Delta Drinking Water Quality and Treatment Costs
Technical Appendix H

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Description

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Summary

This appendix explores the current and long-term effects of Delta export water quality on drinking water treatment cost and public health risk from disinfection byproduct (DBP) formation. While these analyses are preliminary, they should provide a better understanding of the general magnitude of these costs and concerns for strategic decisions on managing Delta water exports.

The analysis considers several intake locations within the Delta, including the South Delta intakes (Contra Costa Canal intake, South Delta pumps at Banks), the North Bay Aqueduct, and upstream locations on the Sacramento and San Joaquin Rivers, the two major tributaries to the Delta. Salinity (electrical conductivity, bromide, and chloride), total and dissolved organic carbon (TOC and DOC), nutrients (total nitrogen and phosphorous), and pesticides/herbicides are the primary water quality constituents of interest. Salinity-associated contaminants will become more significant for South Delta water exports, from both San Joaquin River drainage and seawater intrusion from sea level rise and western island failures. High DOC concentrations also are troublesome, particularly for the North Bay Aqueduct. Although the Sacramento River, a likely intake location for water exports with a peripheral canal, has lower concentrations of salinity and TOC/DOC, it occasionally has pesticide and herbicide issues.

Various DBPs of greatest concern, including those regulated and commonly studied, are considered in light of the current and future conditions in the Delta with regard to water quality and treatment technologies. Ozone and UV disinfection are considered, with additional treatment technologies for removing DBP precursors including enhanced coagulation, adsorption, membrane filtration, and magnetic ion exchange (MIEX). Costs for these technologies are estimated as total annualized capital and operation and maintenance (O&M) costs. Appropriate treatment options and strategies are discussed based on these water quality conditions (TOC and bromide concentrations). Since many DBPs are caused by a combination of DOCs and bromides, and since dissolved bromides largely require expensive reverse osmosis for removal, additional DOC removal can be the least expensive way to reduce DBPs for some range of seawater bromides. Greater seawater intrusion with sea level rise is likely to lead to more advanced and expensive drinking water treatment for DOCs.

The cost information is applied to estimate the current and future costs of treatment alternatives for different export locations with projections of future water quality from hydrodynamic modeling described in Appendix C. The major cost results are summarized in Table H.S1 for two of the locations treating water sourced in the South Delta and for water sourced at the Sacramento River site in the northern Delta. With a peripheral canal, the Sacramento River would supply urban water districts; this source is assumed least susceptible to water quality deterioration from sea level rise and Delta levee failures. Although some combined treatment technologies might be impractical for some simulated water quality conditions, overall, drinking water treatment costs would be lower for Sacramento River water.

The additional drinking water treatment cost of taking water from the South Delta, rather than from an upstream intake on the Sacramento River, is currently about $20 to $60 per

acre-foot (af). These cost differences are likely to increase to $100 to $500/af with sea level rise and island failures, unless net Delta outflows are increased to keep salinity at bay. With roughly 1.5 million af per year of Delta water use for urban water supplies at present, these cost differences amount to $30 to $90 million per year currently. The total treatment cost difference could rise to $200 to $1000 million per year in the future, as Delta water quality deteriorates and as urban demands for Delta exports are likely to rise to 2 million acre-feet annually.

Table H.S1. Estimated treatment costs for treating current and future Delta exports using selected treatment technologies

	Annualized treatment cost[1] ($/af)			
Plant/intake location[2]	Current (2003 - 2007)	1 ft SLR	3 ft SLR	W Is. Fail
Sacramento River (Medium plant)	37 – 62[3]			
Sacramento River (Large plant)	35 – 40[3]			
CCWD	66 – 91	153 – 409	410 – 584	145 – 400
South Bay (South Delta pumps)	53 – 78	126 – 381	160 – 416	124 – 380
Southern California (South Delta pumps)	46 – 53	124 – 360	158 – 394	122 – 359

Treatments include: ozonation, enhanced coagulation, granular activated carbon, microfiltration/ultrafiltration, nanofiltration, and magnetic ion exchange resin

CCWD: Contra Costa Water District, 1and 3 ft SLR: 1 and 3 feet sea level rise, W Is. fail: western islands fail

1. Includes annual operation and maintenance costs of existing enhanced coagulation and ozonation processes and total annualized cost of selected additional advanced technologies granular activated carbon, microfiltration/ultrafiltration, magnetic ion exchange, and nanofiltration.
2. 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. Both sizes are considered for water sourced from the Sacramento River.
3. Assumes water quality in Sacramento River is constant over simulated conditions.

SOURCE: Authors' estimates using professional judgment and cost data from Figures H.7, H.8, and H.10 and Tables H.5 and H.11 through H.13.

Currently, DBPs are manageable for Delta supplies within treatment standards with moderate additional costs. But sea level rise and western island failures would make treatment of Delta water for urban water supply much more difficult and expensive. Residual public health risks also may remain after treatment from unregulated and residual DBPs. Bromide from seawater, combined with TOC, is a particularly problematic precursor of DBPs whose concentration will be most affected by sea level rise and export intake location. Bromide is particularly difficult and expensive to remove and its associated brominated DBPs are among the most harmful. 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. Continuing use of water from the South Delta will likely require modifying the operation of existing treatment or adding new treatment technologies, at a higher cost and with higher residual health risks.

Acknowledgments

We are most grateful to the many people who helped us better understand the drinking water quality and treatment problems of the Delta. These include Elaine Archibald, David Briggs, Douglas Chun, Greg Gartrell, Sam Harader, Paul Hutton, Stuart Krasner, Owen Lu, Terry Macaulay, Kent Nelson, Alex Rabidoux, Curtis Schmutte, and Peter Zhon. Ellen Hanak provided much useful editorial input. We are especially thankful for the detailed reviewer comments on an earlier draft of this work by Elaine Archibald, David Briggs, Sam Harader, Paul Hutton, Owen Lu, Terry Macaulay, and Kent Nelson. Of course, any remaining lack of understanding and errors remain our own.

Research publications reflect the views of the authors and do not necessarily reflect the views of the staff, officers, or Board of Directors of the Public Policy Institute of California.

Acronyms

af	acre-foot
AwwaRF	American Water Works Research Foundation
BLS	Bureau of Labor Statistics
C	carbon
CALFED	state and federal program for the San Francisco-San Joaquin Bay Delta
CCWD	Contra Costa Water District
CVP	Central Valley Project
D/DBP	disinfectants and disinfection byproducts
DBP	disinfection byproduct
DOC	dissolved organic carbon
DPR	California Department of Pesticide Regulation
DWR	California Department of Water Resources
EC	electrical conductivity
ENR	Engineering News Record
EPA	Environmental Protection Agency
GAC	granular activated carbon
HAA	haloacetic acid
HAA5	sum of five selected haloacetic acids
ICR	Information Collection Rule
MF/UF	microfiltration/ultrafiltration
Mgd	million gallons per day
MIEX	magnetic ion exchange
MWDSC	Metropolitan Water District of Southern California
MWQI	Municipal Water Quality Investigations Program
N	Nitrogen
NBRWTP	North Bay Regional Water Treatment Plant
NF	Nanofiltration
NOM	natural organic matter
O&M	operation and maintenance
P	Phosphorous
RO	reverse osmosis
ROD	Record of Decision
SCVWD	Santa Clara Valley Water District
SLR	sea level rise
SWP	State Water Project
SWRCB	State Water Resources Control Board
TDS	total dissolved solids
THM	Trihalomethane
TKN	total Kjeldahl nitrogen
TTHM	total trihalomethanes
TOC	total organic carbon

TOX	total organic halides
TP	total phosphorous
UPS	uninterrupted power supply
UV	Ultraviolet

Introduction

The Sacramento-San Joaquin Delta system is one of the most important drinking water sources in 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 appendix describes the current and likely future state of drinking water from the southern Delta as compared with locations upstream on the Sacramento River. The Sacramento River site represents water quality that would be available to urban agencies if a peripheral canal replaced current through-Delta pumping. There are no plans to use the San Joaquin River as a drinking water source, but it is included in the comparisons to highlight the water quality problems of this Delta inflow. This appendix also compares various advanced drinking water treatment techniques 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.

1. Water Quality in and near Delta

Delta Drinking Water Intakes

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. The main drinking water treatment plants employing these water sources are summarized in Table H.1.

Table H.1. Inventory of drinking water treatment facilities for water drawn from the Delta

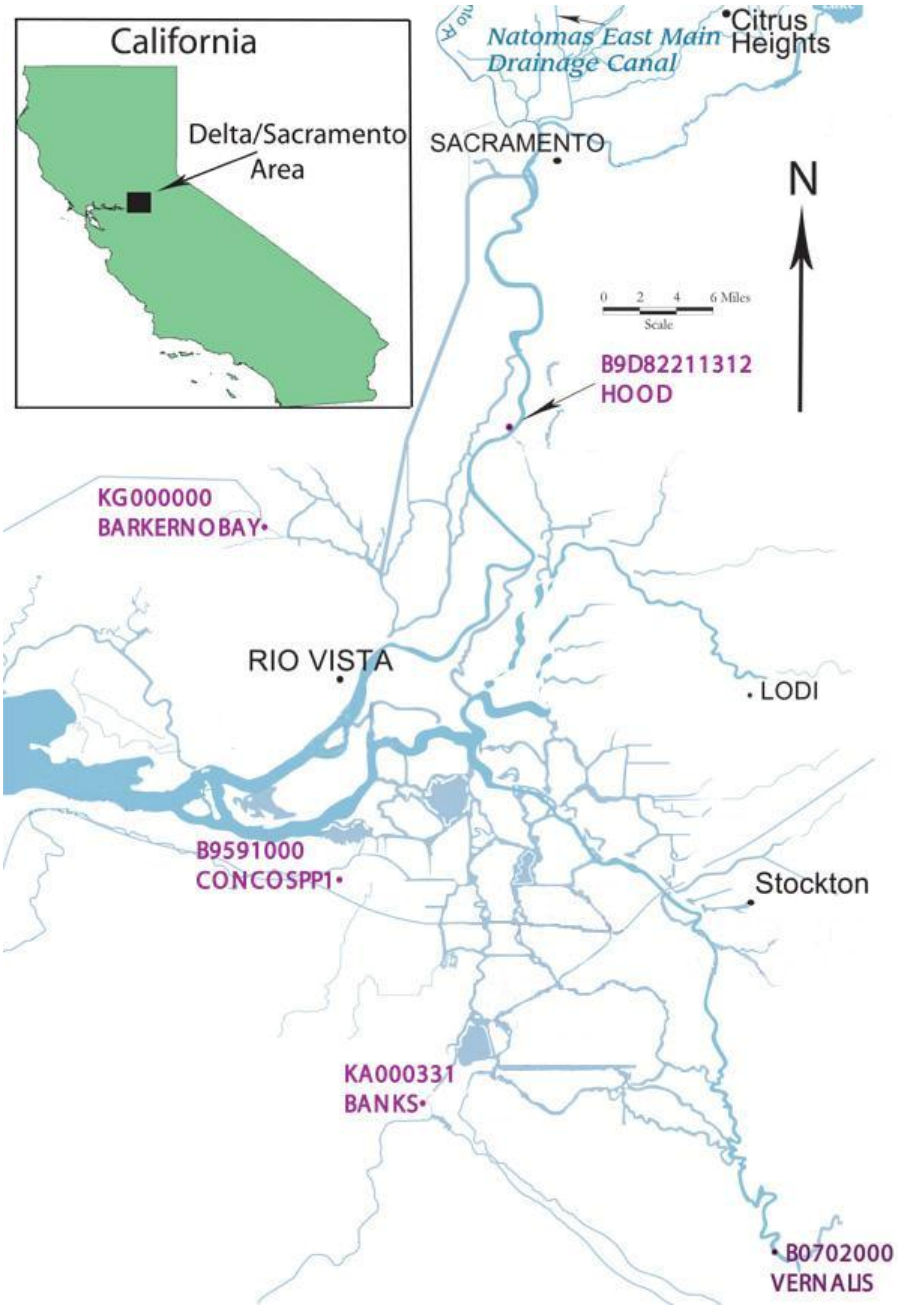
Delta Water Source	Water Agency	Water Treatment Plant	Capacity (mgd)
Contra Costa Canal/ Las Vaqueros[1]	Contra Costa Water District	Randall-Bold	40
		Bollman	75
North Bay Aqueduct (Barker Slough)	Fairfield/ Vacaville	North Bay Regional	40
	Benicia	Benicia	10
	Vallejo	Fleming Hill	42
		Travis Air Force Base	7
South Bay Aqueduct (South Delta pumps)	Zone 7	Patterson Pass	20
		Del Valle	36
	Alameda County Water District	Mission San Jose	10
		Treatment Plant 2	21
	Santa Clara Valley Water District	Penitencia	42
California Aqueduct (South Delta pumps)	Santa Clara Valley Water District (from San Luis Reservoir)	Rinconada	80
		Santa Teresa	100
	Metropolitan Water District of Southern California	Robert B Diemer	520
		Joseph Jensen	750
		Henry J. Mills	326
		Robert A. Skinner	630
		F.E. Weymouth	520

mgd: Million gallons per day

1. Contra Costa Water District has three current intakes (Mallard Slough intake and Contra Costa Canal intakes at Rock Slough and Old River) and one intake under construction at Victoria Canal. The agency varies the use of intakes to obtain the best water quality at different times of the year.

SOURCE: CALFED (2005) and MWDSC website: http://www.mwdh2o.com/index.htm.

This section describes the drinking water quality at three current Delta intakes, including 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) (Figure H.1). It focuses on the drinking water constituents of greatest concern at these three Delta locations. More detailed data on the concentrations of water quality constituents of concern at these locations are presented below and in Appendix H1. These data are used to understand current drinking water quality conditions in the Delta and further to estimate appropriate water treatment technologies for these different locations.



SOURCE: California Department of Water Resources.

Note: Stations of BARKERNOBAY, CONCOSPP1, and BANKS are chosen to collect the water quality information for the North Bay Aqueduct at Barker Slough, the Contra Costa Canal, and the South Delta pumps at Banks, respectively, while the stations of HOOD and VERNALIS represent the locations upstream on the Sacramento and San Joaquin Rivers, respectively. More details are given in Appendix H1.

Figure H.1. Principal monitoring stations of California Department of Water Resources assessing water quality in the Delta system

Water Quality Constituents of Interest

Delta water quality varies considerably by location and constituent of interest. The historical pattern of eight major water quality constituents is described here for the five selected locations. The constituents include electrical conductivity, bromide, chloride, total and dissolved organic carbon (TOC and DOC), nutrients (total nitrogen and phosphorous), and pesticides and herbicides. Table H.2 summarizes the main types of water quality concerns for each constituent.

Table H.2. Drinking water constituents of interest

Constituent	Concern
Electrical Conductivity	Salinity
Bromide	DBP precursor, salinity
Chloride	Salinity
Total Organic Carbon	DBP precursor
Dissolved Organic Carbon	DBP precursor
Total Nitrogen	Algal growth, taste, odor, reduction of dissolved oxygen
Total Phosphorus	Algal growth, taste, odor, reduction of dissolved oxygen
Pesticide/ Herbicide	DBP potential precursor, risks to environmental and public health

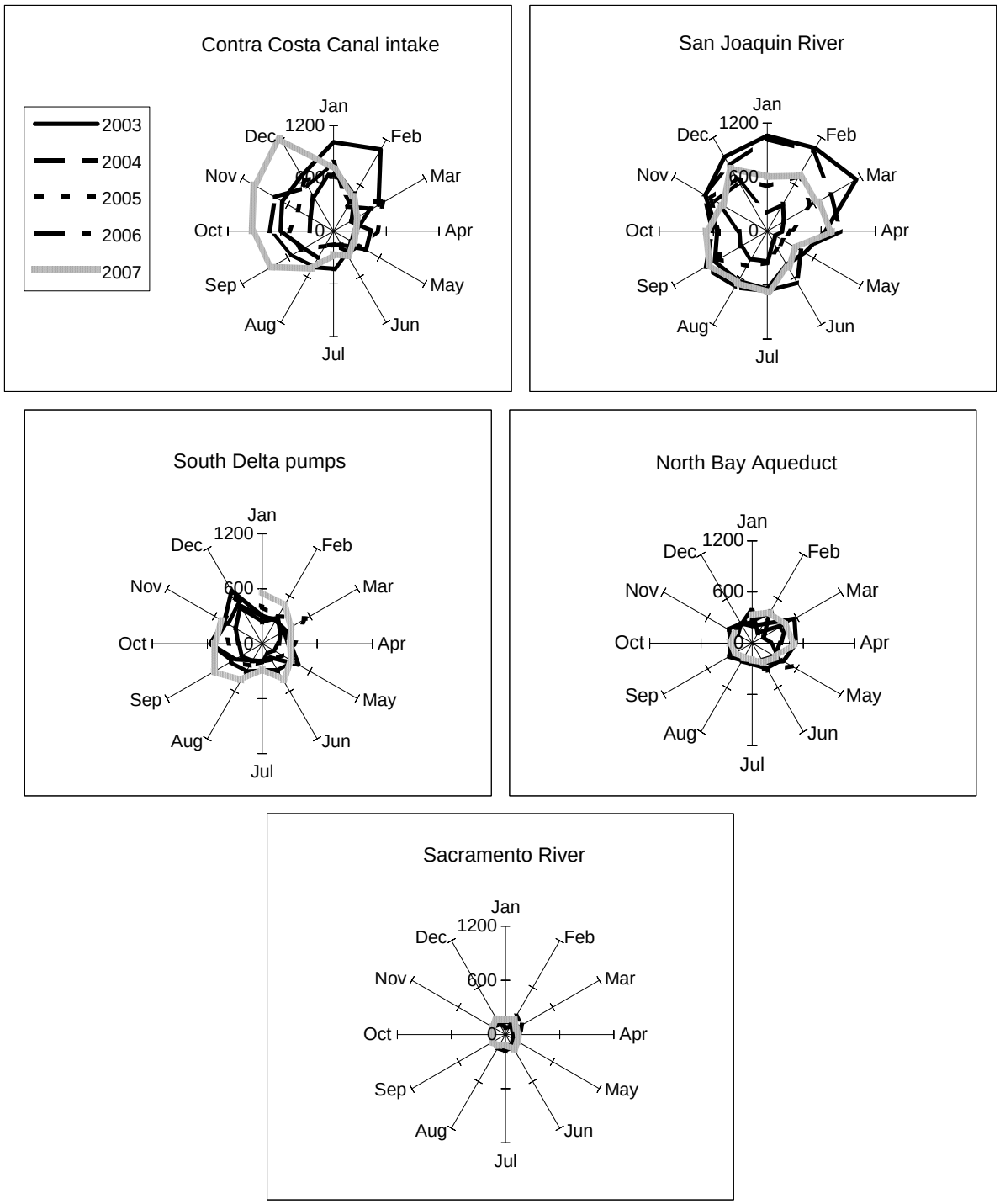
The main sources used for water quality data at the five locations are the Municipal Water Quality Investigations Program (MWQI) and the Water Data Library on the Department of Water Resources (DWR) website.[1] These sources provide data on electrical conductivity, bromide, chloride, TOC, DOC, and nutrients (the total nitrogen, and phosphorous) for locations in Delta. Data were collected over a five-year period from 2003 to 2007. This five-year period was used to understand the existing Delta water quality conditions. Pesticide and herbicide data were obtained from both MWQI and the California Department of Pesticide Regulation (DPR) Surface Water Database. More detailed information regarding the selection of locations and the data sources are given below and in Appendix H1.

Salinity can reflect the effects of seawater intrusion into the Delta as well as wastewater discharges and agricultural runoff from upstream that together are the major sources of bromides and chlorides in the Delta. TOC and DOC from drainage waters are significant precursors of DBPs during disinfection. Nutrients are represented as total concentrations of nitrite, nitrate, total Kjeldahl nitrogen (TKN), and total phosphorous, which are indicators for a suite of problems including algal growth, reductions in dissolved oxygen, increases in organic carbon, release of toxics, and taste and odor problems. In the discussion below, the concentrations of these constituents are presented as monthly averages from each sampling site.

[1] http://wdl.water.ca.gov/wq-gst/

Electrical Conductivity (Salinity)

Salinity in the Delta is commonly measured using electrical conductivity (EC), although bromide and chloride are particularly important salt constituents. Salinity can contribute to taste and odor problems, affect water management programs such as water recycling, and raise costs to residential and industrial water users by increasing corrosion of appliances. Over the five-year period from 2003 to 2007, the highest EC measurement was found at the Contra Costa Canal intake, with annual peaks between 700 and 1200 µS/cm, and at San Joaquin River at Vernalis (Figure H.2). Furthermore, a seasonal pattern was observed at the Contra Costa Canal intake with high EC concentrations typically occurring from late summer to early winter and low EC from winter to early summer. Higher salinity is directly related to higher bromide and chloride concentrations, with bromides being of greatest concern for DBP formation in drinking water treatment.



SOURCE: Water quality data from California Department of Water Resources.

Figure H.2. Annual variability of electrical conductivity (µS/cm) detected at the selected Delta monitoring locations (2003 - 2007)

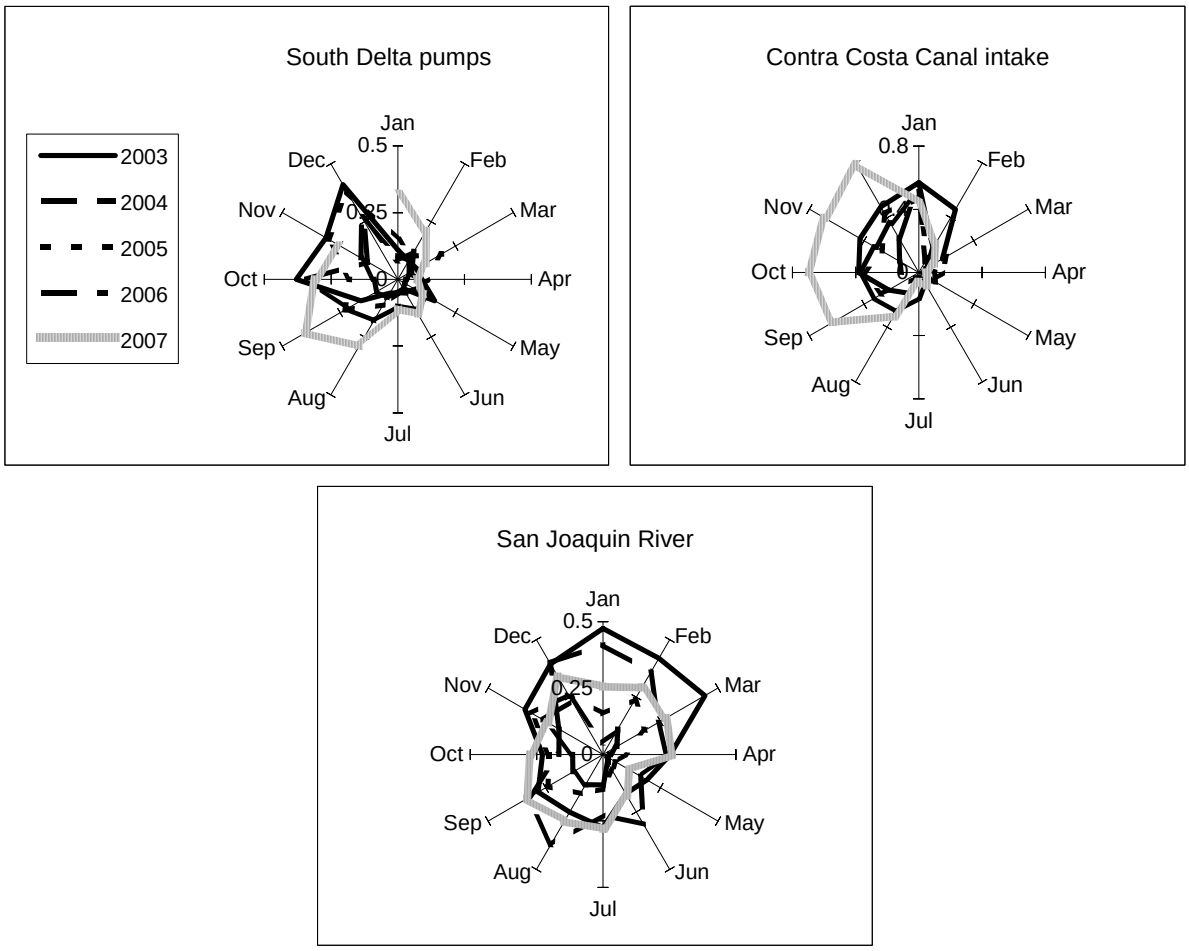
Higher salinity, even seasonally, can require water treatment plants to use other water sources or stored higher-quality waters to avoid additional treatment costs and potential public health risks posed by bromide in the seawater. Addressing these seasonal salinity patterns is a concern for water agencies, particularly those collecting water from a source with significant seasonal salinity variation, such as CCWD, which constructed the Los Vaqueros storage facility primarily to store higher quality water to blend with water withdrawn during periods when salinity is high, near a maximum chloride limit of 65 mg/l.

EC levels are lower 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 months and have less fluctuation at other times. Salinity at Banks is low during the late winter and early summer when river flows are highest, with salinity increasing 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 occurs upstream on the Sacramento River at Hood. The San Joaquin River at Vernalis has a high EC from upstream agricultural drainage (Figure H.2). Although the San Joaquin River is not directly used as a drinking water source, its poor water quality degrades water quality at the Contra Costa Canal intake and the South Delta pumps. The U.S. District Court (Wanger) decision in 2007 to restrict pumping operations in Delta (at Banks and Jones pumping plants for SWP and CVP, respectively) increased the influence of San Joaquin River salinity at the Banks pumping plant. In addition, when San Joaquin River flow exceeds about 3400 cubic foot per second, water at Jones pumping plant is mostly from the San Joaquin River (DWR, 2004).

Bromide

Bromide is of concern in drinking water due to the formation of bromate, a DBP and probable carcinogen, by reacting with ozone to produce potent brominated forms of DBPs during disinfection processes (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) set a bromide target concentration of 50 µg/l to ensure a high level of public health protection by water suppliers (CALFED, 2000).

Bromide concentrations at the Contra Costa Canal intake and South Delta pumps at Banks typically varied from 8 to 790 (µg/l) and between 50 and 410 µg/l, respectively (Figure H.3), mostly exceeding the bromide target concentration in the CALFED ROD. Bromide concentration at Barker Slough has an apparent seasonal variability beginning from spring to summer but was always below 90 µg/l during the 2003-2007 period (Addendum H1). Monthly averages of 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, with peaks from early spring to early summer.



SOURCE: California Department of Water Resources.

Figure H.3. Seasonal variability of bromide concentration (mg/l) detected at the South Delta pumps at Banks, Contra Costa Canal intake, and the San Joaquin River at Vernalis (2003 - 2007)

Depending on the volume of San Joaquin flows, 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 from 2003 to 2007 (Figure H.3). Seasonally, 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 (Appendix H1).

Depending on the volume of San Joaquin flows, 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 from 2003 to 2007 (Figure H.3). Seasonally, 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 (Appendix H1).

Chloride

Most chloride in the Delta is from seawater intrusion. Chloride is not harmful to human health, but it affects the taste and odor of water. More importantly, chloride is a good indicator for salinity contamination. The CALFED ROD has no chloride target concentrations. However, the Water Quality Control Plan for the San Francisco Bay/Sacramento-San Joaquin Delta Estuary prepared by State Water Resources Control Board (SWRCB) (SWRCB, 1995) has a maximum mean daily concentration objective for chloride of 150 and 250 mg/l for municipal and industrial protection.

Similar to results from the bromide data, the Contra Costa Canal intake has higher chloride concentrations, reaching 217 mg/l, with the second highest chloride measurements at the South Delta pumps at Banks (see Appendix H1). Similar seasonal patterns were found at these two locations, with peaks from late summer to winter and lower concentrations from early spring to summer, indicating that EC, bromide, and chloride are strongly correlated in the South Delta. Intermediate to low chloride concentrations occurred at the Barker Slough intake, with most high concentrations occurring in spring. As with bromide, the San Joaquin River has higher chloride concentrations, ranging from 8 to 160 mg/l, with no obvious seasonal pattern, while chloride concentration on the Sacramento River at Hood rarely exceeded 10 mg/l.

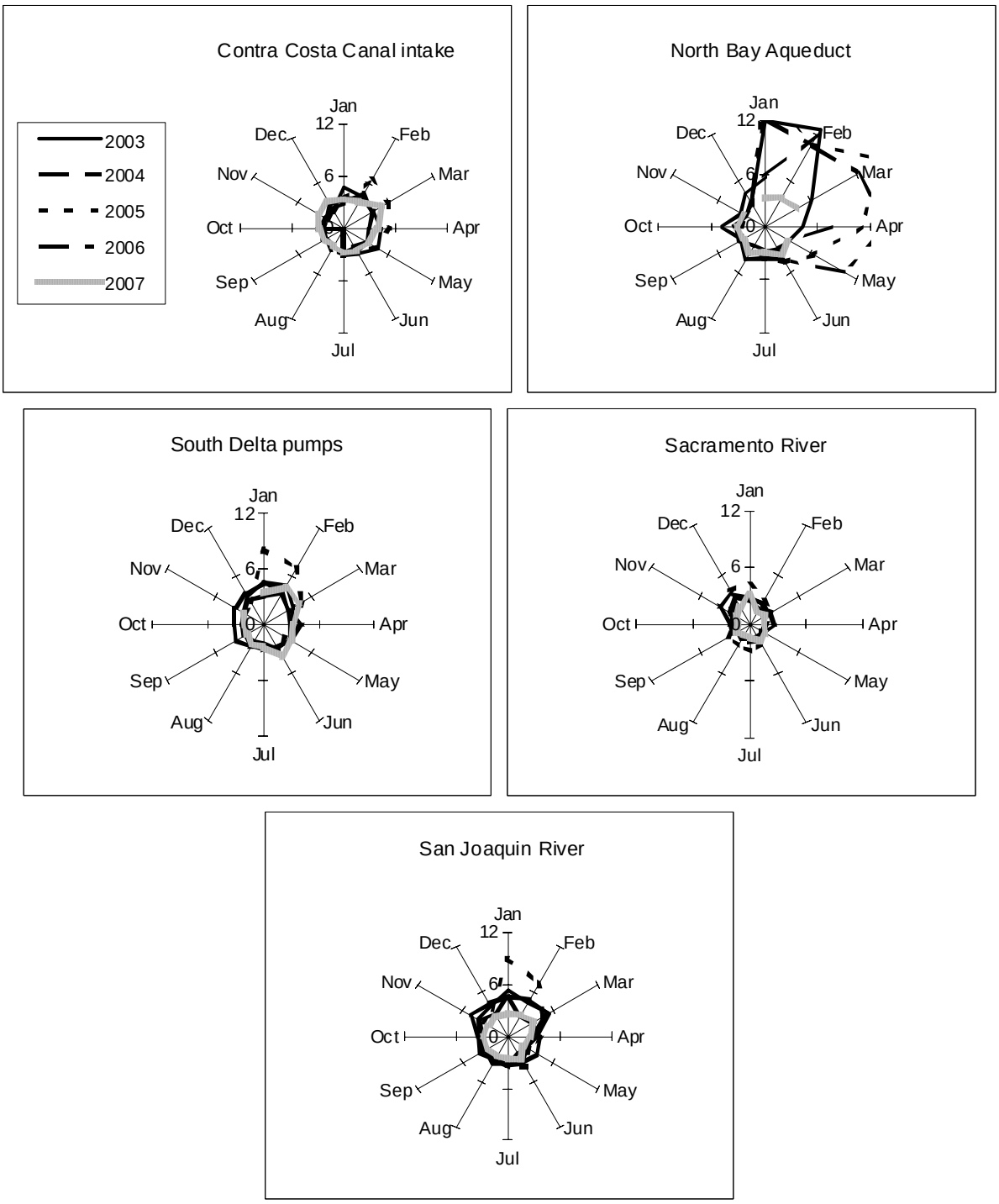
The EC, bromide, and chloride data show more serious salinity problems in the South Delta and San Joaquin River, as also discussed by the SWRCB's revised Decision 1641 (SWRCB, 2000). As described in that decision, the salinity problem in the San Joaquin River at Vernalis is affected by the salt load and low flow quantity resulting from upstream water diversions, subsurface accretions to the river from groundwater, and discharges of saline agricultural drainage water into the San Joaquin River. This high salinity in agricultural drainage results from the CVP and SWP irrigation water, which is withdrawn from the South Delta (a location contaminated by seawater intrusion and San Joaquin River salinity) and distributed to the west side of San Joaquin Valley. The irrigation water picks up additional salts through solid leaching and is re-circulated to the Delta via the San Joaquin River. Downstream of Vernalis, South Delta salinity is influenced by San Joaquin River inflow, tidal mixing (seawater intrusion), water diversions, agricultural return flows, and channel capacity (SWRCB, 2000).

Total and Dissolved Organic Carbon

Organic carbon in source waters 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 the levels of disinfectants required to achieve disinfection goals. In the Delta, organic carbon sources include algae, natural inputs from upstream flows, local and upstream 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 as a result of 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 report. However, the CALFED ROD focused only on TOC – with a target concentration of 3.0 mg/l of carbon (C) at Delta intakes (CALFED, 2004).

The DOC data for the five locations are shown in Figure H.4 (for TOC data, see Addendum H1). The highest DOC concentrations were in the North Bay Aqueduct at Barker Slough, ranging from 2.6 to 16 mg/l 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 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 C. TOC and DOC usually have less annual variability than does salinity.



SOURCE: California Department of Water Resources.

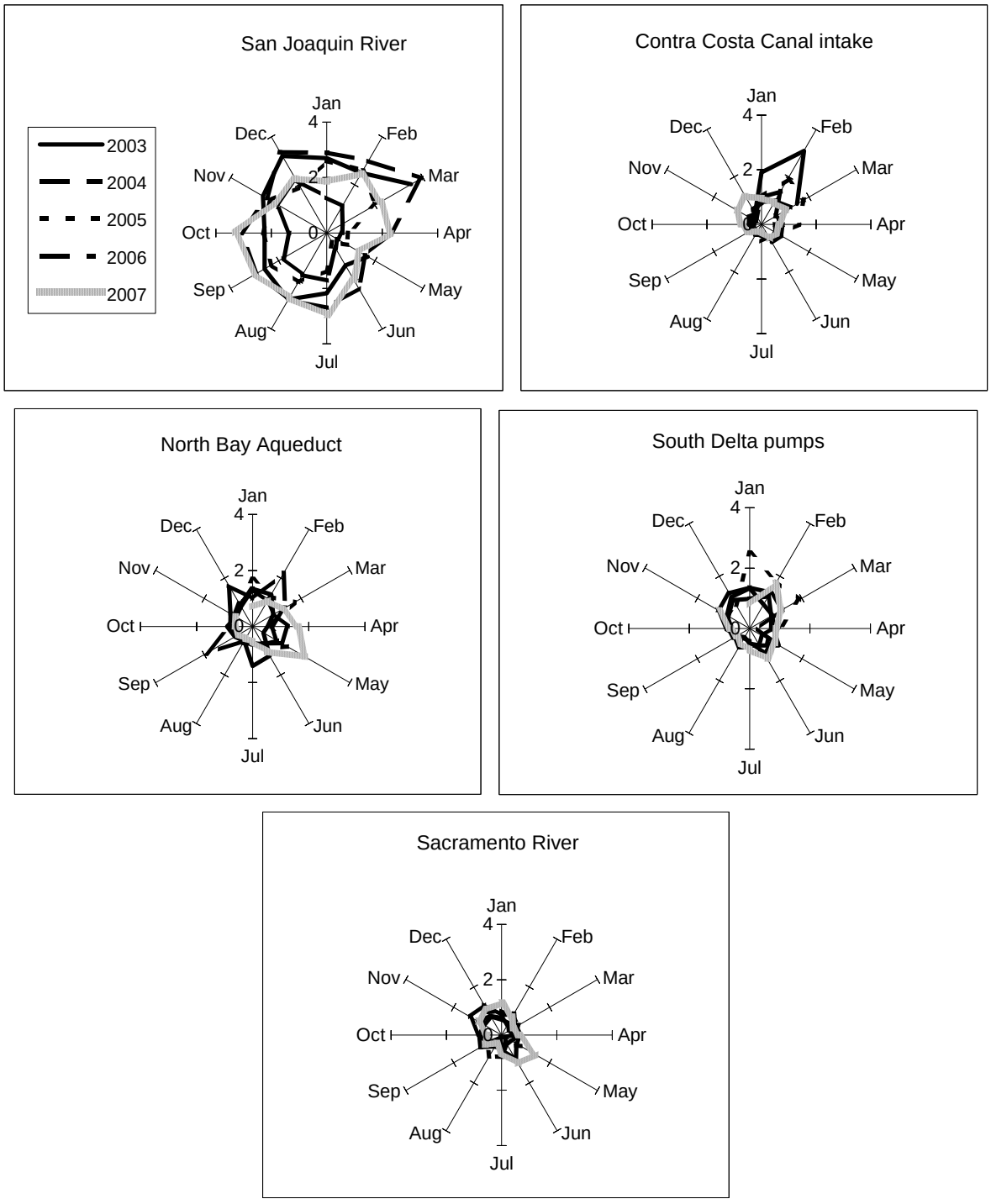
Figure H.4. Seasonal variability of dissolved organic carbon concentration (mg/l C) detected at the selected Delta monitoring stations (2003 - 2007)

Nutrients

Nutrients are various forms of nitrogen and phosphorous, both naturally present in the Delta and generated by human activities, such as wastewater, urban runoff, agricultural drainage and confined animal facilities. Nutrients are important for Delta aquatic life; however, excess nitrogen and phosphorous can stimulate excessive algae, further increasing organic carbon and reducing dissolved oxygen, and also interfere with water treatment processes and cause taste and odor problems. These excesses can create water quality problems for fish and urban water agencies.

In DWR's database, nitrogen is separately measured as the total concentration of nitrite and nitrate, which is the most frequent nitrogen measurement, and TKN, which is the sum of organic nitrogen (primarily ammonia and ammonium). In this appendix, total nitrogen is calculated as the sum of these two measurements.

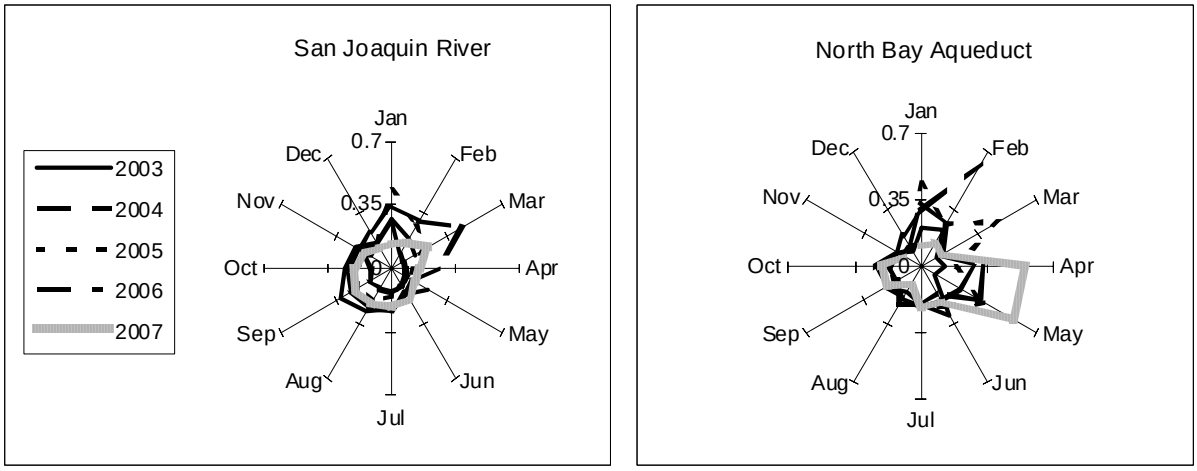
Monthly averages and seasonal variability of total nitrogen concentration appear in Figure H.5 for the five Delta locations. The San Joaquin River at Vernalis has the highest total nitrogen concentration (0.38 to 3.93 mg/l N) of these monitoring locations, with peak concentration from winter to late spring and a secondary peak in the summer from agricultural drainage. For the three in-Delta intakes (the North Bay Aqueduct, Contra Costa Canal intake, and South Delta pumps at Banks), total nitrogen varied from 0.24 to 3.10 mg/l N, with peaks typically found at Contra Costa Canal intake from late winter to spring and slightly later peak periods found at South Delta pumps at Banks from early spring to summer. The value at the Sacramento River at Hood has a much smaller range, between 0.08 and 1.40 mg/l N.



SOURCE: California Department of Water Resources.

Figure H.5. Annual variability of total nitrogen concentration (mg/l N) detected at the selected Delta monitoring stations (2003 - 2007)

Phosphorous (P), typically represented as total phosphorous (TP), is the other significant nutrient in the system. The North Bay Aqueduct and the San Joaquin River at Vernalis have higher concentrations of TP, from 0.1 to 0.63 mg/l and from 0.08 to 0.45 mg/l P, respectively (Figure H.6). Seasonal variability of TP was similar to nitrogen at these two locations. The San Joaquin River at Vernalis TP concentration peaks from winter to late spring, with a secondary peak in the summer. TP levels at the North Bay Aqueduct typically peaked in spring. The other locations in the Delta have typical TP concentrations from 0.03 to 0.3 mg/l P with seasonal a pattern similar to that of nitrogen, as shown in Addendum H1.



SOURCE: California Department of Water Resources.

Figure H.6. Seasonal variability of total phosphorous concentration (mg/l P) detected in the San Joaquin River at Vernalis and the North Bay Aqueduct (2003 - 2007)

Pesticides and Herbicides

Pesticides and herbicides in the Delta are primarily from agricultural uses, although runoff from urban landscaping applications also contributes to the loads. They are generally of concern due to the problems of taste and odor, such as the taste and odor problems associated with rice herbicides in the Sacramento basin. However, pesticides and herbicides also can pose possible health risks in drinking water by contaminating source water. There is a potential of forming DBPs during water treatment processes, although these risks remain unclear (Chen and Young, 2008; Lubick, 2008).

Because pesticide and herbicide concentration data are available only for two of these five stations in the MWQI dataset (BARKENOBAY and BANKS stations for the Barker Slough at North Bay Aqueduct and South Delta pumps at Banks, respectively), 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 had 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, the DPR did not detect any of the pesticides and herbicides it monitors at these two locations during the 2003-2006 period. From 2003 to 2006, DPR's database shows eleven pesticides and herbicides were 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 constituents of concern in the Delta. Table H.3 lists the pesticides and herbicides detected at four Delta locations in MWQI data and DPR's Surface Water Database.

Table H.3. Pesticides and herbicides detected in the Delta system

North Bay Aqueduct[1]	South Delta pumps[1]	Sacramento River at Freeport[2]	San Joaquin River at Vernalis[2]
2, 4- D Bromacil Dimethoate Diuron Metolachlor Molinate Norflurazon Simazine Triclopyr Trifluralin	2, 4- D Chlorpyrifos Dacthal Diuron Metolachlor Molinate Simazine Trifluralin	Diazinon EPTC Molinate Propanil Simazine Thiobencarb	Atrazine Butylate Chlorpyrifos Diazinon EPTC Ethoprop Metolachor Pebulate Propyzammide Simazine Trifluralin
1. From monthly data by MWQI, DWR (2003 – 2007). 2. From weekly data by Surface Water Quality Database, DPR (2003 – 2006).			

SOURCE: California Department of Pesticide Regulation.

Prediction of Future Water Quality

Likely future water quality in the Delta was predicted with respect to EC by using hydrodynamic modeling described in Appendix C to the main report (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 values were then employed in the following regression model (Equation 1):

$$\text{Constituent (mg/L)} = A \times \text{EC } (\mu S/cm) + B \qquad \text{(Eq.1)}$$

The model, developed by MWDSC, correlates EC with other selected constituents at locations in the Delta (Hutton, 2006). It was used to estimate the concentrations of constituents from hydrodynamic salinity model results, which typically include only EC (Table H.4). Although it was not specifically developed for seawater intrusion, the typically strong correlation among EC, bromide, and chloride allow this model to provide reasonable future water quality with respect to the concentrations of bromide and chloride under the three hypothetical future scenarios.

Table H.4. Salinity correlation analysis of EC to concentrations of total dissolved solids, bromide, and chloride for Delta locations)

Constituents	A	B
Total dissolved solids	0.540	5.7
Chloride	0.252	-34.6
Bromide	0.000827	-0.112

SOURCE: Hutton (2006).

NOTES: Table reports recommended regression statistics developed by MWDSC for correlating EC to total dissolved solids, bromide, and chloride at Delta locations. A and B represent the regression coefficients obtained for Eq.1.

The future water quality scenarios are compared to current conditions (from 2003 to 2007) in Table H.5 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, the predicted values for this location are omitted. Although the predictions for EC, bromide, and chloride 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 model results on these constituents.

Two assumptions underlying the estimates presented in Table H.5 are important to highlight. First, it is assumed that CCWD's water comes exclusively from the Rock Slough intake at the Contra Costa Canal. In practice, CCWD has other available intakes (Mallard Slough near Pittsburg, Contra Costa Canal at Old River) and one intake under construction on Victoria Canal. At any given time, the agency uses the intake(s) with the best water quality. When no intake meets CCWD's minimum water quality goal, water from Los Vaqueros Reservoir, which is filled using the intake with the higher water quality between Old River and Victoria Canal, is used to blend with lower quality water.[1] Second, this analysis did not consider changes in upstream or in-Delta operations to meet water quality with sea level rise or island failures. Current Delta water quality standards require meeting salinity levels; if these standards are not adjusted for changing natural conditions in the Delta, additional net outflows would likely be required to maintain water quality. In light of these two assumptions, this analysis should be considered preliminary and for illustrative purposes.

[1] http://www.ccwater-alternativeintake.com/FAQs.htm#2

Table H.5. Current and predicted future water quality conditions at different Delta intakes

Location	Time	Concentration of constituents (Low, **Average**, High)						
		Conductance (EC, µS/cm)	Bromide (mg/l)	Chloride (mg/l)	TOC (mg/l C)	DOC (mg/l C)	Nitrogen (mg/l N)	Phosphorous (mg/l)
Sacramento River	Current (2003 - 2007)[1]	73, **155**, 232	0, **0.01**, 0.02	2, **6**, 10	1.4, **2.4**, 7.0	1.3, **2.0**, 4.3	0.08, **0.68**, 1.40	0.04, **0.09**, 0.17
San Joaquin River	Current (2003 - 2007)[1]	109, **636**, 1143	0.02, **0.25**, 0.48	8, **71**, 160	2.7, **4.8**, 10.7	2.1, **3.7**, 9.0	0.38, **2.02**, 3.93	0.08, **0.18**, 0.45
North Bay Aqueduct	Current (2003 - 2007)[1]	136, **299**, 572	N.D., **0.04**, 0.09	6, **20**, 50	2.7, **7.9**, 52.5	2.4, **5.5**, 15.9	0.44, **0.96**, 2.21	0.08, **0.22**, 0.63
South Delta pumps at Banks	Current (2003 - 2007)[1]	125, **355**, 671,	0.03, **0.15**, 0.41	11, **52**, 130	1.9, **3.8**, 5.7	2.0, **3.2**, 8.2	0.28, **0.89**, 2.50	0.06, **0.10**, 0.28
	1 ft SLR[2]	126, **455**, 1166	0.03, **0.16**, 0.85	11, **80**, 259	N.A.	N.A.	N.A.	N.A.
	3 ft SLR[2]	126, **741**, 2120	0.03, **0.50**, 1.64	11, **152**, 500	N.A.	N.A.	N.A.	N.A.
	W Is. fail[2]	210, **439**, 729	0.06, **0.25**, 0.49	18, **76**, 149	N.A.	N.A.	N.A.	N.A.
Contra Costa Water District	Current (2003 - 2007)[1]	151, **497**, 1212	0.03, **0.25**, 0.79	10, **84**, 217	2.2, **3.5**, 6.3	2.1, **3.3**, 6.5	0.24, **0.74**, 3.10	0.03, **0.06**, 0.11
	1 ft SLR[2]	151, **679**, 2010	0.03, **0.45**, 1.55	10, **137**, 472	N.A.	N.A.	N.A.	N.A.
	3 ft SLR[2]	151, **1153**, 3360	0.03, **0.84**, 2.67	10, **256**, 812	N.A.	N.A.	N.A.	N.A.
	W Is. fail[2]	183, **607**, 1064	0.04, **0.39**, 0.77	12, **118**, 234	N.A.	N.A.	N.A.	N.A.
Record of Decision (ROD) target concentration		-	0.05	-	3		-	

1. Field Data (MWQI, Department of Water Resources)
2. Future water quality data are estimated from hydrodynamic modeling (Fleenor et al, 2008) and water quality regression (Hutton, 2007) (1 ft SLR: 1 foot sea level rise; 3 ft SLR: 3 feet sea level rise; W Is. fail: western islands fail).
3. From the current Sacramento-San Joaquin River Bay Delta Water Quality Control Plan
4. N.A. represents modeling not available
5. For illustrative purposes. Not an urban intake site.

2. Disinfection Byproducts

Most Delta drinking water quality problems result from DBPs produced by the constituents discussed above. Disinfectants, including chlorine, chloramines, ozone, ultraviolet (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 µg/l for total trihalomethanes (TTHMs) and 60 µg/l for five HAAs (two major classes of halogenated DBPs), 10 µg/l for bromate (a typical byproduct of ozonation), and 1 µg/l for chlorite. EPA also suggested best available technologies to control DBP formation.[2]

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.[3] 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 to provide adequate disinfection to protect against pathogens without forming DBPs.

Potential Disinfection Byproducts of Concern in the Delta

Table H.6 lists the DBPs of greatest concern. These 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. Not all DBPs listed in Table H.6 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.

[2] http://www.epa.gov/SAFEWATER/mdbp/dbp1.html
[3] http://www.epa.gov/ogwdw/disinfection/stage2

Table H.6. The priority DBPs typically considered in the regulations and studies

Halomethanes		
Chloroform	**Dibromochloromethne**	**Bromodichloromethane**
Bromodichloromethane	**Bromoform**	
Chloromethane	Bromomethane (methyl bromide)	Bromochloromethane
Carbon tetrachloride	Dibromomethane	
Haloacids		
Monochloroacetic acid	**Trichloroacetic acid**	**Monobromoacetic acid**
Bromodichloroacetic acid	**Dichloroacetic acid**	**Dibromochloroacetic acid**
Bromochloroaceticacid	**Tribromoacetic acid**	**Dibromoacetic acid**
3,3-Dichloropropenic acid		
Haloacetonitriles		
Dichloroacetonitrile	**Dibromoacetonitrile**	**Bromochloroacetonitrile**
Trichloroacetonitrile		
Chloroacetonitrile	Bromodichloroaceto nitrile	Tribromoacetonitrile
Bromoacetonitrile	Dibromochloroacetonitrile	
Haloamides		
Monochloroacetamide	**Dichloroacetamide**	**Trichloroacetamide**
Monobromoacetamide	**Dibromoacetamide**	
Halonitromethanes		
Trichloronitromethane (chloropicrin)		
Chloronitromethane	Bromochloronitromethane	Dibromochloronitromethane
Bromonitromethane	Dibromonitromethane	Tribromonitromethane (bromopicrin)
Dichloronitromethane	Bromodichloronitromethane	
Haloacetates		
Bromochloromethyl acetate		
Haloketones		
1,1-Dichloropropanone	**1,1,1-trichloropropanone**	
Chloropropanone	1-Bromo-1,1-dichloropropanone	1,1,3,3-Tetrabromopropanone
1,3-Dichloropropanone	1,1,3,3-Tetrachloropropanone	1,1,1,3,3-Pentachloropropanone
1,1-Dibromopropanone	1,1,1,3-Tetrachloropropanone	Hexachloropropanone
1,1,3-Trichloropropanone		
Aldehydes		
Chloral hydrate		
Chloroacetaldehyde	Bromochloroacetaldehyde	Tribromoacetaldehyde
Dichloroacetaldehyde	2-Hexenal	Cyanoforaldehyde
Others		
Bromate	**Chlorate**	**Chlorite**
Halogenated furanones	Dimethylglyoxal	Nitrosodimethylamine (NDMA)

SOURCE: The Environmental Protection Agency, and Booman et al. (1999), and Krasner et al. (2006).

NOTES: The DBPs in bold are required to be monitored by the D/DBP Rule or have regulated levels.

The DBPs listed below were selected from Table H.6 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 posed by these DBPs and the costs related to various treatment processes will be addressed below in a discussion of promising strategies for water treatment.

3. Treatment Processes for Disinfection and DBP Precursor Removal for Delta Waters

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.

In addition to those DBP precursors typically of concern (such as TOC and bromide), nutrients, pesticides and herbicides, and pharmaceutical and personal care products (PPCP) also present 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 report 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 by Delta export location and operations.

Alternative Disinfection

One option to treat Delta water is alternative disinfection technologies including UV radiation and ozonation. UV radiation can be accomplished by using UV lamps encased in a quartz sleeve to irradiation the water. The proper dosage of UV irradiation disinfects water without forming DBPs (Tchobanoglous et al., 2003). However, when implementing UV radiation, turbidity and suspended solids must be removed since they can absorb UV light and shield bacteria. Other concerns regarding UV disinfection include low inactivation of microorganisms and viruses under low dosages and fouling of lamp sleeves. Additional operational issues related to UV transmittance variation, UV sensor reliability, and power quality must be addressed during UV system design.

Ozone also can be used to treat Delta water. Although ozonation does not form THMs and HAAs (the major classes of DBPs considered in regulations), other DBPs are formed during ozonation. Especially when the source water contains bromide, ozonation can form bromate. Established methods, such as pH depression, can control bromate formation but may increase the cost and reduce the efficiency of ozonation. Currently, many plants use ozone (such as CCWD) and many are greatly expanding the use of ozone (such as MWDSC). It is likely that ozone will continue to be the primary disinfectant for water agencies using water from the Delta, even though some intake locations have high bromide concentrations.

Treatment Processes for DBP Precursor Removal

Disinfection byproduct formation is a complex process often 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 DBP formation instead of changing the disinfection process. Sometimes the interactions are complex. 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. In addition, these methods are not necessarily exhaustive, and it is possible that other methods, or variants on these methods, could provide better treatment cost performance than we predict.

Enhanced Coagulation

Enhanced coagulation reduces DBP precursors in source water with the objective of removing TOC to control DBPs formation in finished water. The removal of TOC through enhanced coagulation depends on the optimization of coagulant type and dosage added and pH levels during coagulation, and is affected by source water alkalinity, TOC concentration, and the chemical nature of the natural organic matter. Coagulation typically is applied in most water treatment plants for organic matter removal; if a water system can remove a specific percentage of TOC, its coagulation is then considered enhanced.

Adsorption

Adsorption is the process of accumulating dissolved substances onto media. GAC is the most common adsorption media for removing organic compounds as well as some metal and inorganic compounds. However, use of GAC to remove inorganic compounds has not been as widespread due to its low capacity and the difficulty and cost of activated carbon regeneration and disposal. Use of GAC would aid in removing DBP precursors and allow water treatment plants to continue using existing disinfection processes that could create DBPs if high concentrations of TOC were present in the water. GAC also can improve current treatment at relatively low cost.

Membrane Filtration

One option for removing DBP precursors from Delta water is membrane filtration, which includes MF/UF and NF. RO is not considered here due to the lack of cost information required for this analysis. This appendix assumes that a MF/UF or NF system is either added to an existing conventional treatment plant, or used as a replacement for GAC. These technologies use membranes to remove organic materials from the water. MF/UF can be effective for controling microbial contaminants, including *Cryptosporidium*, but addition of coagulants is required to effectively remove TOC. The primary concern with these technologies is membrane fouling from accumulations on the membrane surface. To avoid excessive fouling, pretreatment is often required. Membranes require more energy for pumping and must be replaced every three to five years (Tchobanoglous et al., 2003).

Magnetic Ion Exchange

Magnetic ion exchange (MIEX), a strong base anionic exchange resin with a polyacrylic backbone, is a promising new treatment technology. It is designed to remove natural organic matter (NOM), such as humic and fulvic substances, which comprise most DBP precursor materials in natural waters. When combined with other treatment processes such as coagulation and membrane filtration, MIEX has been shown to have a capacity to remove other anions, such bromide. Given its ability to remove these two water quality constituents, MIEX might be useful to enhance DBP formation control for Delta waters, where bromide could become a concern.

Since it does not remove particles, the MIEX technology is typically combined with other technologies to meet water quality regulations. For instance, where NOM is the primary concern, a traditional MIEX setup prior to coagulation is suitable. The primary concern with the MIEX system is brine disposal. The brine must go undergo toxicity tests. Because these tests frequently fail to meet safety standards, the brine often must be disposed as hazardous waste, at high costs and with risks of long-term liability. These factors have hindered MIEX use in California.

Existing and Future Potential Treatment Processes

Various treatment technologies have been applied to treat Delta waters to meet regulatory requirements. Technologies employed by existing treatment plants are summarized in Table H.7. In the future, changes in source water quality and more stringent regulatory requirements probably will require modification of current treatment processes. Based on current and anticipated drinking water standards, known Delta water quality constituents, and increasing demands for drinking water supplies, several water treatment technologies have been identified by CALFED (Table H.8), with some of these already in use (Table H.7) (CALFED, 2005); tests have demonstrated the effectiveness of those not yet in use in treating Delta water supplies.

Table H.7. Treatment processes currently used in water treatment plants supplied with Delta source waters

	South Bay Aqueduct							Contra Costa Canal/ Los Vaqueros		North Bay Aqueduct				Southern California[1]				
	Zone 7		ACWD		Santa Clara Water District			Contra Costa Water District		Fairfield Vacaville	Benicia	Vallejo		Metropolitan Water District of Southern California (MWDSC)				
Treatment Process	PP	DV	MSJ	TP 2	Penitencia	Rinconada[2]	Santa Teresa	Randall-Bold	Bollman	NBR	Benicia	Fleming Hill	Travis AFB	Robert B. Diemer[3]	Joseph Jensen	Henry J. Mills	Robert A. Skinner[3]	F.E. Weymouth[3]
Water delivered (mgd)	20	36	10	21	42	80	100	40	75	40	10	42	7	520	750	326	630	520
Clarification																		
Sedimentation			X	X	X		X	X	X	X	X	X	X	X	X	X	X	X
Superpulsator		X																
Upflow Clarifier	X					X												
DAF		X																
Filtration/ Separation																		
Anthracite/Sand	X	X		X							X			X	X	X	X	X
GAC/Sand					X	X	X	X	X	X		X	X					
Membranes	X		X															
Disinfection																		
Chlorine	X	X	X		X	X	X			X	X	X	X	X	X	X	X	X
Chloramines	X	X	X	X	X	X	X	X	X					X	X	X	X	X
Ozonation[4]				a	b	(b)	b	b	b	a, c		a, b	a	(a)	a	a	(a)	(a)
Ultraviolet																		

- ACWD: Alameda County Water District; AFB: Air Force Base; DAF: dissolved air flotation; DV: Del Valle water treatment plant (WTP); GAC: granular activated carbon; mgd: million gallons per day; NBR: North Bay Regional WTP; PP: Patterson Pass WTP; MSJ: Mission San Jose WTP; TP 2: Treatment Plant #2; WTP: water treatment plant
- **X** indicates use of a particular process

1. The other treatment plants in southern California treating Delta water include plants of Castaic Lake Water Agency, Antelope Valley East Kern Water Agency, Ventura City, and others. They are not included since they treat smaller volumes than those operated by MWDSC.
2. Rinconada WTP has intermediate ozonation planned and will increase capacity to 100 mgd in 2011
3. Upgrading of the Robert A. Skinner WTP with ozonation is slated for completion in 2009, with MWDSC's Rober A.Diemer and F.E Weymouth plants to follow.
4. a – Pre, b – Intermediate, c – Post – ozonation use

SOURCE: CALFED (2005) and MWDSC (http://www.mwdh2o.com/index.htm)

Table H.8. Technologies available to treat Delta water for drinking water purposes

Treatment process	Turbidity spikes	Algae and by-products	TOC/ DOC	Bromide	Crypto	DBP	Taste/ Odor
Improved clarification							
MIEX	X		X	X		X	
Enhanced coagulation	X		X		X	X	
Actiflo	X		X		X	X	
DAF	X		X		X	X	
Coagulant change	X		X			X	
Filtration	X		X		X		
Separation membranes							
MF/UF			X[1]		X	X	
RO	X	X	X	X	X	X	X
Adsorption							
PAC		X	X				X
GAC	X[2]	X	X			X	X
Disinfection							
Ozone			X		X[3]	X	X
UV		X			X	X	
pH depression			X[4]	X			

Crypto: Cryptosporidium
DAF: dissolved air flotation
D/DBP: disinfectant/disinfection by-products
GAC: granular activated carbon
MIEX: magnetic ion exchange
MF/UF: microfiltration/ultrafiltration
PAC: powdered activated carbon
RO: reverse osmosis
UV: ultraviolet

1. If coagulant is not used, MF/UF is not effective for TOC/DOC removal.
2. If GAC is used as filter media along with dual-media, it is effective to remove turbidity spikes.
3. High ozone dosage may be required be effective in inactivating *Cryptosporidium*, which possibly results bromate formation exceeding existing regulations.
4. pH depression can enhance the performance of coagulation and flocculation, and not unique to TOC/DOC removal.

SOURCE: CALFED (2005).

4. Cost Analysis for Water Qualities and Delta Locations

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 the technological limits on attaining these standards with a given source water. It also investigates alternative treatment processes in terms of estimated capital and operation and maintenance (O&M) costs for conditions in the Delta.

Cost Concepts and Estimation Methods

Water treatment plants treating 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. The base conventional surface water treatment plant employs the usual processes of coagulation, flocculation, clarification, filtration, and chlorine/chloramines application for disinfection and maintenance of a distribution system residual. It is assumed that the technologies investigated here can be directly added to the base 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, power supply access 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 (because 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; EPA, 1999; CALFED, 2005; EPA, 2005; Krasner et al., 2007; Lu et al., 2007). Some modifications were introduced, drawing on engineering judgment and practical experience from water agency experts 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 were established by considering different implementation scenarios, comprising different disinfection and various treatment technologies for DBP precursors removal and treatment goals. Cost estimates are made for design flows generally ranging from 1 to 520 mgd. Although some of the published sources refer to field data from specific water 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 shown here should be considered as a range; more detailed analysis would be necessary 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 commonly used for Delta waters, and several plants are slated for upgrading to include this technology (Table H.7). 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 magnetic ion exchange (MIEX), a new technology not yet used for treating Delta water.

Disinfection Technologies

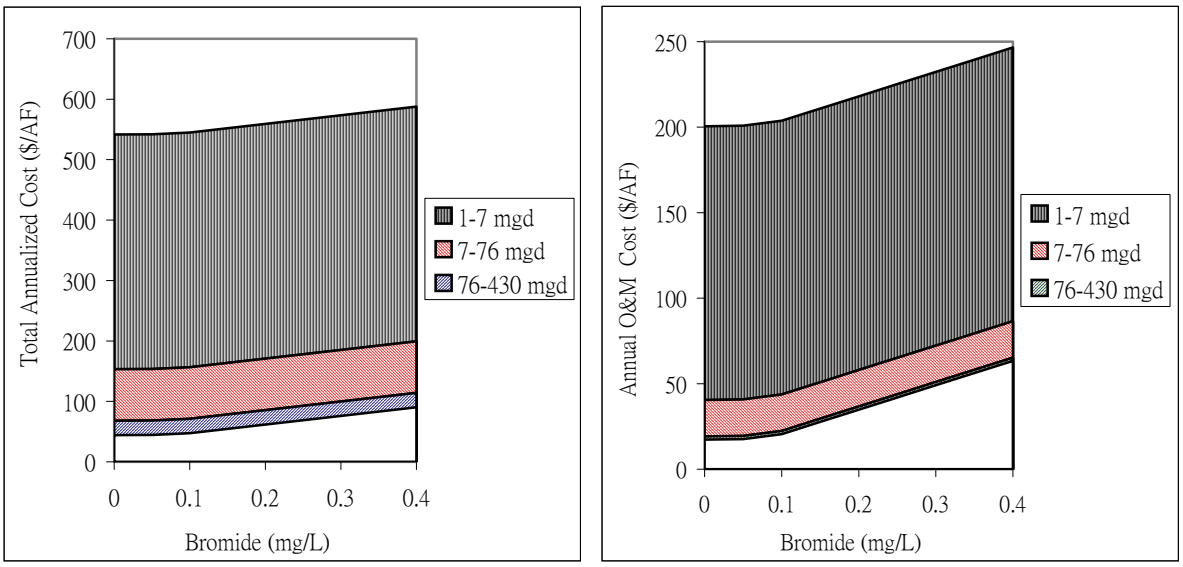
This section examines costs for ozonation and UV application for disinfection in a conventional surface water treatment plant.

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 a high concentration of bromide, the reaction of ozone and TOC can lead to bromate formation in the treated water. Although established methods such as pH depression can control bromate formation during ozonation, such methods increase the ozone dosage required. The result is lower treatment efficiency and higher 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 H.7. 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.

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, the bromide concentration range commonly detected in the Delta. The concentrations of TOC are assumed to be 3.5 and 4.1 mg/l 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.



SOURCE: Authors' calculations using EPA (EPA, 1999; EPA, 2005) and MWDSC (Krasner et al., 2007; Lu et al., 2007).

NOTES: Costs converted to 2007 dollars using deflators from ENR and BLS.

Figure H.7. Bromide concentration effects on total annualized cost and annual O&M cost of ozonation for disinfection and oxidation 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 H.9. These costs were estimated by assuming a UV dose of 40 mJ/cm^2 (EPA, 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, increasing pumping costs. Additional post disinfection treatment (such as post chlorination) may be needed to compensate for the lack of disinfectant residual in UV-treated water, causing additional expense.

Table H.9. Total annualized costs 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 ($/af)	21 - 105	10 - 22	6 – 12
Annual O&M Cost ($/af)	6 - 27	2 - 12	2 – 7

SOURCE: Author's calculation using AwwaRF (AwwaRF, 2007), EPA (EPA, 2005) and Water Environment Research Foundation (Darby et al., 1995).

NOTES: Costs converted to 2007 dollars using deflators from ENR and BLS.

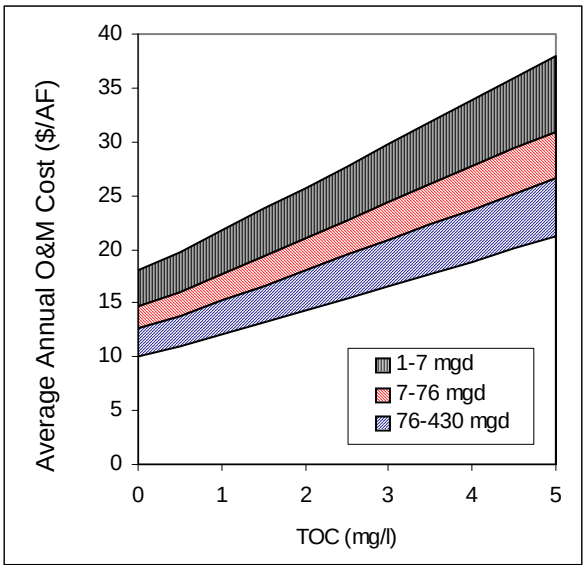
Advanced Treatment for DBP Precursor Removal

Many advanced treatment technologies can remove DBP precursors and other contaminants from source waters. These technologies can be employed in conjunction with existing disinfection processes to reduce treatment costs and public health risks from DBP formation. This section reviews cost components for enhanced coagulation, GAC, MF/UF, and NF, which were selected due to availability of cost information.

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. Costs were adjusted to 2007 dollars using the appropriate cost indices. At this plant, 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 H.8. The TOC concentration was the only water quality parameter considered, and the range of TOC was assumed from 0 to 5 mg/l C. Most TOC concentrations detected in Delta from 2003 to 2007 fell within this range. Potential costs not considered in the estimation include dewatering and hauling of the sludge and standby charges by the contractor.



SOURCE: Author's calculation using data from EPA (EPA, 2005) and MWDSC (Lu et al., 2007).

NOTES: Costs converted to 2007 dollars using deflators from ENR and BLS.

Figure H.8. Effects of total organic carbon concentration on annual operation and maintenance cost of enhanced coagulation

Absorption and Membrane Filtration

Table H.10 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 (EPA, 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 10^0C, 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 H.10. 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[1]	Total annualized cost ($/af)	137 – 877	62 – 282	39 – 146
	Annual O&M cost ($/af)	44 - 568	21 - 126	18 – 74
Microfiltration/Ultrafiltration	Total annualized cost ($/af)	301 – 554	214 - 301	158 – 214
	Annual O&M cost ($/af)	113 - 207	91 - 113	82 – 91
Nanofiltration	Total annualized cost ($/af)	464 – 584	364 – 464	293 – 364
	Annual O&M cost ($/af)	256 - 345	225 – 256	209 – 225

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

SOURCE: Author's calculation using EPA (EPA, 1999; EPA, 2005).

NOTES: Costs converted to 2007 dollars using deflators from ENR and BLS.

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 (AwwaRF, 2007). Table H.11 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 absence of clear scale economies may result from site-specific operations or different safety factors operated by the water agencies for water quality standards.

Table H.11. Summary of planning-level estimated capital costs for magnetic ion exchange resin

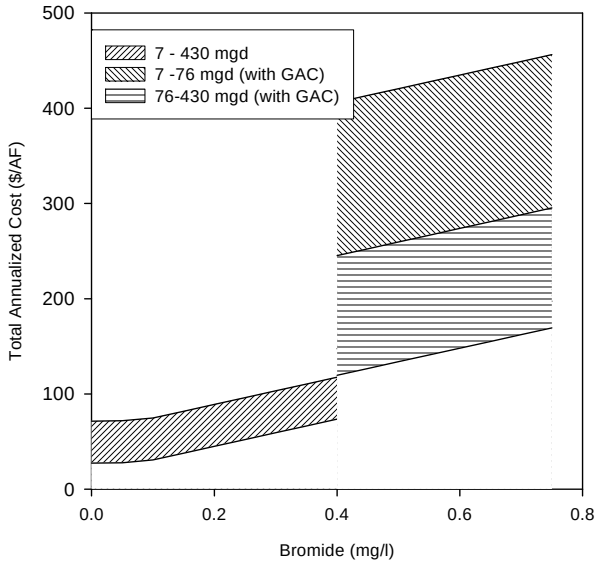
Size of system (mgd)	10[1]	50[1]	100[2]	150[1]
Total annualized capital cost ($/af)	53	27	105	23 - 27
Annual O&M cost ($/af)	N.A.	N.A.	34	N.A.

1. Calculated based on data from a conventional treatment plant using North Bay Aqueduct water and the MIEX system (CALFED, 2005).
2. Calculated based on data from "Advanced Water Treatment of Estuarine Water Supplies" prepared by AwwaRF.

Enhanced Coagulation/Ozone with GAC for Bromate Formation

Cost data for ozonation and GAC were used to investigate the effect of source water quality change on the cost of 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. The effects of TOC concentration on treatment choices and costs

were not investigated here because TOC varies less among Delta export alternatives. However, the TOC concentration was included in the total cost estimates, using the range detected in Delta from 2003 to 2007 (0 to 5 mg/l C). While GAC is not designed to remove bromide, GAC can reduce the TOC level enough to reduce ozone dosage requirement, which in turn reduces bromate formation to help the treatment plant comply with D/DBP rules. Figure H.9 shows the effect of changing bromide concentrations on the annual O&M cost of enhanced coagulation and ozonation, assuming these technologies are already installed.



SOURCE: Calculated using the cost data from Figure H.7 and Table H.10.

Figure H.9. 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

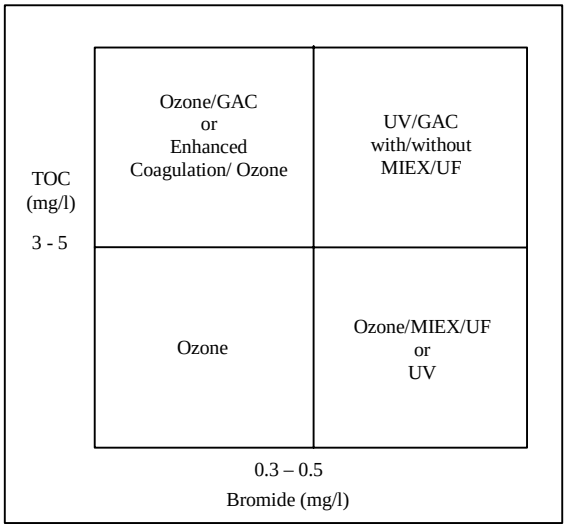
In Figure H.9, GAC is installed when the bromide concentration exceeds 0.4 mg/l. UV and MIEX, two alternative solutions for high bromide concentrations, are not considered due to lack of information regarding source quality effects on their costs. Because other technologies, such as MF/UF and NF, have higher costs than GAC, only GAC is considered in Figure H.9. Results shown in Figure H.9 indicate dramatic increases in costs above 0.4 mg/l of bromide due to new installation of GAC, particularly for a medium-sized treatment plant (7 to 76 mgd).

Treatment Cost Estimation for Water Quality Scenarios and Intake Locations

Treatment Strategies for Various Water Quality Scenarios

Figure H.10 summarizes appropriate treatments for different Delta water quality conditions. TOC and bromide are two of the water quality factors of drinking water concern. The concentration limits of TOC and bromide for various treatment strategies were developed using studies prepared by AwwaRF (AwwaRF, 2007) 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 was examined in the AwwaRF 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 tested in the AwwaRF study) MIEX placed before ultrafiltration removed both bromide and TOC (AwwaRF, 2007). Although likely an expensive process, MIEX seems capable of controlling NOM (and TOC) and low affinity ions such as bromide.



SOURCE: Authors calculations using data from AwwaRF (AwwaRF, 2007) and MWDSC (Krasner et al., 2007; Lu et al., 2007), and information provided by Santa Clara Valley Water District, Alameda County Water District.

Figure H.10. Treatments assumed for different Delta raw water qualities

Other technologies such as NF and RO, which also can help minimize TOC and bromide levels, may have higher treatment costs. Because we are interested in comparing cost-minimizing solutions, only GAC and MIEX/UF are considered here. In some areas (including California), GAC may be more expensive than MF/UF for DBP precursor removal, 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 H.10).

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 the disinfection and oxidation processes can only handle bromide levels of up to 0.3 mg/l when treating Delta water with a TOC level less than 4 mg/l (Lu et al., 2007). However, a pilot study conducted by SCVWD in 2000 found that source water with bromide concentration as high as 0.6 mg/l could still meet the goal of 8 µg/l of bromate concentration with an ozone dose of 2 mg/l at pH 6.4. As another example, 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.

Treatment Costs for Various Treatment Alternatives in Delta

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 H.12. 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 Delta waters at present. Annual O&M costs only were considered for enhanced coagulation and ozonation, since these treatment technologies are already used in most treatment plants using water sourced in the Delta. In contrast, annualized total costs, including both capital and O&M, were used for the technologies that generally are not yet commonly in use, including 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 (Table H.5). 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 the South Bay and Southern California, such as the extent of 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 these estimates should be useful for understanding the general magnitudes of effects of different water sources on water treatment costs.

Table H.12. Summary of estimated treatment costs of treating current Delta water

		Estimated costs ($/AF) [1]			
Plant/Intake location	**Treatment**	**Base cost**	**Combined with GAC**	**Combined with MF/UF**	**Combined with NF**
Sacramento River[2] (Hood; medium plant)	Enhanced coagulation/Chlorine[3]	19 – 25	-	-	-
	Enhanced coagulation/Ozone[4]	37 – 62	100 - 343	251 - 363	402 - 525
	Enhanced coagulation/UV	28 - 45	90 - 327	241 - 346	392 - 509
Sacramento River[2] (Hood; large plant)	Enhanced coagulation/Chlorine[3]	18 - 22	-	-	-
	Enhanced coagulation/Ozone[4]	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[4]	54 – 81	117 - 363	268 - 382	419 - 545
	Enhanced coagulation/UV	44 – 65	107 - 346	258 - 366	409 - 528
CCWD	Enhanced coagulation/Ozone[4]	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[4]	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[4]	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

1. 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.
2. For illustrative purposes. Currently no urban intakes here.
3. Enhanced coagulation/chorine is not possible for other plants. Table reports the base cost of the current drinking water treatment processes used nearby.
4. 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.

SOURCE: Authors' calculations using the cost data from Figures H.7 and H.8, and Tables H.5, and H.9 through H.11.

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 a capacity range of 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 a capacity range of 76 to 520 mgd since larger treatment capacity typically reduces unit treatment costs.

In the time available for this study, we were unable to make cost comparisons among actual plants – as this would require sorting through inconsistent cost accounting methods. Cost estimates can vary widely. For instance, CCWD's new 40 mgd water treatment plant had a capital cost of approximately $48 million, with full capacity operating costs of roughly $2 millions per year (D. Briggs, Personal Communication). At a 5% interest rate, total annualized treatment costs at this plant are on the order of $100/af. For the City of Sacramento's water treatment plant, which collects water from the Sacramento River, recorded operating costs were roughly $300/af (Peifer, City of Sacramento).

At locations with low bromide concentrations (the Sacramento River at Hood), the cost of ozonation is similar to that of UV. Because ozonation cost increases significantly with bromide concentration, UV disinfection combined with other treatments eventually appears to come in at a lower per acre-foot cost (see, for instance, cost estimates for CCWD in Table H.12). Ultraviolet is a potential disinfection alternative to ozonation if the bromide concentration in Delta source waters increases in the future 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 treatment plants that use water sourced in the Delta, revising treatment operations also might help control treated water quality as the Delta water quality degrades for urban uses.

Treatment Costs for Potential Future Quality Condition in Delta

Table H.13 presents the total costs for different combinations of treatment technologies for current and potential future water quality conditions at three intake locations in the Delta. Assumptions regarding the system sizes and cost estimation are similar with those used for Table H.12. Both TOC and bromide concentrations were considered in the cost estimation; however, only bromide concentrations are reported in the table, since these levels vary most among these intake locations under current and 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 H.5) were then used to estimate the annual O&M costs for enhanced coagulation and ozonation.

Table H.13. Summary of estimated costs for treating current and potential future Delta water by various treatment methods (Most likely treatments are in boldface)

			Estimated costs ($/af)				
Plant/intake Location	Condition	Bromide (mg/l)	Enhanced coagulation /Ozone[2, 3]	In combination with GAC[3]	In combination with MF/UF[3]	In combination with MIEX/MF/UF[4]	In combination with NF[3]
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[1]	Current (2003 - 2007)	0.25	**66 - 91**	128 - 373	280 - 392	330 - 492	431 - 555
	1 ft SLR	0.45	91 - 127[5]	**153 - 409**	305 - 428	355 - 528	455 - 591
	3 ft SLR	0.84	147 – 183[5]	209 - 465[5]	360 - 484[5]	**410 - 584**	511 - 647
	W is. fail	0.39	82 - 119[5]	**145 - 400**	296 - 420	346 - 530	446 - 582
South Bay[1] (South Delta pumps)	Current (2003 - 2007)	0.15	**53 - 78**	115 - 359	266 - 379	316 - 479	417 - 541
	1 ft SLR	0.26	63 – 100[5]	**126 - 381**	277 - 401	327 - 501	428 - 563
	3 ft SLR	0.50	98 - 134[5]	**160 - 416**	311 - 435	361 - 535	462 - 598
	W is. fail	0.25	62 - 98[5]	**124 - 380**	276 - 399	326 – 499	426 - 562
Southern California[1] (South Delta pumps)	Current (2003 - 2007)	0.15	**46 - 53**	85 – 199	204 – 266	254 – 366	340 - 417
	1 ft SLR	0.26	61 - 78[5]	**124 – 360**	275 – 379	325 – 479	426 - 542
	3 ft SLR	0.50	96 – 113[5]	**158 - 394**	309 – 414	359 – 514	460 - 576
	W is. fail	0.25	60 – 77[5]	**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

1. 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 is assumed for Southern California.
2. 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.
3. Only annual O&M costs were used to represent the costs of ozonation, since ozonation is already used in most of the treatment plants using Delta source waters. Total annualized costs (annualized capital cost and annual O&M cost) were used for the costs of other treatment technologies.
4. It is assumed that total annualized cost of MIEX ranges from $50 to $100/af based on the data in Table H.11.
5. 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.

SOURCE: Authors' calculations using the cost data in Figures H.7, H.8, and H.10, and Tables H.5, H.10, and H.12.

The future conditions assume seawater intrusion into the Delta from sea level rise or failure of western Delta islands (Table H.5). As above, the treatment costs in the South Bay Area and Southern California were distinguished for water drawn from the same South Delta pumping location to account for differences in 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 these locations, like those in the Delta, might see higher TOC concentrations). Costs for UV were not investigated because this technology is not currently employed in any plant treating Delta waters and information is lacking 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/af (Table H.11). As sea level rises and the 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 expected to be those highlighted in bold in Table H.13. Granular activated carbon already has been employed in some of the treatment plants in CCWD and the South Bay, especially those of larger capacity (Table H.7). 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 can also affect the choice of treatment technology, such as reliability and residuals disposal.

In addition, although bromide concentration is the most important water quality factor used to determine appropriate treatments, potential changes in TOC concentration also should be considered in future work. Various changes in the Delta and upstream can increase TOC concentration levels. In this exercise, the TOC concentration ranges observed in the 2003-2007 period were used to estimate treatment costs, assuming future TOC concentrations will not change significantly with seawater intrusion. Although we believe this to be a reasonable assumption for now, more detailed investigation would be valuable to assess the various potential changes in TOC concentrations at different intake locations.

In Table H.13, GAC is considered as a method for preventing high TOC concentrations in the future. This technology has a relatively low cost, assuming enhanced coagulation also has been employed. When bromide concentration exceeds the range of 0.3 to 0.5 mg/l, the use of MF/UF with MIEX is recommended to remove bromide (see Figure H.10). 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 H.12 and H.13 neglect possible limitations on availability of land and electricity capacity at the existing treatment plant sites. Given these factors, it may be necessary to use other source water containing fewer contaminants/DBP precursors or to relocate treatment plants to accommodate increasing contaminants.

5. 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). If available, other established methods such as using source waters with less bromide may be better to control bromate formation. 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 (AwwaRF, 2007), 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 bacteria might re-grow in the water distribution system. For this reason, 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 for sure. 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. More brominated forms of DBPs are more potent than their chlorine-containing counterparts, because bromide is not removed by ozone or UV and the higher bromide-to-TOC ratio is higher at the point of chlorination/chloramination (Krasner et al., 2006).

TOC and bromide are two of the primary DBP precursors considered in this report. 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 DBP precursors (Chen and Young, 2008; Lubick, 2008). Although the DBP risks from these contaminants remain uncertain due to insufficient information regarding the formation

mechanisms, it is important to consider these contaminants when estimating the residual health risk of water exported from Delta.

Because there is insufficient toxicity and carcinogenicity information for many DBPs, it is difficult to identify and compare the potential health risks of alternative disinfectants and chlorine. 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 most appropriate treatment strategies can the public and environmental health risks of treated water be effectively minimized.

Conclusions

The Delta is California's most important drinking water source, supplying more than two-thirds of California's residents. 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 along 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, nutrients, and pesticide and herbicide concentrations and their consequences for drinking water treatment costs for disinfection by-products, probably the most costly treatment problem for Delta waters, currently and in the future.

Salinity poses the most significant constraints on water treatment at the two South Delta intakes. Salinity in the Delta comes from intruding sea water and agricultural runoff in the San Joaquin River. Salinity varies seasonally at the South Delta intakes, with peaks typically beginning from early summer to late winter. Higher DOC concentrations are observed at the North Bay Aqueduct and South Delta intakes from winter to spring. The South Delta intakes and the San Joaquin River have higher concentrations of total nitrogen and phosphorous, with higher seasonal loads from late winter to early summer at the South Delta intakes. Although the Sacramento River has lower concentrations of salinity and DOC, it has occasional pesticide and herbicide contamination. Detections have been more frequent for a larger number of these contaminants on the San Joaquin River. At other locations, monitoring results vary across data sources. At the North Bay Aqueduct and South Delta pumps, selected chemicals were detected in MWQI data, while chemicals monitored by DPR were below detection limits in DPR's surface water quality database.

Most serious Delta drinking water quality problems result from DBPs produced by reactions between Delta water and disinfectants used. Halomethanes, haloacids, and TOX are the major classes of DBPs considered in regulation and in numerous studies. Aldehydes, halonitromethanes, and notably bromate are common DBPs related to ozone, the frequently used disinfection process for Delta source waters. These same DBPs are associated with UV, a possible future disinfection option. Other DBPs, such as NDMA, may be produced by pesticides or herbicides during disinfection and pose potential public health risks.

Ozonation and UV are the primary existing and alternative disinfection processes considered in this analysis. Additional treatment technologies to remove DBP precursors include enhanced coagulation, adsorption (GAC), membrane filtration (MF/UF and NF), and MIEX. Total annualized capital and O&M costs for these treatment processes were estimated. Estimated costs of technologies for enhanced removal of DBP precursors are lowest for GAC, followed by MF/UF, and NF. TOC and bromide are two water quality constituents considered in the choice between ozone and UV as alternative disinfectants to chlorine, with/without the additional treatment technologies.

Cost information was further applied to projections of future water quality from hydrodynamic modeling described in Appendix C to estimate the future costs of drinking water treatment for water drawn from different Delta intake locations. One to three feet of sea level

rise and failure of western Delta islands increases the costs of treating water from the South Delta intakes (Contra Costa Canal intake and South Delta pumps at Banks). Projections were unavailable for the North Bay Aqueduct. Based on the results of the hydrodynamic modeling, 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 H.14 for two Delta intake locations (Contra Costa Canal intake and the South Delta pump at Banks) and for a hypothetical intake in the northern Delta on the Sacramento River at Hood, with estimates for two plant size categories used for treating water exported from the South Delta. The Contra Costa Canal 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 H.14. Summary of estimated costs of selected treatment technologies for treating current and future Delta water.

	Annualized treatment cost[1] ($/af)			
Plant/Intake location	Current (2003 - 2007)	1 ft SLR	3 ft SLR	W Is. Fail
Sacramento River (Medium plant)	37 – 62[3]			
Sacramento River (Large plant)	35 – 40[3]			
CCWD[2] (Contra Costa Canal intake)	66 - 91	153 – 409	410 – 584	145 - 400
South Bay[2] (South Delta pumps)	53 – 78	126 – 381	160 – 416	124 – 380
Southern California[2] (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

1. 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.
2. 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.
3. Water quality in the Sacramento River is assumed constant over simulated conditions.

SOURCE: Authors' estimates, using professional judgment and the cost data from Figures H.7, H.8, and H.10, and Tables H.5, H.10 through H.13.

The residual health risks from different treatment alternatives and DBP precursors, along with other factors including reliability, ease of operation, and disposal of residuals, might significantly affect the selection and best operational strategies of water treatment alternatives. Furthermore, since neither ozone nor UV produces residual disinfectant in the treated water, these processes require the application of additional chlorine or chloramine. 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 appendix is immediately downstream of the expanded Sacramento Regional wastewater discharge, resulting in another health concern for water from this location.

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, rather than the Sacramento River in the north Delta, is currently about $20 to $60/af, which is in line with the MWD's annualized cost estimates for ozonation.[4] This cost difference is likely to increase to $100 to $500/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. The range 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 the 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 accommodate health risks. Currently, both CCWD and the North Bay Aqueduct plants switch to alternative water sources when water quality is poor, and these agencies are also considering alternative Delta intake locations. More detailed information and studies on 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.

Although there is certainly more room for analysis, this preliminary study should add some structure, detail, and initial analysis to recurrent discussions of drinking water quality issues related to Delta water supplies. We find the treatment costs and residual health risks of using the Delta as a drinking water supply to be significantly higher than using water from the Sacramento River. We also find that these costs and risks are likely to increase. The only uncertainties are how fast and by how much.

[4] http://deltavision.ca.gov/BlueRibbonTaskForce/Nov2007/Handouts/Attachment_%204.pdf

Addendum H1. Water Quality Data

This addendum presents additional figures describing the annual variability of constituents of concern in the Delta. These data were primarily assembled from MWQI and the water quality database provided by DWR from 2003 to 2007, while field data for pesticides and herbicides are from the DPR's Surface Water Data Base from 2003 to 2006.

Data Sources

Water quality data were assembled for five principal intakes in the Delta (Table H1-1). For each region, one intake location was chosen as representative and the associated water quality information was investigated to understand the local seasonal water quality pattern. Locations on the Sacramento River at Hood and San Joaquin River at Vernalis were chosen to indicate the water quality contributed by the two major tributaries. The Banks pumping plant was chosen to represent the South Delta pumps for 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 monitoring locations are identified in Figure H.1.

Table H1-1. Data sources used to assess the water quality constituents of interest in the Delta

	Monitoring locations used to assess the water quality				
Analyte	**Sacramento River (upstream of Delta)[a]**	**San Joaquin River (upstream of Delta)[b]**	**South Delta pump (Banks)[c]**	**North Bay Aqueduct (Barker Slough intake)[d]**	**Contra Costa Canal (Rock Slough intake)[e]**
Electrical Conductivity (EC)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Bromide	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Chloride	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Total Organic Carbon (TOC)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Dissolved Organic Carbon (DOC)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Total nitrogen	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Total Phosphorus (TP)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)	DWR MWQI (2003-2007)
Pesticide/Herbicide	DPR[f] (1992-2006)	DPR[g] (1992-2006)	DWR MWQI (2003-2007), DPR[h] (1992-2006)	DWR MWQI (2003-2007), DPR[i] (1992-2006)	N.A.

MWQI = California Department of Water Resources, Municipal Water Quality Investigations Program, DPR = California Department of Pesticide Regulation, Surface Water Data Base, Complete Chemical Analysis Results, NA = not available. Specific site names are noted.

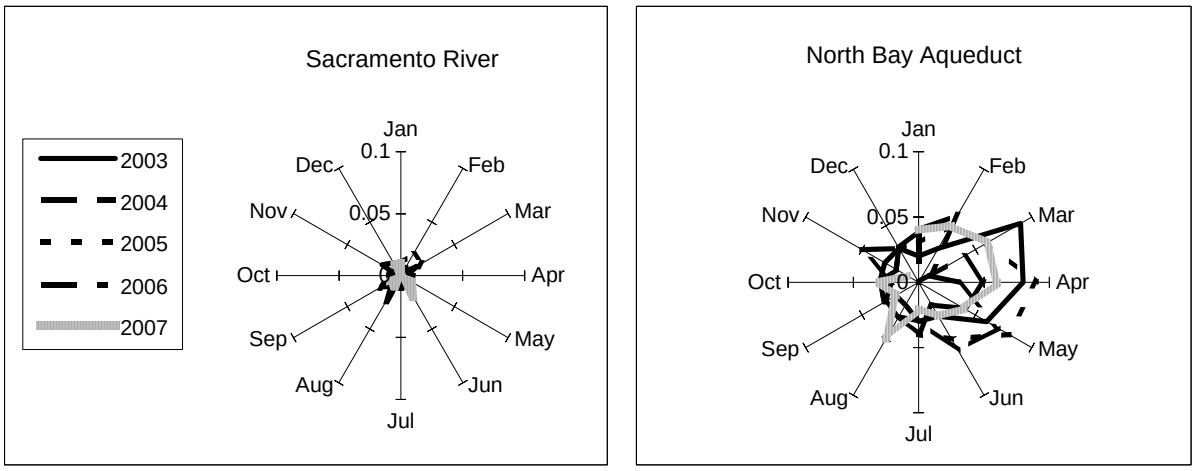
[a] MWQI Station "Sacramento R A HOOD";
[b] MWQI Station "VERNALS";
[c] MWQI Station "Delta P.P. Headworks at H.O. Banks PP";
[d] MWQI Station "BARKERNOBAY"
[e] MWQI Station "CONCOSPP1"
[f] DPR Station " Sacramento River at Freeport"
[g] DPR Station " San Joaquin River at Vernalis"
[h] DPR Station " Old River at Tracy Road (inside Delta)"
[i] DPR Station " Cache Slough near Ryers FerrData were primarily collected from MWQI's Water

Data Library available on DWR's website, [5] which provides comprehensive water quality data including electrical conductivity, bromide, chloride, TOC and DOC, nutrients (total nitrogen and phosphorous), and pesticides and herbicides for locations in Delta. More information on pesticides and herbicides was collected from DPR's Surface Water Database.[6] In some cases the DWR monitoring location is unavailable in the DPR database; in these cases the closest DPR sampling site was used. The data assembled from DWR's database are five years from 2003 to 2007, while data from DPR's database are for four years between 2003 and 2006 (2007 data not available from this source).

Water Quality Constituents of Interest

Bromide

Monthly average of bromide measurement data for the Sacramento River at Hood and the North Bay Aqueduct appear Figure H1-1. Low concentrations of bromide occurred in the Sacramento River at Hood and higher bromide levels were found at the North Bay Aqueduct with a seasonal pattern with the peaks beginning from early spring to summer. Data for some time periods and locations not shown in the figures (e.g., bromide concentration in February 2007 at Sacramento River) indicate that bromide was often not detected.



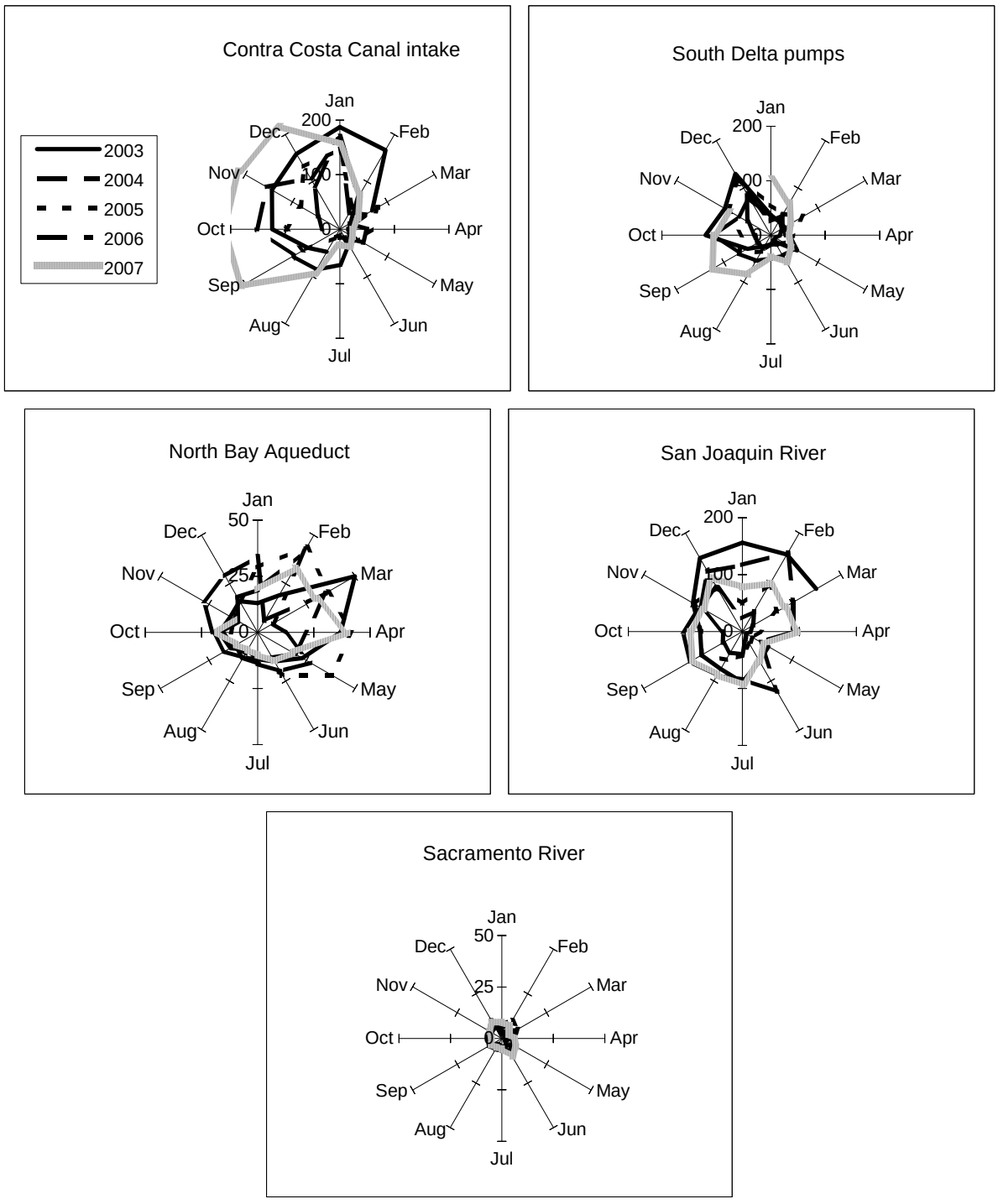
SOURCE: California Department of Water Resources.

Figure H1-1. Annual variability of bromide concentrations (mg/l) at the Sacramento River at Hood and the North Bay Aqueduct from 2003 to 2007

[5] http://wdl.water.ca.gov/wq-gst/
[6] http://www.cdpr.ca.gov/docs/emon/surfwtr/surfdata.htm

Chloride

Monthly average of chloride data at Contra Costa Canal intake, South Delta pumps at Banks, North Bay Aqueduct, Sacramento River at Hood, and San Joaquin River at Vernalis appear in Figure H1-2.

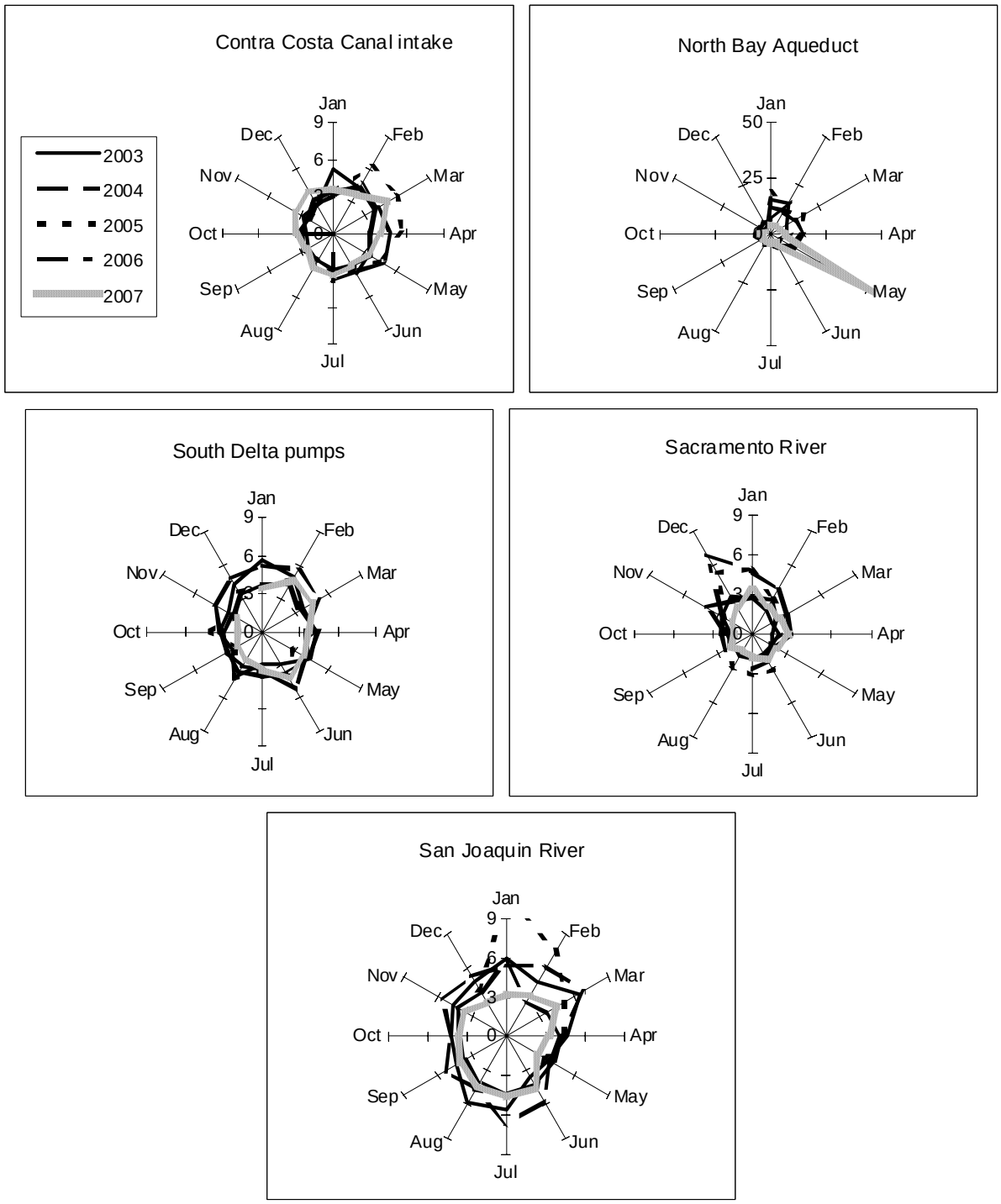


SOURCE: California Department of Water Resources.

Figure H1-2. Annual variability of chloride concentrations (mg/l) at the selected Delta monitoring locations from 2003 to 2007

Total Organic Carbon

Monthly average TOC concentration data are given in Figure H1-3. The North Bay Aqueduct and San Joaquin River have higher TOC concentrations ranging from 3.3 to 19.4 and 2.7 to 10.7 mg/l as C, respectively. The North Bay Aqueduct has a much higher concentration of TOC (52.5 mg/l as C) in May 2007, perhaps from the interference of particulate matter during the measurement. Sacramento River and the Contra Costa Canal intake have lower TOC concentrations, typically ranging from 1.4 to 7.0 mg/l as C, while the lowest TOC detection (between 1.9 to 5.7 mg/l as C) was found at the South Delta pumps at Banks. An apparent seasonal pattern was observed at the Contra Costa Canal intake and South Delta pumps at Banks, with peaks starting from late winter to early summer.

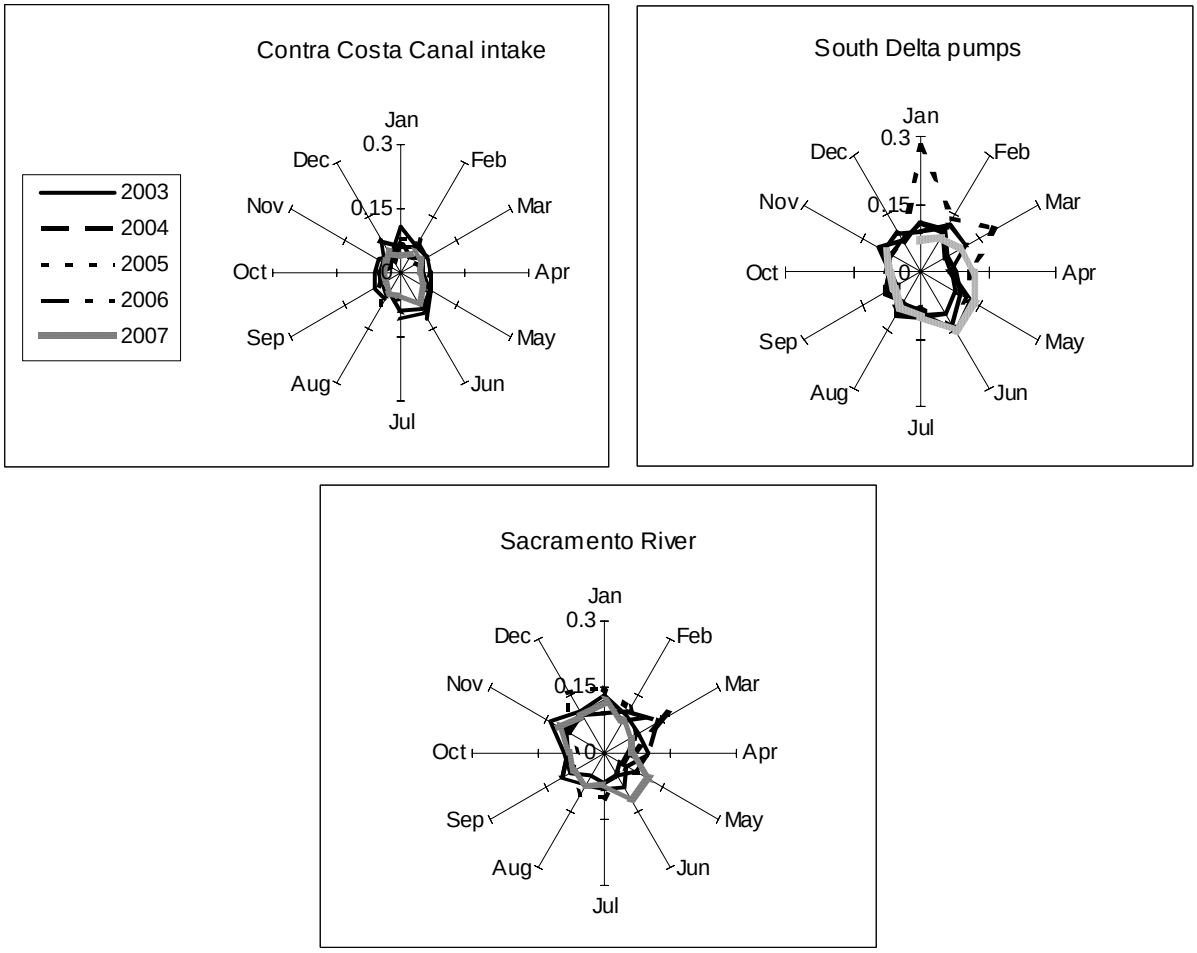


SOURCE: California Department of Water Resources.

Figure H1-3. Annual variability of total organic carbon concentrations (mg/l C) at the selected Delta monitoring locations from 2003 to 2007

Nutrients

Annual and seasonal variability of TP concentration at the Contra Costa Canal intake, South Delta pumps at Banks, and Sacramento River at Hood are presented in Figure H1-4, with a typically measured concentration varying from 0.03 to 0.3 mg/l as P. The total phosphorous concentration at the Contra Costa Canal intake and the South Delta pumps at Banks typically peaked from late winter to early summer, while no significant seasonal pattern was observed at the Sacramento River at Hood.



SOURCE: California Department of Water Resources.

Figure H1-4. Annual variability of total phosphorous concentration (mg/l P) at the Contra Costa Canal intake, South Delta pumps at Banks, and Sacramento River at Hood from 2003 to 2007

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