologies to control DBP formation (http://www.epa.gov/SAFEWATER/mdbp/dbp1.html).

In 2006 the EPA published the Stage 2 Disinfectants and Disinfection Byproducts Rule (Stage 2 D/DBP Rule) to tighten compliance-monitoring requirements for two groups of DBPs, TTHMs and five haloacetic acids (HAA5) and to strengthen public health protection related to DBPs exposure from drinking water (http://www.epa.gov/ogwdw/disinfection/stage2). Water systems are required to comply with this rule beginning in January 2012. The D/DBP Rule, with the combination of the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), which focuses on reducing illness linked with *Cryptosporidium* and other disease-causing microorganisms in drinking water, require water utilities to balance long-term and short-term health concerns posed by DBPs and pathogens, respectively. The challenge is in providing adequate disinfection to protect against pathogens without forming DBPs.

Disinfection byproducts of concern in Delta

The DBPs of greatest concern typically include mono-, di-, tri-, and/or tetra-substituted species of halomethanes, haloacids (including haloacetic acids), haloacetonitrile, haloamides, halonitromethanes, haloacetates, haloketones, aldehydes, halogenated furanones, and others, the priority DBPs typically considered in the regulation (under the Stage 1 and 2 D/DBP Rule) or monitoring events, and those being researched but not yet regulated. However, not all DBPs listed above are of concern for all Delta intakes. For example, the negligible bromide concentration in the Sacramento River largely eliminates public health risks from brominated DBPs for the Sacramento River drinking water plants using chlorination and the risks from bromate if using ozonation.

The DBPs listed below were selected from those of greatest concern with the consideration of water quality characteristics at locations in the Delta and the treatment processes used for each intake, and primarily include halomethanes, haloacids, halonitromethanes, aldehydes, bromate, and total organic halogen. Halomethanes, haloacids, and total organic halides (TOX) are the major classes of DBPs considered in regulation and numerous studies. Aldehydes, bromate, and halonitromethanes are new and common DBPs formed during ozonation (Glaze et al. 1989; Krasner et al. 2006) and the formation of halonitromethane during chlorination can be greatly enhanced by UV (Hua and Reckhow 2005); they are selected due to the frequent use of ozonation in the Delta and the possibility of adding UV disinfection. Other

DBPs, including *N*-nitrosodimethylamine (NDMA), a potent carcinogen formed during chlorination and chloramination and whose cancer potency greatly exceeds those of THMs (Chen and Young 2008; Lubick 2008), can also pose significant risks to public health. The potential public health concerns from these DBPs, and the costs of various treatment processes, are given later in a discussion of promising strategies for water treatment.

Cost analyses for water qualities and treatment technologies

Treatment processes for disinfection and DBP precursor removal

Several alternative processes for disinfection and DBP precursor removal can be used to treat Delta water. Alternative disinfection technologies include UV light irradiation and ozonation, while advanced treatment technologies for DBP precursor removal include membrane filtration (microfiltration/ultrafiltration (MF/UF), nanofiltration (NF), and reverse osmosis (RO)), adsorption (using granular activated carbon (GAC)) and alternative disinfection. These technologies were selected based on the ability to treat specific constituents in Delta water.

Besides those DBP precursors typically of concern in the Delta (such as TOC and bromide), nutrients, pesticides and herbicides, and pharmaceutical and personal care products (PPCP) present additional challenges for water treatment. As the Delta watershed develops, increasing contaminant loads into the Delta and its tributaries are possible. These contaminants typically can be removed by conventional treatments processes, carbon adsorption, and membrane filtration. However, due to different characteristics of the constituents and the complexity of water treatment technologies under local water quality conditions, the effects of different treatment technologies on removal and possible transformation of different constituents may vary significantly. Therefore, this study focuses on TOC and bromide as the primary DBP precursors, and only addresses alternative disinfection processes and those advanced treatment technologies for removing these DBP precursors. These contaminants, particularly bromide, vary most with Delta export location and operations and likely future conditions.

DBP formation is a complex process involving several chemical constituents in the water source as well as various reactions with the disinfection process. Often, several treatment approaches are available for reducing DBP precursors to prevent DBPs formation instead of changing the disinfection process. For example, the least expensive approach to increased bromides in Delta source water is likely to be increased treatment to remove TOC. Reducing TOC reduces the ozonation dose needed for disinfection and reduces the amount of carbon available to form DBPs, both of which reduce the formation of DBPs, especially bromate and other brominated DBPs. These methods are not necessarily exhaustive, and other methods or variants might provide better treatment cost performance than predicted in this study.

Cost analysis

This section examines the potential effects of source water quality changes on whether existing treatment facilities can continue to comply with current water quality standards, considering both the costs of treatment and technological limits on attaining these standards with a given source water. We also estimated capital and operation and maintenance (O&M) costs for conditions in the Delta.

Cost concepts and estimation

Water treatment plants for Delta water vary. Here, costs were developed by modifying a base treatment plant, which represents an existing treatment configuration, by adding alternative disinfection and other technologies. Conventional surface water treatment plant employs the processes of coagulation, flocculation, clarification, filtration, and chlorine/chloramine application for disinfection and maintenance of a distribution system residual. It is assumed that the technologies investigated here can be directly added 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. Costs for each treatment technology include capital and O&M costs. The capital cost includes construction components 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 percent interest rate and 20 years of operation. O&M costs include building-related energy, process energy, maintenance materials, and labor. The annualized capital cost and annual O&M cost were summed to obtain the total annualized cost. Where the investigated treatment technology already exists in the base treatment plant, the capital cost of the technology was not considered (it is a sunk cost), so the total annualized cost equals the annual O&M cost of the technology.

Preliminary cost estimations for selected treatments were obtained from published reports (Coffey et al. 1998; USEPA 1999; CALFED 2005b; USEPA 2005; Krasner et al. 2007; Lu et al. 2007). Some modifications were introduced, drawing on engineering judgment and practical experience from the experts from water agencies in the state. Costs were converted to 2007 dollars with the Building Cost Index and appropriate Producer Price Index developed by Engineering News Record (ENR) and Bureau of Labor Statistics (BLS), respectively. Ranges of estimated costs for each treatment technology are established by considering different implementation scenarios, comprising different disinfection and various treatment technologies for DBP precursor removal, and treatment goals, which are identified later in the cost estimation for each treatment process, for design flows generally ranging from 1 to 520 million gallons per day (mgd) based on the availability of cost information. Although some of the published sources refer to field data for specific treatment plants (Krasner et al. 2007; Lu et al. 2007), many estimates rely on modeling studies and information from manufacturers. As a result, the estimated costs reported here might be very different from actual costs water agencies would incur from introducing these treatment technologies. Therefore, the costs for selected treatments shown here should be considered as a range; more detailed analysis would be needed to develop more reliable estimates for individual locations.

Treatment cost estimation for unit processes

Costs for existing and alternative disinfection strategies and treatment processes for enhanced removal of DBP precursors are discussed in this section. Ozonation disinfection is common for Delta waters, and several plants are slated to employ this technology. Although not yet used for a full-scale system, UV disinfection is often recommended (both MWDSC and CCWD have operated pilot UV systems). Advanced technologies employed for removing DBPs precursors include GAC, MF/UF, NF, and MIEX, a new technology not practically used yet in Delta.

Ozone

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 (Coffey et al. 1998; Krasner et al. 2007). When the source water contains high bromide concentration, with the reaction of ozone and TOC, bromate formation can become problematic in the treated water. Although established methods such as pH depression can control bromate formation during ozonation, it increases the ozone dosage required, decreasing treatment efficiency, and increasing treatment costs due to large amount of acid required to lower the pH of water, and the amount of base required to increase pH after ozonation to prevent corrosion in the distribution system.

The effects of bromide concentration on total annualized cost and annual O&M cost for three system sizes (1 to 7, 7to 76, and 76 to 430 mgd) are shown in Figure 3. Bromide is the water quality parameter considered in this cost estimation for ozone, and costs were estimated based on ozone dosage required to achieve two log *Cryptospordium* inactivation. 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.

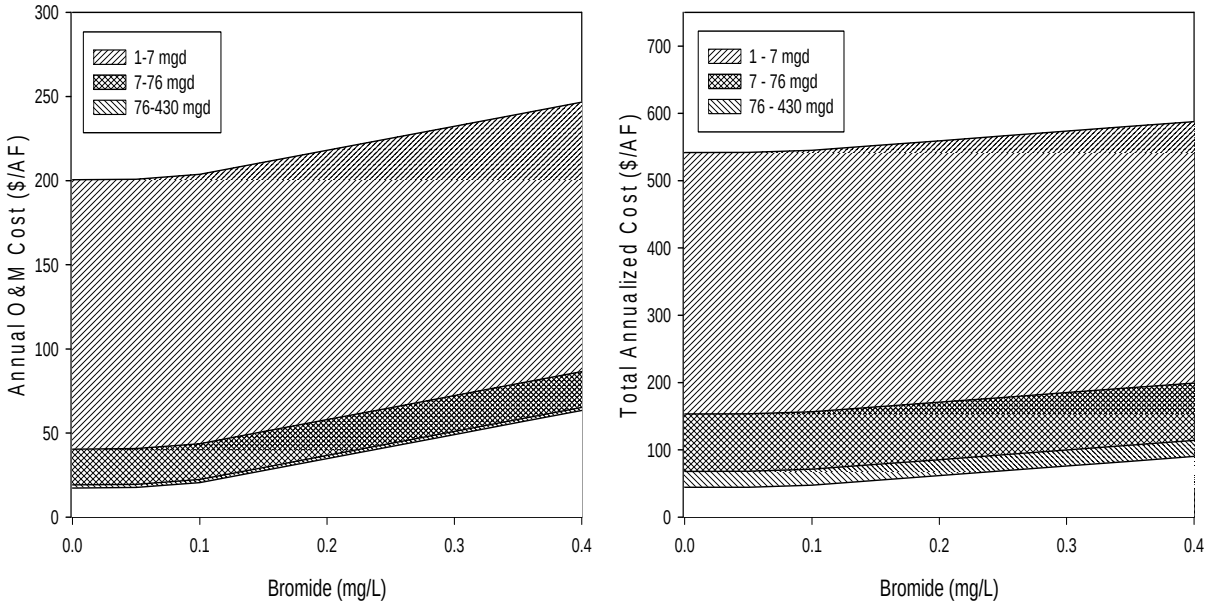

Figure 3. Bromide concentration effects on total annualized cost and annual O&M cost of ozonation for disinfection and oxidation in conventional water treatment. The cost results shown in the figure were estimated by authors' calculations using EPA (USEPA 1999; USEPA 2005) and MWDSC (Krasner et al. 2007; Lu et al. 2007). The costs were converted to 2007 dollars using deflators from ENR and BLS.

Substantial economies of scale occur for larger plants. Both total annualized cost and annual O&M cost per acre-foot (af) 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 commonly detected 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, but the effect of TOC on ozonation cost was not investigated because TOC can be removed by other treatment processes before ozonation in conventional water treatment.

Ultraviolet disinfection

Existing water treatment plants treating Delta waters do not employ UV for disinfection and oxidation, but it is an important alternative disinfection strategy. 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 3. These costs were estimated by assuming a UV dose of 40 mJ cm^{-2} (USEPA 2005). An uninterrupted power supply (UPS) system was considered. Low and medium pressure lamps were 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, which can be expensive. Additional pumping to overcome head losses may be required for some sites. Additional post disinfection treatment (such as post chlorination) may be needed in applying UV from the lack of disinfectant residual in UV treated water, causing additional expense.

Table 3. Total annualized and annual O&M costs of UV disinfection process for systems of different sizes. The cost results shown in the table were estimated by author's calculation using AwwaRF (Briggs et al. 2008), EPA (USEPA 2005) and Water Environment Research Foundation (Darby et al. 1995). The costs were converted to 2007 dollars using deflators from ENR and BLS.

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

Enhanced coagulation

Typically coagulation already exists in most water treatment plants to remove organic matter, so only annual O&M costs were considered. These cost estimates were primarily developed by using the practical cost information from the Mills conventional water treatment plant, which has been operated since 1978 and is one of two Metropolitan plants treating 100 percent State Project Water from the Delta, and adjusted to year 2007 dollars using the appropriate cost indices. Aluminum sulfate and polymer are used for enhanced coagulation.

The effects of TOC concentration on annual O&M cost for three system sizes (1 to 7, 7to 76, and 76 to 430 mgd) are shown in Figure 4. The TOC concentration is the only water quality parameter considered, and the range of TOC was assumed from 0 to 5 mg l^{-1} C in this cost estimate in that most of TOC concentration detected in Delta from 2003 to 2007 is within this range. Additional costs not considered in the estimation might include dewatering and disposal of the sludge, and standby charges by the contractor.

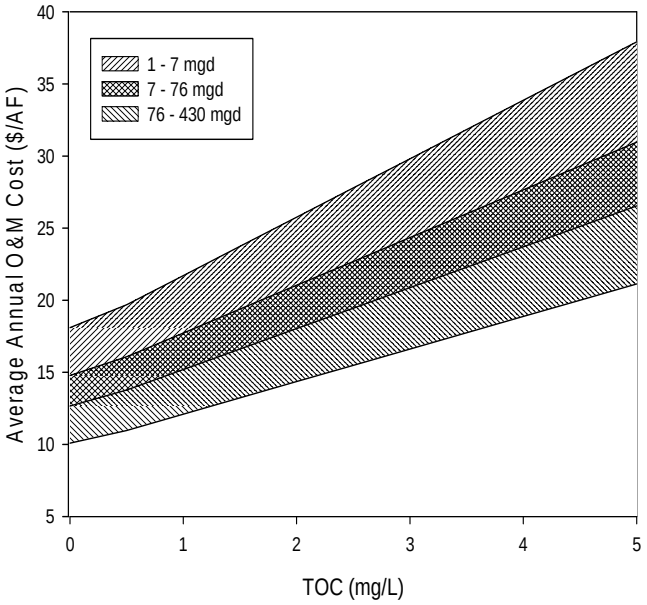

Figure 4. Effects of total organic carbon concentration on annual operation and maintenance cost of enhanced coagulation. The cost result shown in the figure was estimated by author's calculation using EPA (USEPA 2005) and MWDSC (Lu et al. 2007). The costs were converted to 2007 dollars using deflators from ENR and BLS.

Adsorption and membrane filtration

Table 4 presents total annualized and O&M costs of GAC, MF/UF, and NF for various system sizes. These estimated costs were primarily developed from cost data prepared by EPA (USEPA 2005). 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) were considered to account for variability in source water quality. For MF/UF and NF, costs were provided for a design feed water temperature of 10^{o}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. The effects of water quality changes on costs were not calculated due to the lack of information.

Table 4. Total annualized cost and O&M costs of selected technologies for DBP precursor removal. The cost results shown in the table were estimated by author's calculation using EPA (USEPA 1999; USEPA 2005). The costs converted to 2007 dollars using deflators from ENR and BLS.

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.				

Magnetic ion exchange

MIEX resin is another technique for treating the constituents in Delta waters, and has been studied for the Fairfield and Vacaville North Bay Regional Water Treatment Plant (NBRWTP) by CALFED (CALFED 2005) and in a report published by American Water Works Association Research Foundation (Briggs et al. 2008). Table 5 presents the construction costs for a conventional treatment using North Bay Aqueduct water and the MIEX system. Annual O&M cost was not investigated due to the lack of data. The economy of scale, which is not observed in Table 5 (total annualized capital cost of $100 per af for system size of 100 mgd), may result from site-specific operations or different safety factors operated by water agencies for water quality standards.

Table 5. Summary of planning-level estimated capital costs for magnetic ion exchange resin

Size of system (mgd)	10[a]	50[a]	100[b]	150[a]
Total annualized capital cost ($ af^{-1})	53	27	105	23 - 27
Annual O&M cost ($ af^{-1})	N.A.	N.A.	34	N.A.

a. Calculated based on data from a conventional treatment plant using North Bay Aqueduct water and the MIEX system (CALFED 2005).
b. Calculated based on data from "Advanced Water Treatment of Estuarine Water Supplies" prepared by Briggs et al. 2008.

Enhanced coagulation/ozone with GAC for bromate formation

Cost data for EC, ozonation, and GAC were used to investigate the effect of source water quality change on the total cost of these selected treatments. Bromide was chosen as the primary factor of water quality concern as it varies most among Delta locations and is expected to increase with sea level rise in the future. Although the effect of TOC concentration on treatment choices and costs were not investigated here since TOC varies less among Delta export alternatives; however, the TOC concentration was considered and the range of TOC was assumed from 0 to 5 mg l^{-1} C in this cost estimate, which is the most TOC detected from 2003 to 2007. While GAC is not designed to remove bromide, GAC can reduce TOC enough to reduce ozone dosage requirement, which in turn reduces bromate formation to help the treatment plant

comply with D/DBP rules. The effect of bromide concentration change on the annual O&M cost of enhanced coagulation and ozonation, assuming these technologies are already installed, appears in Figure 5.

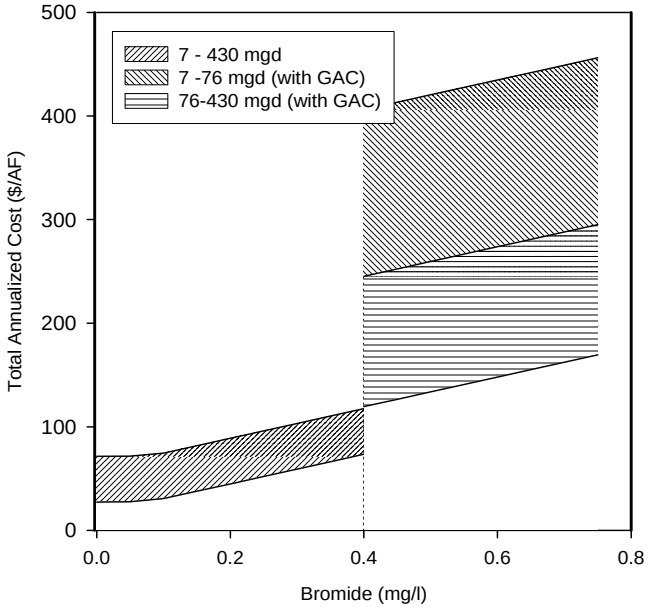

Figure 5. Effects of bromide concentration on annual O&M cost of enhanced coagulation and ozonation in combination with granular activated carbon added above 0.4 g l^{-1}. The cost result shown in the figure was calculated using the cost data from Figure 3 and 4 and Table 4.

In Figure 5, GAC is installed when the bromide concentration exceeds 0.4 mg l^{-1}. UV and MIEX, two alternative solutions for high bromide concentrations, are not considered due to lack of information regarding source quality effects on their costs. Because other technologies, such as MF/UF and NF, have higher costs than GAC, only GAC is considered in Figure 5. Results in Figure 5 indicate dramatic increases in costs above 0.4 mg l^{-1} of bromide due to new installation of GAC, particularly for a medium treatment plant sizing from 7 to 76 mgd.

Treatment cost estimation for water quality scenarios and intake locations

Treatment strategies for various water quality scenarios

Figure 6 summarizes appropriate treatments for different Delta TOC and bromide conditions. The concentration limits of TOC and bromide for various treatment strategies were developed using studies prepared by AwwaRF (Briggs et al. 2008) and MWDSC (Krasner et al. 2007; Lu et al. 2007), and information provided by SCVWD and Alameda County Water District. Ozonation is assumed to be the base treatment technology for disinfection and oxidation because it is employed in most water treatment plants for Delta waters. 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. To remove bromide with MIEX, the precise manner of combining MIEX with other treatment technologies is important. For example, when MIEX is a pretreatment to

coagulation/flocculation, it is excellent for TOC removal, but less efficient for bromide removal. But when the treatment order is reversed, or combined with UF, MIEX is more suitable for bromide removal. For medium bromide concentrations (0.4 mg l^{-1} was examined in the study), 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 (Briggs et al. 2008). Although likely an expensive process, MIEX seems capable of controlling NOM (and TOC) and low affinity ions such as bromide.

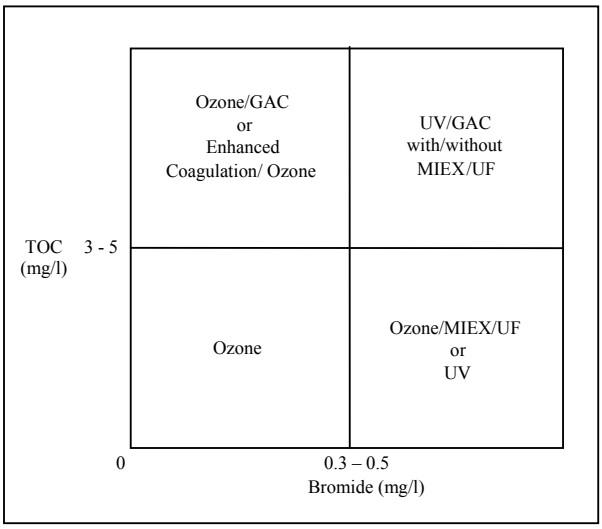

Figure 6. Treatments assumed for different Delta raw water qualities. The figure was developed by authors' calculations using AwwaRF (Briggs et al. 2008) and MWDSC (Krasner et al. 2007; Lu et al. 2007), and information provided by Santa Clara Valley Water District, Alameda County Water District.

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/UF 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/UF than with UV (cost difference not shown in Figure 6).

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 Mills water treatment plant operated by MWDSC using ozonation for disinfection and oxidation process can only handle bromide levels of up to 0.3 mg l^{-1} when treating Delta water with a TOC level less than 4 mg l^{-1} (Lu et al. 2007). However, a pilot study conducted by Santa Clara Valley Water District (SCVWD) in 2000 found that source water with bromide concentration as high as 0.6 mg l^{-1} can still meet a 8 μg l^{-1} of bromate concentration goal when ozone dose was 2 mg l^{-1} at pH 6.4. For CCWD, bromide is also not a problem when the TOC concentration is low. 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 or locations.

Costs for various Delta treatment alternatives

Estimated cost information for several disinfection processes and advanced treatment technologies for DBP precursor removal were then used to estimate total costs to treat Delta water using various combinations of treatment technologies, as summarized in Table 6. Treatment combinations include enhanced coagulation with ozonation or UV, with or without GAC, MF/UF, or NF treatment. Magnetic ion exchange was not considered due to the relatively modest bromide concentration in the current Delta. Annual O&M costs only were considered for enhanced coagulation and ozonation, since these treatment technologies are already used in most Delta treatment plants, while annualized total costs, including both capital and O&M, were used for GAC, MF/UF, and NF. Costs of ozone and enhanced coagulation were estimated using the average concentrations of bromide and TOC from 2003 to 2007 at the five intake locations examined above, respectively (Table 2). Cost estimates for South Bay and Southern California plants assume that South Delta exports occur at Banks. Different water quality issues might occur for water treatment plants in South Bay and Southern California, affecting the quality of their source waters taken from South Delta pumps, such as their blending of Delta, non-Delta, and stored water sources. It is likely that true treatment costs of scenarios involving other source waters or technologies (e.g., enhanced coagulation/UV) differ from the estimates provided here. But estimates should be useful for estimating general magnitudes of effects.

Table 6. Summary of estimated treatment costs of treating current Delta water. The cost results shown in the table were estimated by authors' calculations using the cost data from Figures 3 and 4, and Tables 2 through 4.

		Estimated costs ($ AF^{-1})[a]			
Plant/Intake location	**Treatment**	**Base cost**	**Combined with GAC**	**Combined with MF/UF**	**Combined with NF**
Sacramento River[b] (Hood; medium plant)	Enhanced coagulation/Chlorine[c]	19 – 25	-	-	-
	Enhanced coagulation/Ozone[d]	37 – 62	100 - 343	251 - 363	402 - 525
	Enhanced coagulation/UV	28 - 45	90 - 327	241 - 346	392 - 509
Sacramento River[b] (Hood; large plant)	Enhanced coagulation/Chlorine[c]	18 - 22	-	-	-
	Enhanced coagulation/Ozone[d]	35 - 40	74 - 187	193 - 254	329 – 405
	Enhanced coagulation/UV	24 – 33	63 - 179	182 - 247	318 - 397
North Bay Aqueduct	Enhanced coagulation/Ozone[d]	54 – 81	117 - 363	268 - 382	419 - 545
	Enhanced coagulation/UV	44 – 65	107 - 346	258 - 366	409 - 528
CCWD	Enhanced coagulation/Ozone[d]	66 – 91	128 - 373	280 - 392	431 – 555
	Enhanced coagulation/UV	32 – 50	94 - 332	246 - 351	396 - 514
South Bay (South Delta export)	Enhanced coagulation/Ozone[d]	53 – 78	115 - 359	266 - 379	417 - 541
	Enhanced coagulation/UV	33 – 51	100 - 333	246 - 352	397 - 515
Southern California (South Delta export)	Enhanced coagulation/Ozone[d]	46 – 53	85 - 199	204 - 266	340 - 417
	Enhanced coagulation/UV	25 - 35	64 – 181	183 – 249	318 - 400

UV: ultraviolet, GAC: granular activated carbon, MF/UF: macrofiltration/ultrafiltration, NF: nanofiltration, CCCD: Contra Costa Water District

a. Assumes that the size of a treatment plant at each location ranges from 7 to 76 mgd, except Southern California where the size ranges from 76 to 520 mgd.
b. For illustrative purposes. Currently no urban intakes here.
c. 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.
d. 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. Costs of ozonation and enhanced coagulation were estimated using the average concentration of TOC and bromide at Delta intake locations from 2003 to 2007.

It is assumed that the size of a treatment plant at the Sacramento River, North Bay Aqueduct, and CCWD ranges from 7 to 76 mgd. For water taken from the South Delta, two separate estimates are provided, one for smaller capacity plants used in the Bay Area (ranging from 7 to 76 mgd), and one for larger facilities used in Southern California (with capacities from 76 to 520 mgd), based on information available to estimate treatment costs. For some plants with a capacity larger than 520 mgd (such as the Jenson plant operated by MWDSC), it is assumed that treatment costs will be slightly less than the cost estimated for capacities from 76 to 520 mgd since larger treatment capacity typically reduces unit treatment costs.

Recently, CCWD built a new 40 mgd water treatment plant for a capital cost of approximately $48 million with fully capacity operating costs of roughly $2 million per year (Briggs, PerCom.). For a 5% interest rate, the total annualized treatment cost is roughly $100 per af. For the water treatment plant operated by the city of Sacramento that collects water from the Sacramento River, accounted operating costs were roughly $300 per af (Peifer, City of Sacramento). Inconsistent cost accounting across agencies prevented cost comparisons among actual plants for our rapid study.

At locations with low bromide concentrations (the Sacramento River at Hood), the cost of ozonation is similar to that of UV. Ozonation cost increases significantly with bromide concentration, with UV disinfection combined with other treatments eventually having an apparently lower cost (CCWD). Ultraviolet is a potential disinfection alternative to ozonation if the source water quality degrades in the future, such as if bromide concentration increases due to seawater intrusion, and it can be employed with other treatments to remove DBP precursors. However, providing a sufficient dose for targeted inactivation level 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 the in-Delta water quality degrades for urban uses.

Treatment costs for potential future water quality condition in Delta

Table 7 presents the total costs for different combinations of treatment technologies for current and potential future water quality conditions at three in-Delta intakes. Assumptions regarding the system sizes and cost estimation are similar with those used for Table 6. Both TOC and bromide concentrations were considered in the cost estimation; however, only bromide concentrations are particularly indicated in the table, since it varies most among these intake locations and under hypothetical future scenarios. The average annual concentrations of bromide and TOC at each Delta location from 2003 to 2007 and the model prediction for likely future water quality (Table 2) were then used to estimate the annual O&M costs for enhanced coagulation and ozonation.

Table 7. Summary of estimated treatment costs for treating current and potential future Delta water by various treatment methods (Most likely treatments are in boldface). The cost results shown in the table were estimated by authors' calculations using the cost data in Figures 3, 4, and 6, and Tables 2, 4, and 5.

			Estimated costs ($/af)				
Plant/intake Location	Condition	Bromide (mg/l)	Enhanced coagulation/ Ozone[b,c]	In combination with GAC[c]	In combination with MF/UF[c]	In combination with MIEX/MF/UF[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[e]	**153 - 409**	305 - 428	355 - 528	455 - 591
	3 ft SLR	0.84	147 – 183[e]	209 - 465[5]	360 - 484[5]	**410 - 584**	511 - 647
	W is. fail	0.39	82 – 119[e]	**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[e]	**126 - 381**	277 - 401	327 - 501	428 - 563
	3 ft SLR	0.50	98 – 134[e]	**160 - 416**	311 - 435	361 - 535	462 - 598
	W is. fail	0.25	62 – 98[e]	**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[e]	**124 – 360**	275 – 379	325 – 479	426 - 542
	3 ft SLR	0.50	96 – 113[e]	**158 - 394**	309 – 414	359 – 514	460 - 576
	W is. fail	0.25	60 – 77[e]	**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, 1and 3 ft SLR: 1 and 3 feet sea level rise, W Is. fail: western islands fail

a. Medium treatment plant ranging from 7 to 76 mgd is assumed for CCWD and the South Bay; a large plant ranging from 76 to 430 mgd 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, since ozonation is already used in most of the treatment plants in Delta. Total annualized costs (annualized capital cost and annual O&M cost) were used for the costs of other treatment technologies.
d. It is assumed that total annualized cost of MIEX ranges from $50 to 100/AF based on the data from Table 5.
e. 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.

The future conditions assume seawater intrusion into the Delta from sea level rise or failure of western Delta islands (Table 2). As above, the treatment costs between the South Bay Area and Southern California were distinguished for water drawn from the South Delta based on treatment plant sizes. The North Bay Aqueduct is excluded because salinity projections are unavailable for this site. The Sacramento River location is examined only for current conditions, given our assumption that upstream locations on this river will not see greater costs due to seawater intrusion, although they, like Delta locations, might see higher TOC concentrations. Costs for UV were not investigated because it is not currently employed in any Delta treatment plant and the lack of information regarding the effects of water quality changes on UV costs. Due to the increasing bromide concentration, MIEX was considered as one option to treat Delta water, with an assumed total annualized cost ranging from $50 to $100 per af (Table 5). As sea level rises and Delta's western islands fail, total costs to treat Delta water from the current CCWD intakes will be highest.

Given the current treatment technologies employed, the estimates of future conditions and costs, and the available knowledge of treatment processes, the most likely treatment processes and costs are those indicated in bold in Table 7. Granular activated carbon has been employed in some treatment plants in CCWD and the South Bay, especially larger plants. Therefore, the most likely treatment costs of 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. Although bromide concentration is the most important water quality factor used to determine appropriate treatments, TOC concentration also was and should be considered. Various changes in the Delta and upstream can increase TOC concentration. Since the future water quality conditions do not include TOC predictions, the TOC concentration ranges between 2003 and 2007 were used to estimate treatment costs, assuming future TOC concentrations will not change significantly with seawater intrusion.

In Table 7, 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 6). Some combinations of treatment technologies might not be practical for some water quality conditions. UV or combinations of additional treatment technologies might be needed. In addition, the treatment cost estimates in Table 6 and 7 neglect possible limitations on availability of land and electricity capacity at the existing treatment plant sites. As a result, using other source water containing less contaminants/DBP precursors or a relocation of a treatment plant might be needed to accommodate increasing contaminants, which will further increase treatment costs.

Residual health risk

Given the ability of ozone and UV treatment to produce lower levels of the regulated THMs, most HAAs, and TOX, many water treatment plants (including those using Delta source waters) have already switched from chlorine, or are considering switching, to meet the Stage 1 and/or Stage 2 D/DBP Rules. However, some priority or more potent DBPs remain in higher concentrations, while the regulated THMs and most HAAs are minimized with use of non-chlorine alternative disinfectants (Glaze et al. 1989; Krasner et al. 1989; Krasner et al. 2006). This section discusses DBPs produced by ozonation and UV to explore possible residual health risks when Delta water treatment plants employ these disinfection processes.

Ozone is a powerful oxidizer, which inactivates pathogens but does not produce chlorinated DBPs. But ozonation forms ozonation DBPs, including aldehydes, ketones, nitromethanes, haloamides, and the oxidation of bromide to bromate (Glaze et al. 1989; Krasner et al. 2006; Krasner et al. 2007; Lu et al. 2007). Among these compounds, bromate raises the most concern because it is potentially most harmful and is related to bromide concentration in source water. Bromate can be effectively controlled, within limits, by depressing the pH or lowering the ozone residual in treatment, but this also can significantly affect efficiency and cost of ozonation (Coffey et al. 1998; Krasner et al. 2007; Lu et al. 2007). Other established methods such as using source waters with less bromide may be better to control bromate formation if available. Compared to ozonation, UV has fewer DBP issues since it is a physical process without chemical disinfectants, eliminating some concerns. However, UV is not effective when treating water with high turbidity or suspended solids. In addition, formation of some DBPs from other disinfection processes, such as halonitromethane (Hua and Reckhow 2005) and chlorate (Briggs et al. 2008), can be enhanced by UV although UV itself does not form these DBPs.

Neither ozone nor UV treatment provides a residual disinfectant in the treated water, which means that organisms (bacteria) might re-grow in the water distribution system. So, ozone and UV often are used with chlorine or chloramines to provide a residual disinfectant. As a consequence, some chlorination and chloramination DBPs may remain problematic. The health risks should be lower with this staged treatment process, since most DBP precursors would have been removed in earlier treatment stages, but this is not known with certainty. Employing ozone or UV with high bromide concentrations may produce residual health risks in the treated water. Additional chlorination/chloramination to maintain a residual after ozone or UV disinfection could shift speciation to the more brominated forms of DBPs, which are more potent than their chlorine containing counterparts, because bromide is not removed by ozone or UV and the higher bromide-to-TOC ratio at the point of chlorination/chloramination (Krasner et al. 2006).

TOC and bromide are two of the primary DBP precursors considered in this paper. However, as the Delta's watersheds develop, other contaminants such as pesticides, herbicides and even PPCP, might increase in the exported water, representing another group of DBPs precursors (Chen and Young 2008; Lubick 2008). Although the DBP formation risks from these contaminants remain uncertain due to insufficient information regarding the associated formation mechanisms, it is important to consider these contaminants when estimating the residual health risk of water exported from Delta.

Currently, insufficient toxicity and carcinogenicity information for many DBPs make it difficult to identify and compare the potential health risks of alternative disinfectants and chlorine. Besides typically known and investigated DBPs, more DBPs remain unknown and/or do not have comprehensive information regarding their formation mechanisms, such as NDMA, increasing difficulties for estimating the potential public health risks from these DBPs. Since different DBPs are formed by different disinfectants, the public health risks from different treatment alternatives might vary significantly. There is no perfect disinfection option. Only by understanding the source water quality and applying the best and appropriate operation strategies can the public and environmental health risks of treated water be effectively minimized.

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. Several in-Delta locations including the South Delta intakes (the Contra Costa Canal intake at

Rock Slough, and the South Delta pumps at Banks), the North Bay Aqueduct at Barker Slough, and locations on the two primary tributaries to the Delta system, the Sacramento and San Joaquin Rivers, were chosen to understand drinking water quality in the system in terms of salinity, TOC and DOC, and pesticide and herbicide concentrations and their consequent drinking water treatment costs currently and in the future.

The current and projected future water quality data, with estimated cost information for selected treatment technologies, were applied to estimate the future costs of drinking water treatment for different Delta sources. Sea level rise or failure of Delta's western islands increases the costs of treating water from the South Delta intakes (Contra Costa Canal intake and South Delta pumps at Banks). Water from the Contra Costa Canal intake will be more expensive to treat. Sacramento River intakes upstream of the Delta are assumed to be unaffected by sea level rise or failure of Delta islands.

Minimum increases of annualized treatment cost for simulated future conditions, with various treatment combinations are presented in Table 8 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. The Contra Costa Canal and Sacramento River intakes show the highest increases in annualized treatment costs. These cost estimates, rough as they are, are intended to illustrate the magnitude of likely cost differences for strategic planning purposes.

Table 8. Summary of estimated costs of selected treatment technologies for treating current and future Delta water. The cost results shown in the table were estimated by authors' estimates, using professional judgment and the cost data from Tables 6 and 7.

	Annualized treatment cost[a] ($ af^{-1})			
Plant/Intake location	Current (2003 - 2007)	1 ft SLR	3 ft SLR	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, 1and 3 ft SLR: 1 and 3 feet sea level rise, W Is. fail: western islands fail

a. Includes annual operation and maintenance costs of existing enhanced coagulation and ozonation processes and total annualized cost of selected additional advanced technologies including granular activated carbon, microfiltration/ultrafiltration, magnetic ion exchange, and nanofiltration.
b. Medium treatment plant (7 to 76 mgd) is assumed for CCWD and South Bay, while a large plant (76 to 430 mgd) is assumed for Southern California.
c. Water quality in the Sacramento River is assumed constant over simulated conditions.

The residual health risks from different treatment alternatives and DBP precursors, with other factors including reliability, ease of operation, and residual disposal, might significantly

affect the selection and best operational strategies of water treatment alternatives. Furthermore, neither ozone nor UV produces residual disinfectant in the treated water, requiring additional chlorine or chloramine application. This may create another public health concern related to the formation of chlorinated or more potent brominated DBPs when source water has a high bromide concentration. Besides TOC and bromide, as the Delta's watersheds develop, there could be increasing loads of pesticide, herbicide, and PPCP, which represent another potential group of contaminants/DBP precursors. The Sacramento River site considered in this study is immediately downstream of the expanded Sacramento Regional wastewater discharge, resulting in another health concern for water from this location. More associated studies, such as formation mechanisms of DBPs from precursors under different disinfection alternatives, and risk assessment of different DBPs will be helpful to assess appropriate water treatment strategies.

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 treatment cost differences 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 af, which is in line with the MWD's annualized cost estimates for ozonation (Harader 2007). This cost difference is likely to increase to $100 to $500 per af with sea level rise and failures of the Delta's western islands. With roughly 1.5 million af per year of Delta water currently used for urban water supplies, 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, when urban use of Delta waters are likely to rise to 2 million acre-feet annually. The increasing likelihood of bromides 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 health risks. Currently, both 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. More detailed information and studies from different aspects including treatment technologies and costs, DBPs formation, and risk assessment of potential DBPs will be necessary to assess the best management options for drinking water sourced from the Delta.

This preliminary study should add some structure, detail, and initial analysis to recurrent discussions of drinking water quality issues related to Delta water supplies. There is certainly room for much additional analysis and study of these issues. Nevertheless, the treatment costs and residual health risks of using the Delta as a drinking water supply are higher than using water from the Sacramento River. These costs and risks seem likely to increase. The only uncertainties are how much and how fast.

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