Title
Potential Effects of Organic Carbon Production on Ecosystems and Drinking Water Quality

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Introduction

The quality and quantity of organic carbon produced within, and moving through, the San Francisco Bay or “Bay” (Figure 1) and Sacramento-San Joaquin Delta or “Delta” (Figure 2) are important in regulating ecosystem processes and affects the drinking water quality of over 22 million Californians. Decreased ecosystem productivity has been suggested as a contributing factor to the declines of invertebrates and fishes of concern in the Estuary (combined Bay and Delta) (Bennett and Moyle 1996; Kimmerer and Orsi 1996; Orsi and Mecum 1996). This hypothesis is based on observations that concentrations of chlorophyll-*a* in estuarine water—a measure of standing crop of phytoplankton—have declined and remained depressed since the mid to late 1980s (Jassby and others 2002). Jassby and others (2002) calculated a 43% decline in Delta primary production from 1975 to 1995. The mechanisms proposed for this decline have included export of primary production from the Delta by the federal and state water facilities (see Figure 1) (Jassby and Powell 1994), and consumption of phytoplankton in Suisun Bay by the introduced Asian clam, *Potamocorbula amurensis* (Alpine and Cloern 1992; Jassby and others 2002). However, analyses of the existing data indicate a considerable seasonal and annual variability in the system even after these and some other likely mechanisms are considered (Jassby and others 2002). Whatever the mechanism, reductions in phytoplankton populations—an easily assimilated form of organic carbon (Sobczak and others 2002)—result in less food for upper trophic levels (consumers), including the zooplankton that form a large part of the diet of larval and juvenile fish of most species and for the adults of some species. Furthermore, the Asian clam may also have significant direct and indirect grazing effects on zooplankton that may have additional effects on fish populations (Kimmerer and others 1994; Kimmerer and Orsi 1996; Orsi and Mecum 1996).

The CALFED Bay-Delta Program, a collaborative effort among 23 state and federal agencies, has the basic mission of developing and implementing a long-term comprehensive plan to restore ecological health and to improve water management for the beneficial uses of the Bay-Delta (CALFED 2001). Restoration of tidal wetlands in the Estuary (i.e., the combined Bay and Delta) and especially the Delta is a key feature of the Ecosystem Restoration Program (ERP) of CALFED (CALFED 2001). It has been assumed that restored tidal wetlands will not only provide valuable habitat, but will also produce organic carbon in various forms, such as phytoplankton and fresh detrital matter. Exported to deeper, less productive habitats such as deep channels and bays, this wetland organic matter could support production of fishes and other organisms throughout the Delta.

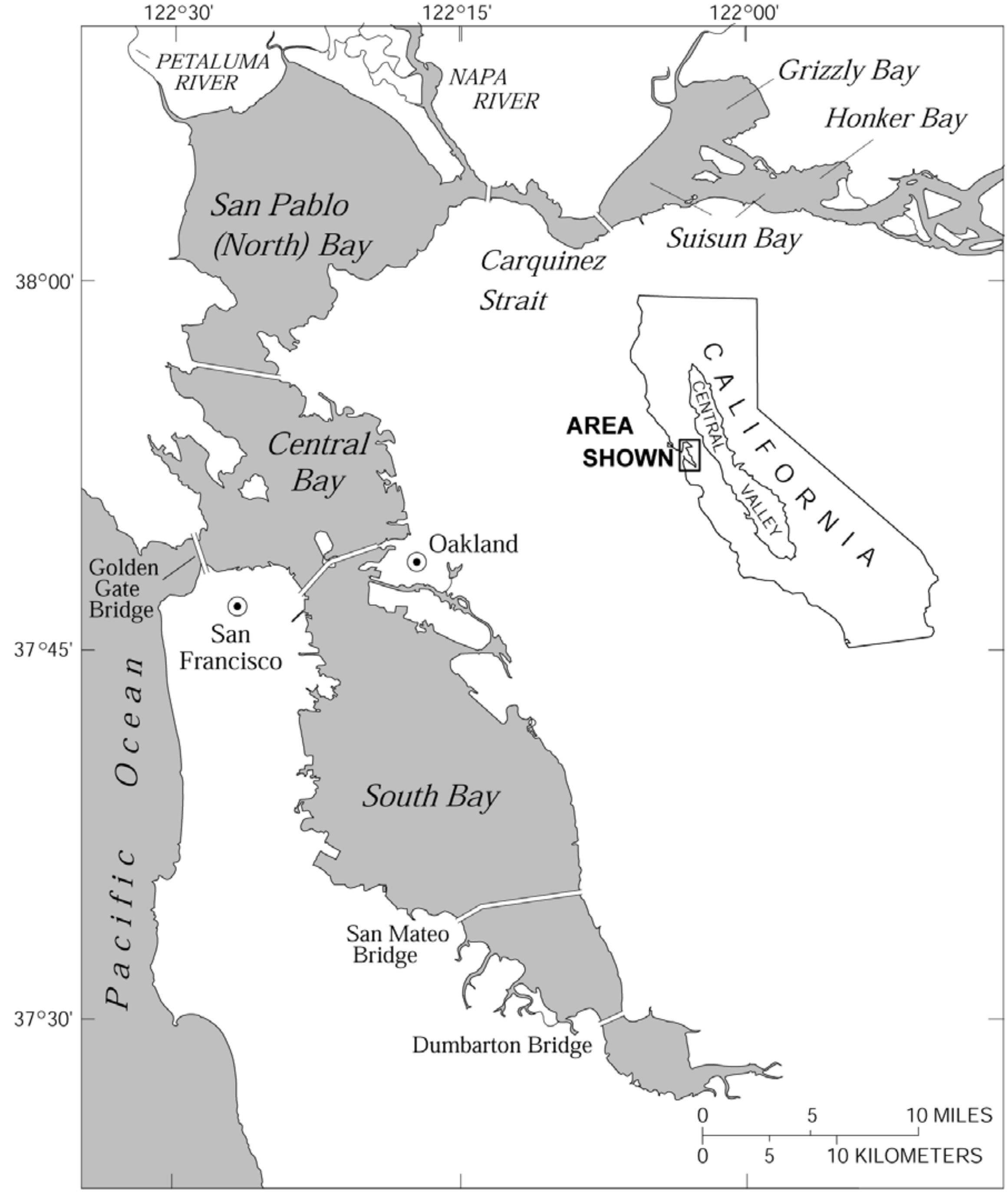

Figure 1 Areas and features within San Francisco Bay

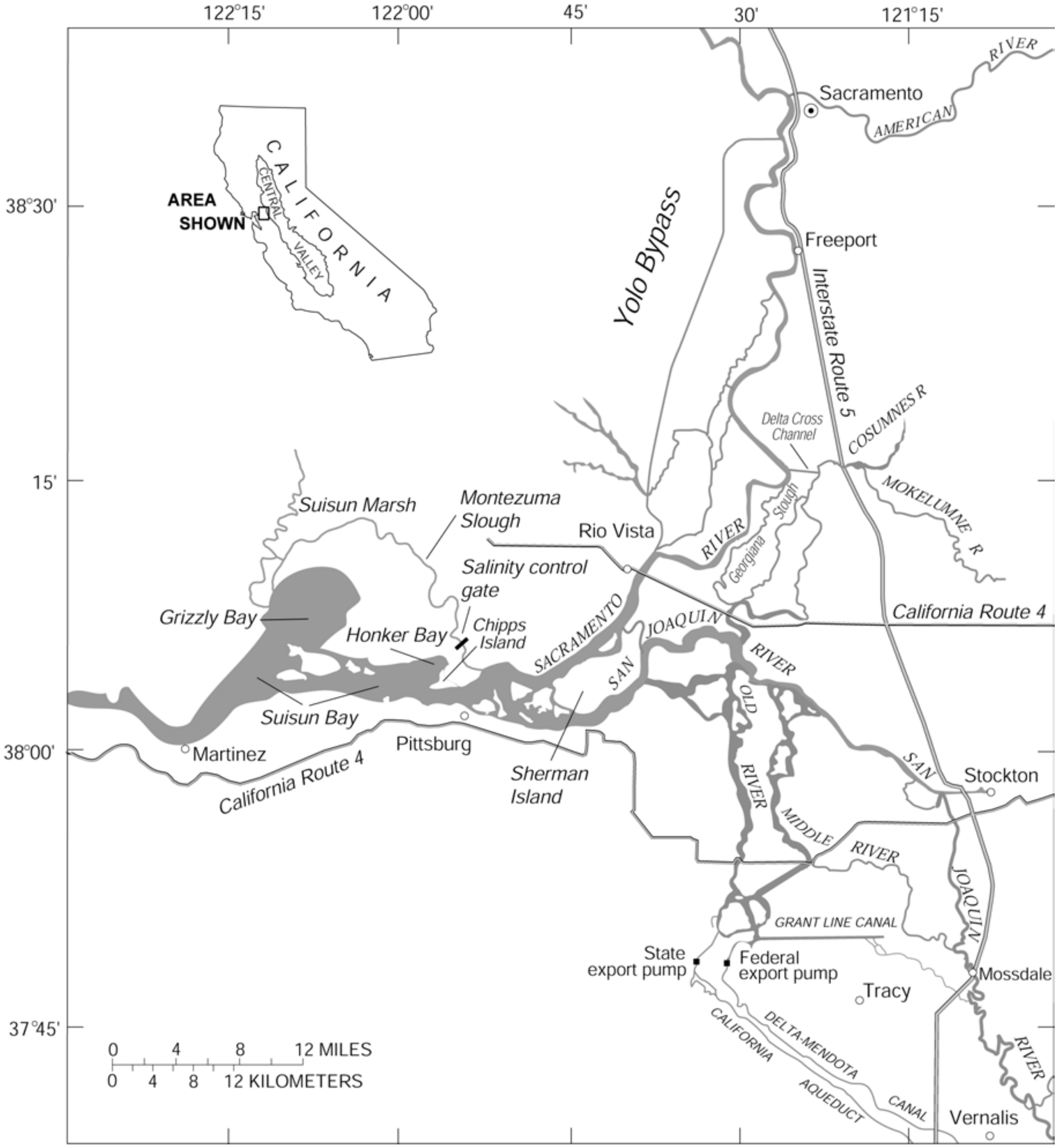

Figure 2 Areas and features within northern San Francisco Bay (west of Chipps Island) and the Sacramento-San Joaquin Delta (Delta). The Delta is approximately defined by Chipps Island to the west, Sacramento to the north, and the river confluence near Vernalis to the south.

Some forms of dissolved organic carbon (DOC), and under some circumstances particulate organic carbon (POC), are important in the formation of a variety of chemicals referred to as disinfection byproducts (DBPs). These compounds are formed during the process of disinfection in drinking water treatment plants. DBPs are of concern for reasons ranging from objectionable odors to human health risks (CALFED 2000) posed by some classes of DBPs including trihalomethanes, haloacetic acids, and bromates. These three classes of DBPs are regulated by the U.S. Environmental Protection Agency (USEPA 1998). Formation of trihalomethanes (THMs) has been a particular concern in Delta waters (CDWR 1994), and this article stresses THMs because recent and ongoing studies provide a sufficient body of information for discussion. Thus, export of organic carbon from restored tidal wetlands in the Delta might have negative effects on water quality for those people using the Delta as a source of drinking water. This is an important issue for CALFED because improving drinking-water quality is also an objective of the program (CALFED 2001). The situation is made even more complex by the fact that agricultural lands on peat soils and managed nontidal wetlands, already provide significant inputs of various forms of organic carbon to Delta waters (Amy and others 1990). It is unclear how conversion of such lands to tidal wetlands will affect the quality and quantity of organic carbon produced.

The purpose of this article is to review existing information on the role of organic carbon in ecosystem processes and in drinking water quality in the Estuary, to evaluate the potential for interactions between the ecosystem and water quality functions of organic carbon with regard to restoration of tidal wetlands, and to consider major uncertainties and potential actions to reduce uncertainty. For the purpose of this article, the “quality” of organic carbon relates to the nutritional value of a source of organic carbon to higher trophic levels when discussed in the context of ecosystem processes and to the potential of organic carbon to form DBPs when discussed in the context of drinking-water quality.

Review and Conceptual Models

Ecosystem Issues

Jassby (1992) and Jassby and others (1993) provided the first estimates of an organic carbon budget for the Bay. They identified a variety of sources of organic carbon to the Estuary including both production within the Estuary (autochthonous), production transported into the Estuary from rivers, land, and atmosphere (allochthonous), and exchange with the ocean (transport sources) (Table 1). Jassby and others (1993) synthesized available information on sources and sinks of organic carbon in the Bay and considered spatial and temporal variability to the extent possible with the available data. Spatially, they considered South San Francisco Bay (South Bay) and the combined San Pablo and Suisun Bay (North Bay) (see Figure 1). In this analysis they considered the Delta as riverine input and Suisun Marsh as a tidal wetlands input.

South Bay and North Bay were dominated by different carbon sources (Jassby and others 1993). South Bay was dominated by phytoplankton production (60%), but benthic microalgae was also important (28%). North Bay was dominated by river inflow (68%) with benthic microalgae production and marsh export as possibly important secondary sources (7% and 6%, respectively). However, the large value for riverine input is somewhat misleading because it includes forms of organic carbon not readily available as food to higher organisms (e.g., recalcitrant detritus and dissolved organic carbon). Therefore, only one-tenth of the actual input was considered as biologically available. Much of the biologically available organic carbon in Delta discharge appeared to be phytoplankton and breakdown products from dead phytoplankton. Comparison of carbon sources and sinks suggested that most organic carbon produced within South Bay was consumed within South Bay (Jassby and others 1993). In contrast, the organic carbon sources for North Bay were larger in magnitude than carbon sinks, largely a result of the less biologically available forms of organic carbon dominating the riverine loading, which passed through North Bay into downstream areas. Jassby and others (1993) also noted that interannual variability was much higher in North Bay because of the importance of riverine inputs, which have large interannual variability caused by annual differences in precipitation.

Table 1 Sources of organic carbon to the San Francisco Bay (Jassby 1992)

Source
Unidirectional sources
Autochthonous sources
Phytoplankton
Benthic microalgae
Seagrasses
Microalgae
Photosynthetic bacteria
Allochthonous sources
Delta discharge
Tidal marsh export
Point source discharges
Surface runoff
Atmospheric deposition
Oil spills
Groundwater
Exchange processes
Circulation and mixing
Dredging activity
Biotic transport

Jassby and others (1993) relied on literature estimates for many variables in their calculations, including several values related to tidal wetlands. Estimates of annual primary productivity for marsh vascular plants throughout the Bay range from 500 to 1500 g dry weight m^{-2} yr^{-1} (Josselyn 1983). Both Atwater and others (1979) and Josselyn (1983) estimated average vascular plant productivity in the Estuary at 800 g dry weight m^{-2} yr^{-1}. The highest values measured were associated with the brackish marsh species, *Spartina californicus* and *Spartina robustus*; however, most of these estimates are likely low because the methods that were used did not include losses to decomposition, tidal export and import, leaching from leaves, and herbivory (Hopkinson and others 1980; Long and Mason 1983). Also, below-ground primary productivity (roots) was not included. Below-ground production has not been measured for Estuary species, but the average root to shoot biomass ratio for Pacific cordgrass has been estimated at 3.6 (Mahall and Park 1976), a value typical of smooth cordgrass (*Spartina alterniflora*) on the Atlantic coast (Good and others 1982). Additional carbon export may also occur from below-ground processes. For example, Yelverton and Hackney (1986) estimated export of 52 g carbon m^{-2} yr^{-1} via pore water flux in a North Carolina *Spartina* marsh. On the basis of the review of literature values, Jassby and others (1993) estimated an export of 150 g carbon m^{-2} yr^{-1} from tidal marsh habitats to adjacent open water habitats. This value represents the net export of organic carbon after all internal tidal marsh processes were considered.

In addition to primary production by emergent macrophytes, such as *Spartina* and *Salicornia*, primary production by benthic microalgae can be important on tidal flats and in vegetated tidal marsh. Benthic microalgae production may be quite high even under relatively closed vascular plant canopies (Zedler 1982). Jassby and others (1993) compiled values from previous reviews and studies and found that most values for benthic microalgae production fell in the range of 50 to 200 g carbon m^{-2} yr^{-1}. They selected the median value of 110 g carbon m^{-2} yr^{-1} for use in their calculations. This value was applied to all shallows within the photic zone.

The work of Jassby and others (1993) was followed by additional studies of organic carbon flux in the Estuary to mainly address primary production (Jassby and Powell 1994; Jassby and others 1996; Jassby and others 2002), the sources and fate of particulate and dissolved organic carbon (Canuel and Cloern 1996; Cloern and others 2002), and the role of microbial organisms in carbon flux (Hollibaugh and Wong 1996; Murrell and Hollibaugh 1998, 2000). Several recent studies have addressed carbon flux from the Delta to Suisun Bay (Schemel and others 1996) and the sources and fate of organic carbon in the Delta (Jassby and others 2002; Müller-Solger and others 2002; Sobczak and others 2002; Lucas and others 2002).

Schemel and others (1996) indicated that the estimate of the allochthonous sources of organic carbon to the Delta in Jassby and others (1993) was too low. Further, organic carbon (and suspended sediment) transport from the Delta to downstream areas was determined to be highly episodic with most transport occurring in large, short-term pulses related to flooding events when the Yolo Bypass transported significant quantities of

Sacramento River flow (Schemel and others 1996). However, the importance of allochthonous sources to the organic carbon budget of the Delta and the estuary as a whole has been based on estimates from literature values of the bioavailability of allochthonous carbon, which may include large portions of recalcitrant detritus. Jassby and others (1996) re-estimated the carbon budget for the estuary and found little effect of higher estimates of riverine input because of decreased transit time during high flows. Jassby and Cloern (2000) have also concluded that primary production within the Yolo Bypass, while important to organisms within the bypass, does not provide a significant additional source of primary production to downstream areas in the Delta because of dilution.

Recent studies in the Delta indicate that phytoplankton production is the dominant food supply to the planktonic food web (Jassby and Cloern 2000; Müller-Solger and others 2002; Sobczak and others 2002). It appears that the dissolved and detrital particulate organic carbon delivered to the Delta does not enter the planktonic food web to a significant degree even though it may support net microbial ecosystem metabolism (Sobczak and others 2002). Laboratory growth assays showed that the growth of the cladoceran, *Daphnia magna*, was dependent on phytoplankton biomass and unrelated to the amount of detrital organic matter (Müller-Solger and others 2002). These results were unexpected because phytoplankton production is usually a minor portion of total organic carbon production in the Delta, and phytoplankton standing crop usually represents only a small portion of the total amount of organic carbon present in the Delta at any time (Jassby and Cloern 2000). The combination of metabolic losses, recalcitrance of detrital POC, and short residence time combine to minimize the importance of riverine sources of particulate and dissolved organic carbon to Delta consumers (Jassby and Cloern 2000). These results suggest that incidental export of phytoplankton associated with water export from the Delta may be more important than originally thought. In the Delta, significant amounts of primary production are exported at the state and federal pumping facilities (Arthur and others 1996; Jassby and Powell 1994; Jassby and others 1993,1996; Jassby and Cloern 2000). Jassby and Powell (1994) calculated that the median chlorophyll exports to water projects exceeded chlorophyll outflow to the Bay by 60% from 1975 to 1989. The importance of phytoplankton production in the Delta was unexpected because the common conceptual model for estuaries is that organic detritus is the most important form of organic carbon. The evolving conceptual model regarding the relative importance of phytoplankton primary production in the carbon budget of the Delta may be particularly important in guiding new research and in evaluating the benefits of various management actions (e.g., Jassby and Cloern 2000; Lucas and others 2002).

Jassby and Cloern (2000) and Lucas and others (2002) considered the effects of several likely ERP restoration strategies on productivity of the Delta. Jassby and Cloern (2000) considered three scenarios: (1) an isolated diversion channel that diverts Sacramento River water before it enters the Delta; (2) fish and flow barriers that alter water flow within the Delta; and (3) increases in floodplain and flooded island habitat. Flooded islands refer to areas presently protected by levees where levees would be breached and the areas allowed to flood, creating areas of shallow water habitat. They concluded that all such actions had potentially important effects on the organic carbon budget of the Delta, but the benefits of such actions varied with season and water year such that neither was clearly better than the others. Lucas and others (2002) considered the flooded island option in more detail and concluded that the production and distribution of phytoplankton biomass can be highly variable within and between habitats of the same general type, such as flooded islands, because of the interaction of hydrodynamics with spatial variability in sources (phytoplankton production rates) and sinks (grazing rates of consumers) of primary production.

Tremendous progress has been made in understanding organic matter dynamics in the Delta, and this growing body of knowledge will clearly be helpful in evaluating various restoration actions (Jassby and Cloern 2000). However, it is significant that tidal wetland habitat has not been examined in detail with respect to the carbon budget of the Delta. The original estimate of 150 g carbon m^{-2} yr^{-1} estimated from literature values by Jassby and others (1993) remains the best estimate of export of organic carbon from tidal wetlands habitat. Jassby and Cloern (2000) note the possibility that export may result from processes that occur only at the margin of tidal wetland areas. If this is the case, then the interior areas of large patches of tidal marsh may contribute little organic carbon to Delta waterways, and edge-to-area relationships may be extremely important in predicting the flux of organic carbon from existing and restored tidal wetlands. This lack of information about Delta tidal wetlands is, in many respects, a historical artifact. The water quality monitoring programs in the Delta are focused on the larger channels that transport water through the Delta to either the export facilities to the south or into the Bay. Fish monitoring has also concentrated on larger channels for ease of sampling and because monitoring has emphasized pelagic species, particularly striped bass (*Morone saxatilis*), chinook salmon (*Oncorhynchus tshawytscha*), and, more recently, delta smelt (*Hypomesus transpacificus*). Further, tidal wetlands had been a minor habitat by the time comprehensive monitoring started in the 1960s, so monitoring of such habitat probably did not seem important. The conceptual model for organic carbon in the Delta in Jassby and Cloern (2000) does suggest a conceptual model for considering the role of tidal wetlands in the carbon budget of the Delta (Figure 3); however, virtually none of the processes depicted have been measured.

Water Quality Issues

The Delta supplies all or part of the drinking water for over 22 million Californians, so water quality in the Delta is extremely important (CALFED 2001). At present, Delta waters sometimes contain sufficient DOC and bromide (Br) to exceed the U.S. Environmental Protection Agency (USEPA) maximum contaminant level for THM when water is chlorinated for drinking water purposes (Amy and others 1990; California Department of Water Resources 1994). Precursors to THM formation include natural organic matter (organic carbon) derived from plant detritus, peat soils, algae, and other sources, and bromide, typically from seawater intrusion, but also from geologically isolated ancient seawater and oil-field brines. The main sources of precursors under present conditions in the Delta have been identified as salt-water intrusion (Br), DOC in drainage water from

Delta islands with peat soils, and various other sources of DOC (California Department of Water Resources 1994). Because of annual and seasonal variability in saltwater intrusion and flooding of soils, there is a great deal of variability in the potential of Delta waters to form THMs (California Department of Water Resources 1994). Various methods have been used for quantification of organic carbon and its propensity for formation of THMs (Table 2).

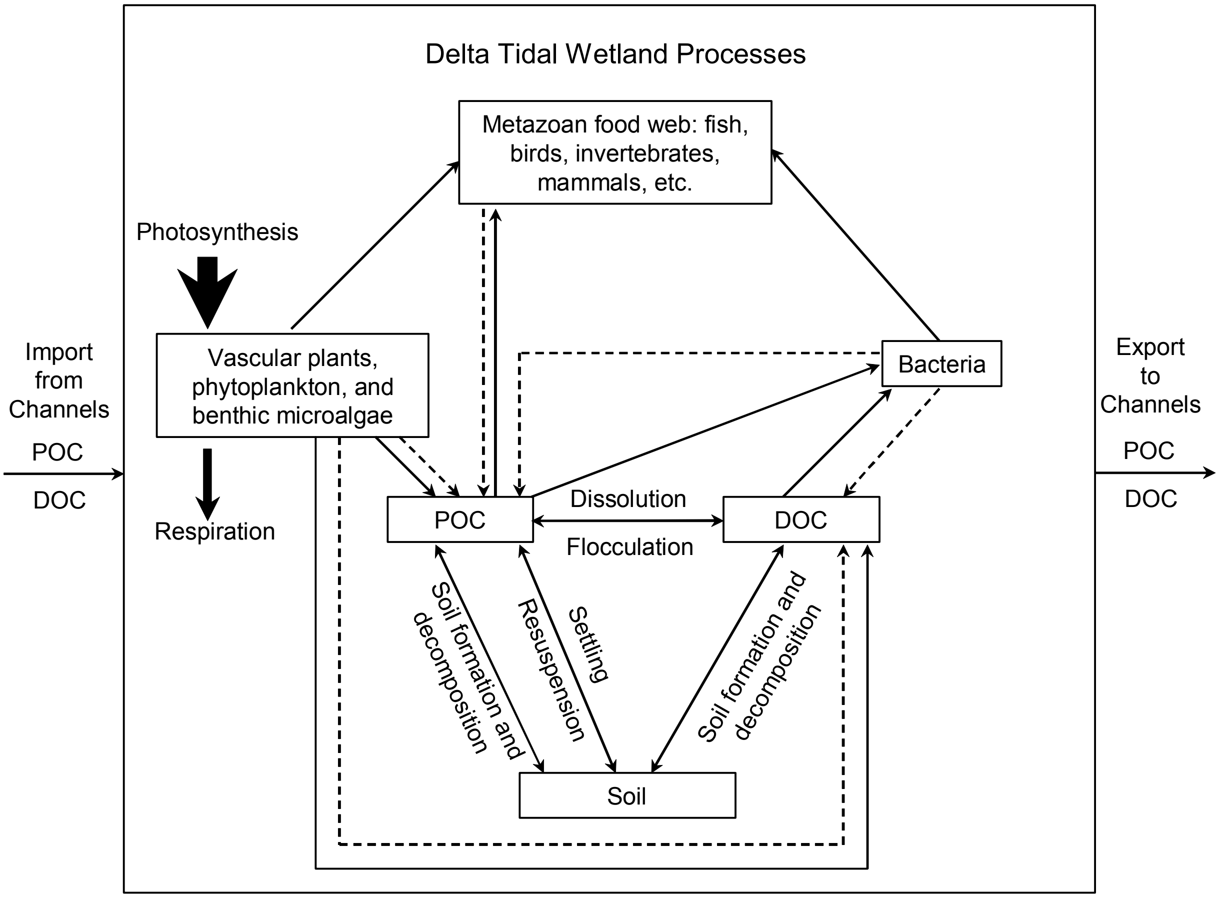

Figure 3 Basic conceptual model for the production and transfer of organic carbon between various pools (indicated by boxes) of organic carbon within the Sacramento-San Joaquin Delta tidal wetlands (adapted from Jassby and Cloern 2000). Solid arrows indicate transfers of material or energy. Dotted arrows indicate transfers resulting from microbial decomposition. Processes within pools of carbon, such as photolysis and hydrolysis within the DOC pool, are not shown. (POC, particulate organic carbon; DOC, dissolved organic carbon).

Table 2 Terms for methods of quantifying organic carbon and the propensity of organic carbon to form disinfection byproducts

Variable	*Code*	*Description*
Dissolved organic carbon	DOC	Mass of carbon atoms per unit volume (mg L^{-1}) in the dissolved form. The dissolved form is defined functionally as all material passing through a filter of some pore size (e.g., 0.45 micron filter)
Particulate organic carbon	POC	Mass of carbon atoms per unit volume (mg L^{-1}) in the particulate form. The particulate form is defined functionally as all material not passing through a filter of some pore size (e.g., 0.45 micron filter)
Total organic carbon	TOC	The sum of DOC and POC
C^{13} nuclear magnetic resonance	C13-NMR	A measure of the aromatic carbon content of a sample. Aromatic carbon molecules include one or more benzene rings.
Ultraviolet absorbance	UVA	Ultraviolet absorbance at 254 nm of a water sample. This measure is used as an indicator of the amount of aromatic forms of DOC present.
Specific ultraviolet absorbance	SUVA	UVA divided by the DOC content. This standardizes UVA on the basis of the amount of organic carbon present, indicates the proportion of absorbing forms of carbon, and indicates the average aromaticity of the DOC in the sample.
Trihalomethane formation potential	THMFP	A measure of the amount of trihalomethane compounds that could be formed from the DOC and bromide in a water sample in the presence of excess chlorine and allowed to react for a specified time, usually seven days.
Specific trihalomethane formation potential	STHMFP	THMFP divided by DOC. By standardizing to DOC, this measure better indicates the reactivity of the DOC in a sample. When expressed on a molar basis (mmoles THMs • mole C^{-1}), STHMFP indicates the number of moles of THMs produced per 1,000 moles of carbon.
Trihalomethane formation potential carbon	TFPC	A measure of trihalomethane (related to STHMFP) formation potential standardized by weight of carbon (STHMFP is standardized on a molar basis or the number of atoms present).

Trihalomethane formation potential or “THMFP” (see Table 2 for a description) and organic carbon concentrations have been monitored in the Delta since the 1980s (California Department of Water Resources 1994). Drainage water from Delta islands, which is pumped over levees into Delta channels, is estimated to contribute from 20% to 50% of the DOC contributing to the formation of THMs in water exported from the Delta by the State Water Project (Amy and others 1990). The main source of this DOC in drainage water is believed to be leachate from organic peat soils (Amy and others 1990). The concentrations and character of DOC in drainage water depends on many factors including frequency of flooding and drying of the soils and the presence or absence of oxygen in the soils (Fujii and others 1998). The sources of the remaining DOC have not been quantified with respect to THM formation, but Jassby and Cloern’s (2000) organic carbon budget for the Delta suggests that riverine inputs might be a major source. Other possible sources include phytoplankton, macrophytes, tidal marsh export, and wastewater discharge (Jassby and Cloern 2000). The importance of peat soils highlights the potential significance of CALFED wetland restoration to water quality issues. Flooding islands with peat soils for restoration purposes inundates remaining peat soils and reestablishes the same tidal wetland processes that led to the formation of such soils over time.

The chemical reactions forming THMs generally involve DOC (such as organic acids); however, under some circumstances POC may also be involved. Dissolved organic carbon is actually a complex mix of substances (Fujii and others 1998). This heterogeneous mixture may include types of organic carbon that vary widely in a number of characteristics including molecular weight, solubility, polarity, chemical reactivity, and availability to organisms. Bergamaschi and others (2000) and Fujii and others (1998) found a poor correlation of specific trihalomethane formation potential or “STHMFP” (see Table 2 for a description) with specific ultraviolet absorbance or “SUVA” (see Table 2 for a description) in Delta drainage water. The accepted model of THM formation assumes that aromatic carbon compounds are more likely to form THMs, which would be reflected in a strong correlation of STHMFP with SUVA. The lack of this correlation suggests that more detailed characterization of the aromatic compounds that form THMs is needed and also suggests that non-aromatic components of DOC may be significant THM precursors in Delta drainage water.

Detailed studies of organic carbon in the Delta suggest that there is considerable variability in reactivity of organic carbon from different sources (Fram and others 1999). SUVA and STHMFP varied widely among different sources of water in the Delta ranging from open channels to agricultural drainage water. In further work, DOC was isolated from Delta waters, then analyzed for SUVA, STHMFP, and aromatic carbon content. Analysis of the data revealed considerable variability in the relationships between the three variables. Bergamaschi and others (2000) also observed wide variability in the quality of organic carbon in Delta waters and noted that the organic carbon at the export pumps did not seem to be a simple mixture of organic carbon from the rivers and from Delta agricultural drains. These results suggest the importance of other Delta sources of organic carbon (upland drainage, wetlands, and algae) that may differ in chemical characteristics and in the physical and chemical processes within the Delta (microbial degradation, flocculation, photolysis) that can change the character of the organic carbon and its likelihood of forming DBPs.

None of these data directly address the issue of conversion of Delta lands, such as farmed islands, to tidal wetland habitat. Some of these issues are being addressed by ongoing research (Fujii and others 1998) in experimental ponds with different physical characteristics and flooding regimes. However, it is unclear how useful these results will be for evaluation of land conversion to tidal wetlands. Because of the tidal exchange of water in and out of tidal wetlands, measurements of concentrations are not sufficient.

Studies of tidal wetlands will require calculations of net flux of organic carbon to Delta waterways. It seems likely that chemical processes and rates might also differ between flooded ponds and tidal wetlands.

Conceptual Model

Although the existing information does not explicitly address tidal wetland issues, consideration of the available data does suggest the outline of a conceptual model. First, sources of organic carbon and processes that modify organic carbon within tidal wetlands must be considered (Figure 4). POC and DOC enter and exit the tidal wetland during water exchanges related to the tidal cycle. This imported organic carbon and organic carbon generated internally through photosynthesis by vascular plants and algae then enter the food web or various chemical cycles within the wetland environment. These internal processes may change the chemical or biological nature of the organic carbon. Some portion of this organic carbon is exported to the deeper channels in a variety of forms ranging from passively transported DOC that might form DBPs to carbon incorporated into the tissues of individuals of special-status fishes.

Sources of organic carbon other than tidal wetlands and Delta hydrodynamics further complicate the situation (Figure 4). Export of organic carbon from tidal wetlands to channels does not necessarily determine the quality and quantity of organic carbon in exported waters. Organic carbon from other sources (e.g., agricultural drainage water) mix with the exported tidal wetland organic carbon. Also, additional ecological and chemical processes occur in the channels, possibly changing the chemical composition and quantity of the exported organic carbon. Tidal water exchange will result in some portion of the organic carbon cycling between channels and tidal wetlands more than once. These processes will likely result in organic carbon in different regions of the Delta having somewhat different chemical characteristics because of the relative importance of different sources, including tidal wetlands.

DBPs are only an issue for water exported from the Delta and subsequently disinfected for use as drinking water. Delta hydrodynamics determine both the residence time of water in the Delta and net flow paths through the system. Any contribution of tidal wetland organic carbon to THM formation will depend not only on the character of the organic carbon produced but also on the location of existing and restored tidal wetlands and hydrodynamic conditions. The conceptual model (Figure 4) also does not include temporal variability. As discussed earlier, the quality and quantity of organic carbon entering and exiting the Delta and the extent of salt water intrusion supplying bromide, changes considerably depending on flow conditions.

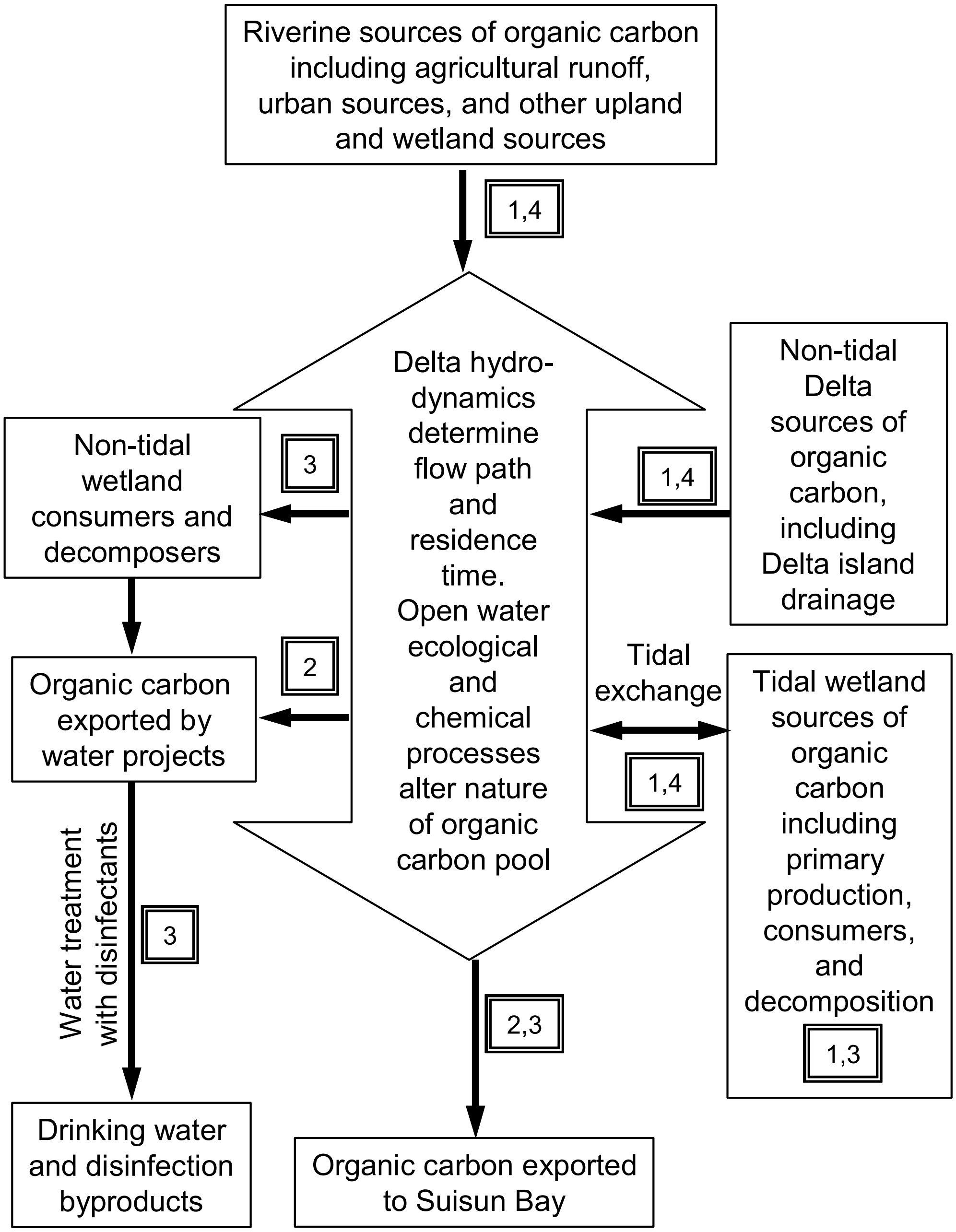

Figure 4 A simple conceptual model of the processes that determined the quality and quantity of organic carbon exported to Suisun Bay or out of the Sacramento-San Joaquin Delta by the water projects. Numbers correspond to the major uncertainties identified in the text: (1) sources of organic carbon, (2) transport processes, (3) quality of organic carbon, (4) management actions. The location of the numbers indicates where a major uncertainty is particularly important in the conceptual model. Addressing these uncertainties is key to understanding and managing the system.

Evaluation of Problem

On the basis of the review by Jassby and others (1993), it is clear that restored tidal wetlands will export organic carbon to adjacent deep water habitats, but the specific quantity is unknown and the degree of enhancement to upper trophic levels or potential formation of DBPs is unknown. Some fraction of the DOC exported from tidal wetlands will likely be very reactive in formation of DBPs; however, it is unclear how important this contribution will be in quantity and reactivity compared with other sources of DOC. It also seems likely that organic carbon export from a restored wetland can be expected to change as the wetland evolves over time (Orr and others 2003). Another important factor is the construction method used to restore the wetland. Agricultural land that is opened to tidal action for wetland restoration might export more organic carbon than agricultural land that is covered with clean dredge spoils as part of project construction. The situation becomes even more complex when considering trade-offs among different land uses, such as converting Delta island agricultural lands to permanent wetlands, seasonally flooded wetlands, tidally influenced wetlands, water storage areas, or maintaining agriculture, but treating drainage water before returning it to Delta waterways. The data are insufficient at this time to choose among any of the alternatives with high confidence. If tidal wetlands produce organic carbon that is less likely to form DBPs than the organic carbon in agricultural drainage from peat soils, then restoration of tidal wetlands near the pumps might be an advantage rather than a detriment for drinking water exports. If the opposite were true, then tidal wetland restoration would be targeted for locations distant from diversion points. This issue potentially has great importance in determining locations for restoration actions.

Despite the data gaps detailed above, it is clear that knowledge of organic carbon sources and processes is progressing rapidly. The continuing refinement of carbon budgets from the early efforts of Jassby (1992) and Jassby and others (1993) to the more detailed budgets of Jassby and Cloern (2000) and Jassby and others (2002), suggests that approximate answers to many questions may be possible on the basis of simple models, existing data, and estimates from literature values. In many respects, the interaction between the ecosystem restoration and water quality issues can be viewed as the simple mass-balance model:

$$\text{Change in Delta TOC} = \text{TOC from restored tidal wetland} - \text{TOC from current use}$$

However, there is considerable complexity hidden within each element of the equation. Considering just the TOC from tidal wetlands, one might want to know the proportion of DOC and POC, the proportion of POC easily consumed by higher trophic levels, the chemical composition of the DOC, the STHMFP of the exported carbon, the location of the restored tidal wetland and whether the exported organic carbon is likely to be diverted from the Delta for use as drinking water on the basis of the results of hydrodynamic models. Many of these complexities have already been incorporated into the conceptual models presented in this article (see Figures 3 and 4). The remaining challenges include linking the tidal wetland model (see Figure 3) with the export-transport model (see Figure 4), determining or estimating quantities or rates, and determining how to incorporate regional and seasonal variability and hydrodynamics. Balancing the complexity of a model against the required accuracy of predictions will be a challenge. Jassby and Cloern (2000) provide a valuable model for how such work might proceed.

It is interesting to note that conflicts over organic carbon in the Delta are not restricted to ecosystem and drinking water quality issues. CALFED is currently funding work regarding a zone of oxygen depletion in the San Joaquin River near Stockton, which forms in the fall of some years, and inhibits upstream migration of adult chinook salmon into the San Joaquin River system (Lehman 1999; Kevin Wolf & Associates 2002). Decomposition of organic material, including phytoplankton, from the San Joaquin River is suspected to be a major factor causing the oxygen depletion. If this suspicion is correct, management actions to solve the oxygen depletion problem would likely include reductions in nutrient loading in the San Joaquin River system to control phytoplankton production upstream of Stockton. Alternatively, Jassby and Cloern (2000) identify the San Joaquin River as a rich source of organic matter that has important potential compensatory effects on productivity of the Delta in the context of management strategies that would otherwise decrease productivity of the system. Thus, there might be a trade-off between solving the oxygen depletion problem and maintaining the productivity of Delta waters. This and similar conflicts among management endpoints are likely to occur throughout the CALFED program (Jassby 2001).

Major Uncertainties

The major uncertainties regarding organic carbon in the ecosystem and drinking water quality are intertwined (Figure 4), suggesting that much will be gained by coordinating activities among the various technical and management groups who address the two topics. The uncertainties regarding organic carbon exports from restored Delta tidal wetlands are clearly only a subset of the water quality concerns overall; however, the tidal wetland issues may be perceived as especially important because of the possible conflicts between ecosystem and water quality goals and associated proposed actions. The major uncertainties are reflected in the organic carbon export conceptual model (Figure 4) and include:

1. **Sources and fate of organic carbon.** Regarding drinking-water quality, the issues are the quantity and potential of organic carbon from the different sources in the Delta to form THMs and other DBPs of concern. Ecosystem issues revolve around the different types and amounts of organic carbon production possible in tidal wetlands including primary production by benthic microalgae, vascular plants, and phytoplankton. The resulting primary producer biomass is consumed by higher trophic levels within tidal wetlands, exported to open water systems for consumption, or decomposes, possibly to the detriment of drinking water quality.

2. **Transport.** How do location of tidal wetlands (or other sources of organic carbon) and hydrodynamics interact to determine if tidal wetland organic carbon is exported by the water projects or exported into Suisun Bay?

3. **Quality of organic carbon.** Ecologically, this relates to the nutritional value and bioavailability of a source of organic carbon to consumers. In drinking-water quality this relates to the potential of organic carbon to form DBPs. Ecologically, DOC and POC that are derived from decomposing plant material appear to be of fairly low importance in supporting higher trophic levels. In contrast, DOC is very important for drinking water quality. Conceptually, minimizing DOC export from restored tidal wetlands would be beneficial; however, it is unclear how such reductions could be accomplished for large areas of tidal wetlands.

4. M**anagement actions that affect sources, transport, and quality.** Each class of the proposed management actions is interactive with the others. Flooding of agricultural lands on Delta islands for wetland restoration represents a trade-off of agricultural sources of organic carbon for tidal wetland sources of organic carbon. Similarly, selection of tidal wetland restoration sites to maximize connections with upland habitats might represent a different set of conditions for organic carbon quality and quantity. Site selection for tidal wetland restoration could be important depending on Delta hydrodynamics. DOC produced in tidal wetlands from one geographic area of the Delta may be much less likely than another to reach a drinking water intake. Tidal wetlands downstream from the Delta in the Bay should have little or no effect on water quality concerns because water from those areas is not generally exported. A partial list of management actions that could affect organic carbon quality and quantity include:

    a. Changes in agricultural management practices on Delta islands to decrease the quantity of agricultural drainage.

    b. Treatment of agricultural drainage water before discharge to reduce DOC.

    c. As already discussed above, tidal wetland restoration may affect drinking water quality depending on a number of factors including geographic location and hydrodynamics. Methods of construction, initial organic carbon content of soils, and management of the restored wetlands will all be important in determining the quality and quantity of organic carbon produced.

    d. Riverine sources of organic carbon from agricultural and municipal point and nonpoint sources might be reduced.

    e. Changes in discharge of the Sacramento and San Joaquin rivers related to other CALFED actions (e.g., water management decisions, environmental water account actions) could affect the quantity of organic carbon exported at the water facilities. Similarly, changes in facility operations or water storage options (e.g., in-Delta storage in flooded Delta islands) could affect organic carbon quality and quantity in exported water.

Addressing Uncertainties

The techniques and concepts to address the uncertainties outlined above are now available for both ecosystem (Jassby and Cloern 2000; Sobczak and others 2002; Müller-Solger and others 2000; Lucas and others 2000) and drinking water quality (Fujii and others 1998; CDWR 1994) applications. These and other tools are currently being applied in a variety of studies regarding various aspects of organic carbon in the Estuary (Bergamaschii 1999; Cloern 2001; Fujii 1999; Lehman 1999; Sickman 2002), including application to the tidal wetland restoration problem. However, the need to consider tidal flux of organic carbon to open waters does add considerable complexity. Only carefully designed experiments will provide the data needed to reduce uncertainty. These new studies may decrease the uncertainty regarding tidal wetlands organic carbon and may help focus new research to further reduce uncertainty.

One possible strategy for addressing uncertainties is to use the carbon budget of Jassby and Cloern (2000) as a framework for further studies that would focus on better characterizing the role of tidal wetlands. An interdisciplinary group including ecologists and experts in drinking water quality issues should design the studies. Completed, ongoing, and proposed tidal wetland restoration projects, and the remaining areas of natural wetlands in the Delta, provide a wide variety of opportunities for project specific assessments of many of the issues discussed in this article, such as restoration project size and design. Similar, more detailed assessments of carbon sources to the Delta other than Delta island drainage would also be useful in assessing the effects of land use changes. In all cases, sustained long-term data collection will be necessary to reach strong conclusions. As additional data are gathered, numerical models could be developed or existing models improved such that informed decisions can be made regarding any trade-offs necessary between ecosystem and drinking water quality objectives.

Conclusion

Although much has been learned about the role of various forms of organic carbon in ecosystem processes and drinking water quality of the Delta, the contribution of tidal wetlands to the carbon budget remains essentially unexplored. There appear to be no overt constraints to the study of tidal wetland and drinking water quality interactions. Coordination and integration of new studies and programs by an interdisciplinary team would likely be useful in gathering the data needed to make informed decisions. Early coordination and integration would also be beneficial in minimizing perceived conflicts as study results become available and in avoiding real, negative effects of projects that can only be corrected by additional expenditures of money.

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