TOWARDS A NEW CONCEPTUAL MODEL FOR DRINKING WATER CONCERNS IN THE SACRAMENTO-SAN JOAQUIN DELTA

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ABSTRACT

Dissolved organic carbon is ubiquitous in water. It is the dissolved residue of all living things, beneficial to aquatic organisms, and largely benign for humans. Yet dissolved organic carbon (DOC) is troublesome for drinking water utilities because it reacts with disinfectants used for drinking water treatment to form unwanted byproducts (DBPs) that are harmful to human health and regulated by the EPA. The amount of DBPs that form from Sacramento-San Joaquin Delta water are particularly problematic because of much higher than average concentrations of bromide, a minor component of sea salt contributed in trace amounts by San Francisco Bay. Tidal wetlands, island drains and algal growth in Delta waters compound the issue by adding additional DOC to river water during transit, occasionally resulting in water that could exceed regulatory thresholds for DBPs without blending or some other DBP reduction strategy.

Cognizant of the high cost and technical difficulty of treating Delta water, CALFED has set an average target concentration at drinking water intakes of 50 $\mu g\ L^{-1}$ bromide and 3.0 $mg\ L^{-1}$ total organic carbon, or, if this is not possible through source reduction, a solution that includes additional source waters and treatment technologies which yield the same effective quality. CALFED has also funded several studies that examined DOC both in and upstream of the Delta to assist in managing source water. Recent results from these studies have reshaped our understanding of DOC, indicating that river sources of DOC are more important than previously thought, and that wetlands, floodplains, peat island drains, and other sources all contribute significant amounts of DOC in the Delta.

INTRODUCTION

As California's growing population continues to stress available water supplies, the role of the Sacramento-San Joaquin Delta as a source for drinking water becomes more important. The number of Californian's that drink water originating in the Delta now exceeds 23 million. But as Sacramento and San Joaquin River water transits the Delta in route to drinking water intakes and export facilities, the water quality is affected by the addition of bromide and dissolved organic carbon (DOC).

Bromide is a small component of seawater and is mixed into the Delta from San Francisco Bay by tides and changes in river flow. DOC has numerous sources within the Sacramento and San Joaquin Rivers as well as in the Delta.

Unfortunately, the presence of high concentrations of organic material and bromide cause public health concerns; when treated with disinfectants such as chlorine or ozone, DOC and bromide can form carcinogenic disinfection byproducts (DBPs). The concentration of some DBPs in drinking water is stringently regulated by the EPA.

DOC sources include forests, wetlands, agricultural operations, urban runoff, wastewater, and various other land uses in the watershed as well as

material derived from algal production. DOC is present in river water that flows to the Delta where additional DOC is added. This water largely continues into the San Francisco Estuary where DOC is an essential nutritive material that provides three quarters of the energy necessary for the aquatic microbial foodweb.

Importantly, the chemical composition of DOC affects both the potential for foodweb uptake (and thus natural attenuation) as well as the potential for formation of DBPs. The chemical composition of DOC is a function of its source as well as the processing that occurs in the environments through which it travels. For example, DOC from algae is more rapidly used by aquatic organisms but forms fewer DBPs than DOC derived from wetlands or soils. It is the combination of the source and environmental processing that ultimately determines both the amount and composition of DOC present in the River and Delta waters.

Drinking water concerns

Typically, only a few percent or less of the DOC present in source waters reacts during drinking water treatment to form DBPs that have potential adverse health impacts. There are several types and classes of DBPs that may form, depending on the water treatment process used. Only some of these DBPs are regulated. The most commonly used disinfection process is chlorination, which results in the formation of trihalomethanes (THMs) and haloacetic acids (HAAs), the two most prevelant classes of DBPs. Both classes are currently regulated by the EPA.

But THMs and HAAs are far from the only DBPs that are problematic for drinking water treatment. Over 600 disinfection byproducts have been reported in the literature for the major disinfectants (chlorine, ozone, chlorine dioxide, chloramines), and the regulations are subject to radical changes in thinking as new information and technologies become available. For example, recent EPA regulatory actions have focused attention on sources of material that form highly toxic nitrogen-containing DBPs during ozonation - but ozone is often thought to be the disinfectant of choice for high DOC source waters.

The presence of trace sea water bromide is problematic because it may react during disinfection in two ways. First, when ozone is used for treatment, bromide forms bromate, a regulated carcinogen. Second, when chlorine or other disinfectants are used, bromide reacts directly with the DOC to form DBPs that are more stringently regulated and reputed to be more toxic than their chlorinated counterparts.

As a consequence of the problems with DOC and bromide in Delta waters, to provide safe, reliable and affordable drinking water, CalFed has proposed an average target concentration at drinking water intakes of 50 $\mu g\ L^{-1}$ bromide and 3.0 $mg\ L^{-1}$ total organic carbon, or an equivalent level of public health protection using a cost-effective combination of alternative source waters, source control, and treatment technologies.

SOURCES OF DOC IN THE DELTA

DOC concentration peaks in the late winter and declines through the summer and fall throughout the Sacramento and San Joaquin Valleys and in the Delta (Fig. 1). This is similar to the trend observed in major DOC sources such as

tidal wetlands, peat island drains, and agricultural sloughs. In the Rivers and Delta, DOC concentration exhibits a stronger relationship with temperature than with precipitation, and there is no significant difference in DOC concentration in historic data for the Delta between wet and dry years. Together these observations indicate that DOC concentrations in the Delta are the broad expression of physical and biological processes rather than the contribution of a single or small number of sources.

Processes that produce and release DOC

A complex interaction of landscape attributes, soil, vegetation, hydrologic and biogeochemical processes, management, as well as other factors determines the amount and timing of DOC from the terrestrial and aquatic environments into the surface water system. On a global scale, DOC has been found to correlate to watershed topography, percent of wetlands in the watershed, and average C:N of watershed soils.

Runoff from agricultural fields, natural landscapes, and urban environments may all lead to elevated DOC concentrations in surface waters. Concentrations measured in peat island agricultural drainage waters vary seasonally from 10 to 70 mg/L. Similar seasonal variability is common elsewhere; concentrations in relatively pristine areas of Willow Slough range to over 10 mg/L in the winter. Arcade Creek, which drains an urban area, has spikes of DOC in this magnitude during storms.

But DOC may also arise in soils and move through the groundwater system. It is widely held that DOC in Delta peat island drains may largely result from groundwater flow through oxidized peat soil layers. DOC concentrations in peat soil waters may exceed 100 mg/L. However, peat soils are not necessary to produce elevated DOC concentrations. Soil water DOC concentrations in a San Joaquin Valley field ranged up to 70 mg/L despite having soil organic carbon percentages less than 1.5%.

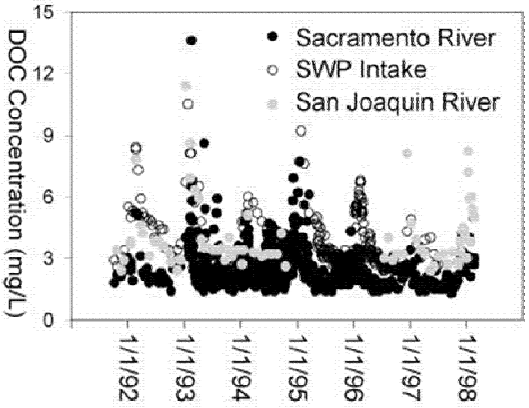

Figure 1. Time series of DOC concentrations in Sacramento and San Joaquin Rivers, and near the Banks Pumping plant, the State Water Project intake. Data from DWR.

Wetland plants and soils may also be a significant source of DOC to the surface water system, particularly where tides may carry the DOC from wetlands into the major channels. Wetland DOC concentrations range may exceed 80 mg/L. However, wetlands are not automatically important sources of DOC; a particular wetland may release insignificant amounts of DOC, depending on its configuration.

Water entering the Delta is replete in nutrients and thus, baring light limitations, conditions are ideal for algal production. However, there is little evidence to suggest that algal production is a major contributor to elevated DOC concentrations in the Delta, likely because algal derived material degrades

more quickly and fully than other sources.

Each of the sources described above add DOC both in the Rivers and in the Delta, but how much is from the Delta itself? Two independent modeling efforts have demonstrated that the Rivers supply the bulk of DOC to the Delta, and that the DOC added in the Delta varies with season. The proportion of DOC from the Delta appears to highest in winter, when it accounts for 50% of the DOC arriving at the Banks pumping plant – the principal drinking water export location in the Delta. This is the period when DOC loads are largest from the rivers to the Delta, but also the time of greatest in-Delta contributions. During periods of low river flow, the proportion of River-derived material apparently increases as a proportion of total DOC, accounting for approximately 75% of the annual average DOC arriving at Banks. Late summer and fall appear to be a period when there is little contribution from in-Delta sources, and river DOC accounts for greater than 80% of the DOC arriving at Banks.

It has long been thought that the DOC added in the Delta was largely from the peat island drains. Most islands in the Delta are highly subsided because of oxidation of their peat soils and thus to offset the influx of water that seeps through the levees and accumulates from irrigation and precipitation, water must be continually pumped off the islands into neighboring Delta channels. Although the concentrations of DOC found in peat island drains are high, and the area of agriculture in the Delta is large, there is an accumulating body of evidence that other sources of DOC within the Delta may be of equal or greater magnitude than the island drains, and that the relative contribution of these sources changes over the course of the year.

A study using a long term record of the composition of DOC at the Banks pumping plant showed that major sources of DOC besides island drains must exist because the composition of DOC at Banks cannot be explained as a mixture of river and island drain DOC. Another study examined the radiocarbon age of DOC in the Delta. The idea was that since peat-derived DOC is old, and River DOC nearly modern, it should be possible to estimate the contribution of island drain DOC. This study found, that the age of the DOC arriving at Banks was not appreciably different from that in the Rivers, confirming that island drains were not a significant source of DOC for most of the year, and indicating there must be a modern source.

Yet another study examined the inputs from rivers and island drains, but also sampled wetlands. It found that the composition of DOC at Banks was best explained as a mixture of river-, wetland-, and island-derived material, with larger contributions from wetlands from early spring, through fall, and larger contributions of island drains in early winter. Other sources likely exist, but they have not yet been studied.

Together, these and other studies demonstrate that there are a number of sources of DOC within the Delta, with substantial variability in their relative contribution during the year. The notion that the island drains are the sole significant in-Delta source of DOC has been replaced by the realization that other in-Delta sources such as wetlands, flood plains and riparian areas appear to be significant sources. Understanding

the impact of these and other sources warrants further study.

DOC quality

One underappreciated aspect of the DOC-DBP story is the extent to which the source and composition – the "quality" – of the DOC may affect the amount of DBPs that form. DOC concentration explains only about 60% of the variability in THM formation (Fig. 2), indicating that the source and processing of material is nearly as important as the concentration. The amount of THMs formed in samples collected from across the Delta varies by a factor of 5, similar to the variability caused by changes in DOC concentration at Banks (Fig. 2). In particular, wetland DOC formed more THMs than most other sources, and island drains had higher HAA formation.

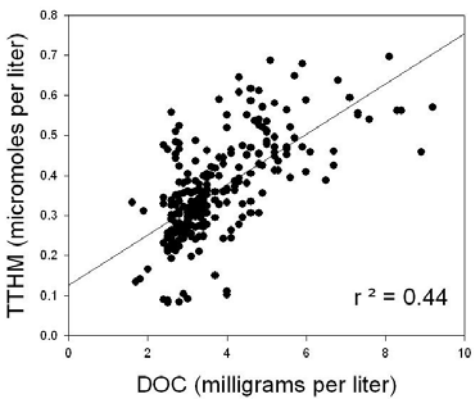

Figure 2. Relationship between the concentration of DOC and the formation of trihalomethanes in samples from near Banks pumping plant. Data from DWR.

These findings should send up a red flag about our knowledge of DBP formation from Delta sources of DOC. Our understanding of DBP sources is based almost entirely on studies of THM and HAA formation during chlorination. Other DBPs formed by chlorination and other treatment schemes will likely also have a similar variability, but with greater amounts forming from a different set of sources. At this time, we simply do not know. Detailed knowledge of the underlying structure and reactivity of DOC in the Delta is necessary to manage water quality as future DBPs are discovered and come under regulation.

TOWARDS A NEW CONCEPTUAL MODEL FOR DOC IN THE DELTA

The results from these recent studies allow us to reform our conceptual model of DOC in the Delta (Figure 3). Rivers, it turns out, supply the majority of DOC found in Delta waters. For all seasons, the greatest proportion (~50-90%) of DOC in the Delta is contributed by the Rivers, with concentrations determined by a combination of runoff timing and basin-wide biogeochemical processes. On an annual basis wetlands and island drains appear to each contribute similar proportions of DOC within the Delta, with island drains contributing a greater proportion in early winter, and wetlands a greater proportion from early spring into the summer. In the late summer and fall, a period of high State Water Project export, there appears to be little addition of DOC in the Delta.

In sum, it is apparent that land-use change or flow alteration in and above the Delta has the potential to affect DOC concentrations at drinking water intakes and export locations. Less certain is the extent to which these changes will affect the propensity of DOC to form DBPs. Flow changes that lower bromide or DOC concentrations at intakes and export locations will improve treatability with respect to currently regulated DBPs. Large scale restoration of tidal wetlands within the Delta has the potential to increase the DOC concentrations, and in particular add DOC that has a high propensity to form

THMs. But, it appears that the contribution of DOC from wetlands may be effectively controlled through design and management. Together these findings demonstrate the need to include DOC, bromide and other drinking water constituents of concern in planning for flow alterations or land use changes in the Delta.

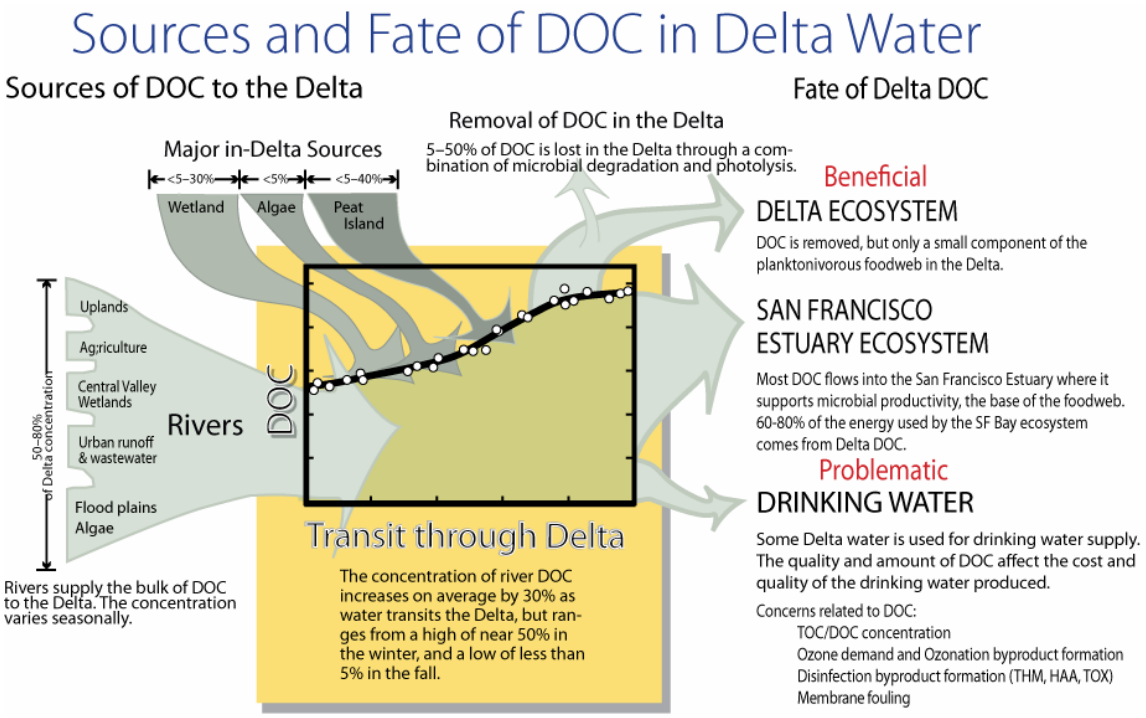

Figure 3. Revised conceptual model for DOC sources and fates in the Delta showing important River and in-Delta sources.