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Effects of Flow Diversions on Water and Habitat Quality: Examples from California's Highly Manipulated Sacramento-San Joaquin Delta

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ABSTRACT

We use selected monitoring data to illustrate how localized water diversions from seasonal barriers, gate operations, and export pumps alter water quality across the Sacramento-San Joaquin Delta (California). Dynamics of water-quality variability are complex because the Delta is a mixing zone of water from the Sacramento and San Joaquin Rivers, agricultural return water, and the San Francisco Estuary. Each source has distinct water-quality characteristics, and the contribution of each source varies in response to natural hydrologic variability and water diversions. We use simulations with a tidal hydrodynamic model to reveal how three diversion events, as case studies, influence water quality through their alteration of Delta-wide water circulation patterns and flushing time. Reduction of export pumping decreases the proportion of Sacramento- to San Joaquin-derived fresh water in the central Delta, leading to rapid increases in salinity. Delta Cross Channel gate operations control salinity in the western Delta and alter the freshwater source distribution in the central Delta. Removal of the head of Old River barrier, in autumn, increases the flushing time of the Stockton Ship Channel from days to weeks, contributing to a depletion of dissolved oxygen. Each shift in water quality has implications either for habitat quality or municipal drinking water, illustrating the importance of a systems view to anticipate the suite of changes induced by flow manipulations, and to minimize the conflicts inherent in allocations of scarce resources to meet multiple objectives.

KEYWORDS

Sacramento-San Joaquin Delta, diversion, water management, numerical modeling, water quality

SUGGESTED CITATION

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INTRODUCTION

Water flow through California's Sacramento-San Joaquin Delta (Delta) is manipulated to satisfy multiple objectives, including: exports to meet distant agricultural and municipal demands and routing of flows with barriers or gates to facilitate migration of salmon, enhance flushing to prevent anoxia, or repel salt intrusion that degrades drinking water quality. Each hydraulic manipulation is implemented to satisfy a specific, often geographically localized objective. However, localized diversions can have regional-scale consequences, some unintended and conflicting with other management objectives.

Hydrodynamic models can be applied to identify and measure the processes through which localized diversions influence regional-scale flow paths and water quality, building toward a broad ecosystems perspective of the exceedingly complex and highly manipulated Delta. While a systems perspective is inherent in single-objective water operations, it has not been developed to guide the broader challenge of optimizing allocation of California's water supply to satisfy agricultural and municipal demands and sustain effective strategies of ecosystem restoration. Increasingly challenging conflicts of water allocation motivate the search for a consensus vision of the Delta's future (Mount et al. 2006), and the visioning process requires quantitative approaches for assessing the ecosystem-scale consequences of multiple hydraulic manipulations. Here we illustrate how diversions through gate, barrier, and pump operations can rapidly change water quality conditions within the Delta. These changes have important implications for habitat quality and sustainability of the Delta's native biota.

The spatial patterns and temporal variability of water-quality indicators in the Delta are complex and driven by natural processes, such as seasonal river flow or tidal oscillations of salinity gradients (e.g. Figure 1A,B) or oscillations of dissolved oxygen over the diel light cycle (Figure 1C). Water-quality indicators also shift, sometimes rapidly, in response to water diversions. Here we use a tidal hydrodynamic model to explore cause-effect relationships between flow manipulations and shifts in water quality using three diversion events as case studies: salinity increase in the central Delta when pumped exports were curtailed (Figure 1A); salinity increase in the lower San Joaquin River when gates were closed at the Delta Cross Channel (Figure 1B); and oxygen depletion in the Stockton Ship Channel when a temporary barrier across Old River was removed (Figure 1C). Model simulations explain how each diversion alters the flow path, source mixture, and flushing rate of water within the Delta, providing mechanistic and spatially-explicit representations of how diversions influence water quality.

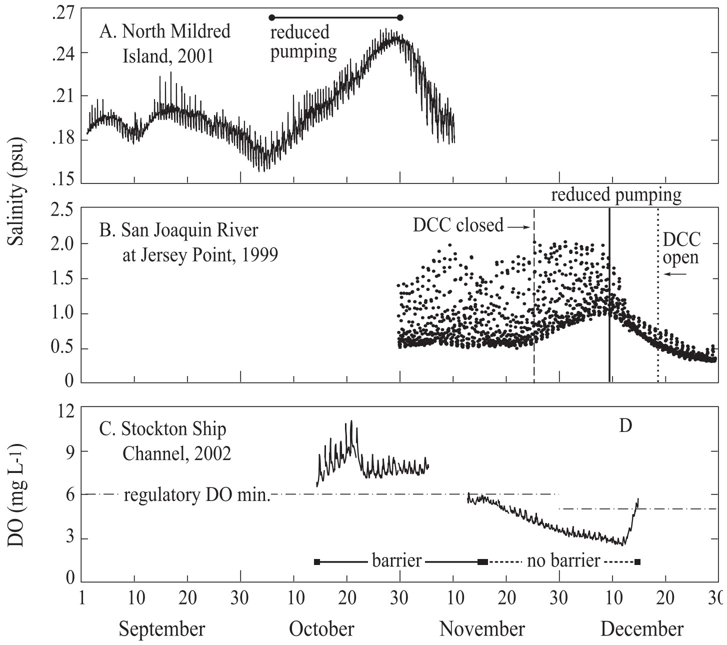

Figure 1. Water quality time series data used in three case studies. (A) Salinity measured 1 m above the channel bottom at the northern opening of Mildred Island. (B) Salinity measured at Jersey Point (San Joaquin River). (C) Dissolved oxygen concentration 1 m below the surface in the Stockton Ship Channel at Rough and Ready Island.

The effects of individual water operations on water quality have been learned empirically over time, but the underlying mechanisms of those effects, their interactions, and their spatial complexity have not been clearly established. Our goal here is to illustrate the value of simulations with hydrodynamic models to understand how diversions modify the routing and rates of water flow through the Delta, and how these modifications influence water quality through their alteration of source mixtures and flushing rates. We view this as a step toward a comprehensive understanding of how diversions interact with other processes to influence habitat quality and sustainability of diverse native biota, including species on the brink of extinction in the Delta ecosystem.

BACKGROUND AND STUDY DESIGN

The Delta is the convergence zone of two large rivers (Figure 2), the Sacramento and San Joaquin, draining a 153,000 km^2 watershed that captures runoff from winter-spring rainfall in the Central Valley and spring snowmelt in the Sierra Nevada mountains. The Delta, formerly a 1,400-km^2 wetland (Atwater and others 1979), has been transformed into a patchwork of agricultural tracts surrounded by leveed channels, tidal lakes and remnant patches of marsh. As the transition zone between a large river-watershed and San Francisco Bay, the Delta is a migration route for anadromous fish such as salmon, sturgeon, and shad, and permanent habitat for native species such as Delta smelt and Sacramento splittail.

The Delta is the hub of a water-development infrastructure that captures runoff during the wet season and transfers an average of 7.1 km^3/year (1995 level of development) from the north to the south and coast during the dry summer-autumn (CDWR 1998). The Sacramento contributes the largest volume of freshwater inflow to the Delta, with daily median flows ranging seasonally from 320 to 1230 $m^3\ s^{-1}$. The San Joaquin, which has several significant diversions upstream of the Delta, is a smaller river by volume with daily median flow between 36 and 150 $m^3\ s^{-1}$ (www.iep.water.ca.gov/dayflow/, median based on data from water years 1956-2001). In contrast, tidal flow at the Delta's western boundary is typically in the range of ±8500 $m^3\ s^{-1}$.

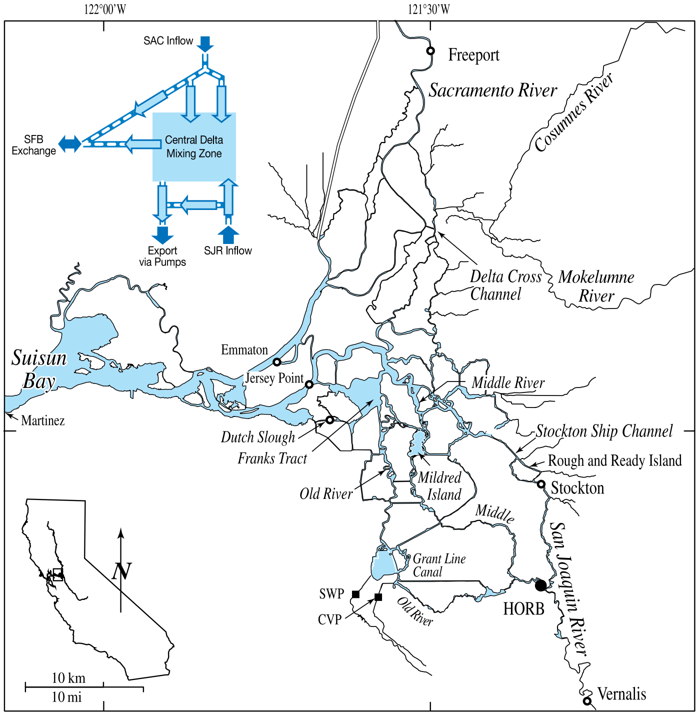

Figure 2. Map of the Sacramento-San Joaquin Delta. Inset: Schematic illustrating the base flow routes through the Delta.

Upstream reservoir releases are routed across the Delta to provide drinking water for 22 million people in coastal cities, and supply water to over 18,000 km^2 of irrigated farmland producing crops valued over $13 billion annually (CDFA 2002). These interbasin transfers are pumped from the south Delta (Figure 2) by the State Water Project (SWP) and the Central Valley Project (CVP). The daily median export from the SWP and CVP ranges between 63 and 292 $m^3\ s^{-1}$ (www.iep.water.ca.gov/dayflow/, median based on data from water years 1956-2001). Over 2,200 diversions from Delta channels also supply water for municipalities and irrigation of local farmland (Herren and Kawasaki 2001).

The challenge of satisfying multiple demands on the Delta's water resource is complex because this critical habitat for native species is a mixing zone of estuarine brackish water and three primary sources of fresh water, each having distinct water chemistry (Table 1). The San Joaquin River contains a large fraction of irrigation drainage and has high concentrations of dissolved salts, nutrients, organic carbon, and toxic contaminants such as selenium (Table 1). The Sacramento River is less impacted by upstream agricultural inputs and has low concentrations of these constituents. Agricultural drainage from peat-rich Delta soils is highly enriched in dissolved organic carbon. In addition to these freshwater sources, tides transport brackish estuarine water into the Delta during periods of low river inflow, degrading drinking water quality and agricultural supplies.

Inflows to the Delta are manipulated by an array of diversions, and we illustrate examples from operations of three diversion types: (1) exports from the South Delta through pumping by the SWP and CVP; (2) gates that divert flows from the Sacramento River into the

Table 1. Water quality comparison between the Sacramento River, San Joaquin River, and In-Delta Agricultural Return water for water years 1999-2001.

Water Quality Parameter	Sacramento at Freeport [1]	San Joaquin at Vernalis	In-Delta Agricultural Return Water [2]
Specific Conductance (mmhos cm^{-1})	144 ± 28	621 ± 183	562 ± 206
pH	7.8 ± 0.2	8.0 ± 0.4	6.8 ± 0.4
Alkalinity (mg $CaCO_3$ L^{-1})	55 ± 12	85 ± 24	83 ± 18
Dissolved Oxygen (mg L^{-1})	9.8 ± 1.4	9.6 ± 1.4	5.5 ± 2.1
Nitrite+Nitrate (mg N L^{-1})	0.12 ± 0.05	1.62 ± 0.59	
Orthophosphate (mg P L^{-1})	0.024 ± 0.007	0.107 ± 0.054	
Dissolved Organic Carbon (mg C L^{-1})	1.84 ± 0.53	2.83 ± 0.47	14.1 ± 7.7
Total Dissolved Selenium[3] (nmol L^{-1})	0.91 ± 0.27	8.6 ± 2.5	Negligible[4]

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[1] USGS Water Quality Database (WY1999-WY2001) for Sacramento (USGS 11447650) and San Joaquin (USGS 11303500) rivers unless otherwise noted.

[2] California Department of Water Resources Municipal Water Quality Investigations Program (WY1999-WY2001) for Bacon Island Pumping Plant (DWR B9V75881342), and Twitchell Island Pumping Plant 1 (DWR B9V80661391) (CDWR 2003); DOC data only from Bacon Island. Different crops produce varying levels of DOC, agricultural return water DOC is expected to vary significantly throughout the Delta.

[3] Sacramento river average from two studies (1984-2000). San Joaquin average from 1997-2000 sampling period. (Cutter and Cutter 2004)

[4] Personal communication AR Stewart, 14 May 2003

central Delta via the Delta Cross Channel; and (3) a barrier placed at the head of Old River to maintain flows in the San Joaquin River (see Figure 2). We use selected time series data to illustrate the coherent responses of water-quality indicators to operations of these diversions, and then use a hydrodynamic model to identify the transport mechanisms of those responses. We use salinity as an example of an indicator that is influenced by changing source mixtures of water within the Delta, and dissolved oxygen (DO) as an example of an indicator influenced by both transport processes and biogeochemical reactions.

METHODS

Data Sources

The primary data source was the archive of federal and state monitoring data maintained by the Interagency Ecological Program (IEP, www.iep.water.ca.gov). Electrical conductivity is measured at Emmaton, Jersey Point, and Dutch Slough (Figure 2) by the U.S. Bureau of Reclamation. Salinity at these locations was computed from electrical conductivity using water temperature measured by the California Department of Water Resources (CDWR) at Rio Vista (Sacramento River) and Antioch (San Joaquin River). We used these salinity records as an indicator of water-quality responses to operations of the Delta Cross Channel gates during autumn 1999. The CDWR measures near-surface DO continuously within the Stockton ship channel, and the U.S. Geological Survey (USGS) measures San Joaquin flow both at Vernalis, upstream of Old River, and at Stockton directly upstream of the Stockton ship channel (Figure 2). We used flow and DO measurements during autumn 2002 to illustrate effects of a barrier diversion.

We also used results from a study to measure transports and water quality dynamics in Mildred Island, located in the central Delta (Figure 2). Moored instruments measured electrical conductivity, temperature, and velocities through the major entrances to Mildred Island and surrounding channels every 10 minutes from 22 August through 14 November 2001 (for detailed methods see Lucas et al. 2006). Velocity was converted into flow (Simpson and Oltmann 1993), and salinity was computed from temperature and electrical conductivity measured with Seabird sensors. We used flow and salinity measurements around Mildred Island to illustrate shifts in freshwater source resulting from changes in export pump operations.

Numerical Modeling

We used the multi-dimensional hydrodynamic model Delta TRIM3D to identify the transport processes of water quality variability induced by each diversion. Gross et al. (1999) incorporated scalar transport routines into the TRIM3D hydrodynamic computation core developed by Casulli and Cattani (1994). Monsen (2001) created a Delta specific version of the model (Delta TRIM) that incorporated Delta bathymetry and hydraulic structure operations. Delta TRIM has been calibrated and compared to measured stage, flow, and salinity under a variety of flow boundary conditions and hydraulic operations (Monsen 2001). The model was run in two-dimensional mode to calculate depth-averaged stage, velocity, and scalar concentrations at 150,000 points on a 50-m grid with a 40 second time step. All model simulations were ramped up for at least a 24 h simulation period before the introduction of scalars or discrete particles.

Delta TRIM was run for the periods August-December 2001 and August-December 2002, using a tidal boundary condition as measured stage at Martinez and flow boundary conditions as discharge of the Sacramento River at Freeport and San Joaquin River at Vernalis (Figure 2). All pump and gate operations, within-Delta diversions and placement/removal of barriers were represented in the model. Model simulations were used to compute source mixtures of water from concentrations of conservative scalars introduced at the model boundaries as tracers, and flushing times from the displacement of discrete particles.

Water Source Composition

Water at any location was assumed to be a mixture of three sources: Sacramento, San Joaquin, and “other ” water. The “other ” category included bay, agricultural return, and “old” water (having a residence time greater than the simulation period). The total scalar mass (M_{TOT}) in a water column is the sum of scalar masses from each source:

$$(1) \quad M_{TOT} = M_{SAC} + M_{SJR} + M_{OTHER}$$

Re-writing equation (1) in terms of source concentrations (C_{SAC}, C_{SJR}, C_{OTHER}) and water column volume (V_{TOT}):

$$(2) \quad C_{TOT}V_{TOT} = C_{SAC}V_{TOT} + C_{SJR}V_{TOT} + C_{OTHER}V_{TOT}$$

where C_{TOT} is the scalar concentration from all sources. We divided equation (2) by $C_{TOT}V_{TOT}$ to calculate the mass fraction from each freshwater source at any location (equation (3)).

$$(3) \quad 1 = \frac{C_{SAC}}{C_{TOT}} + \frac{C_{SJR}}{C_{TOT}} + \frac{C_{OTHER}}{C_{TOT}}$$

Because the numerical model conserves mass (Gross et al. 1999), we traced Sacramento and San Joaquin source waters as two different scalars. The total scalar concentration, C_{TOT}, was fixed at a constant value at each river boundary. Boundary conditions for the Sacramento source scalar were $C_{SAC} = C_{TOT}$ at the Sacramento boundary (Freeport) and $C_{SAC} = 0$ at all other boundaries. Similarly for the San Joaquin source scalar, the boundary conditions were $C_{SJR} = C_{TOT}$ at the San Joaquin boundary (Vernalis) and $C_{SJR} = 0$ at all other boundaries. In the domain interior, both the Sacramento and San Joaquin tracer concentrations were initialized to zero at all grid cells at the beginning of the simulation.

During the simulation, scalar concentrations at all grid cells in the region of interest (e.g. Mildred Island) were recorded hourly. Although inflows, exports and gate operations changed constantly, tracer concentrations approached quasi-steady state distributions. Based on equation (3), the fraction of water originating from any source (i.e. Sacramento or San Joaquin) in a grid cell was the scalar concentration divided by the total concentration (C_{TOT}).

Flushing Time

Flushing time is an integrative parameter that describes the general exchange characteristics of a water body. We used Delta TRIM to compute an e-folding flushing time in which a number (P_o) of neutrally buoyant particles was introduced into the model domain of interest (Monsen et al. 2002). Trajectories of each particle were calculated each time step based on the model velocity field (e.g. see Lucas et al. 2002, Figures 3-5), using the method of Cheng et al. (1993). The e-folding flushing time (T_f) was calculated from a linear regression of the time series of the number of particles, P(t), remaining in the domain of interest every hour using the equation:

$$\ln P(t) = -\left(\frac{1}{T_f}\right)t + \ln P_o \tag{4}$$

RESULTS AND DISCUSSION

The effects of each diversion are generalized in schematics showing water sources and transport paths linked to the central Delta (Figure 3). Fresh water is delivered as inflows from the Sacramento and San Joaquin Rivers, exported as pumped diversions by the SWP and CVP, and mixed with estuarine waters by tidal exchange with the San Francisco Estuary. The central Delta network of channels and open water regions is a dynamic mixing zone where the source mixture of water changes with fluctuating river discharge, tides, and export rates (Figure 3A). The source mixture is not uniform throughout this mixing zone. For example, the mixture on Middle River (Figure 2) can be different from Old River at any time. Flow paths are modified by closure of DCC gates that route fresh water into the Sacramento River (Figure 3B), and by seasonal construction of the head of Old River barrier to route flows into the San Joaquin River (Figure 3C).

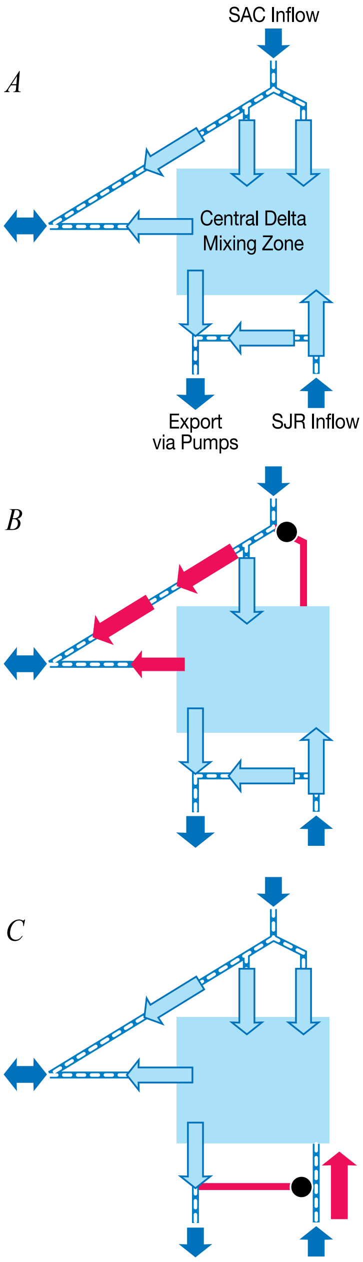

Figure 3. Schematics illustrating how diversions alter flow routing through the Delta. Dark blue arrows represent fresh water inputs to and exports from the Delta. The bi-directional arrow represents tidal exchange of Delta water with San Francisco Bay. Red denotes flow alterations caused by each diversion. (A) Base flow routes repeated from Figure 1, inset. (B) Closing gates at the Delta Cross Channel redirects flow to the Sacramento River toward San Francisco Bay and away from the central Delta. (C) The head of Old River barrier directs San Joaquin flow to the central Delta mixing zone rather than to the south Delta toward the export pumps.

Export Diversions Alter Regional Flows and Salinity Distributions

The SWP reduced its exports between 7 October and 31 October 2001 (Figure 4A). This pumping curtailment allowed more fresh water to exit the Delta through its western boundary (Figure 3A), which, as intended, lowered salinity in the western Delta. However, the salinity response in the central Delta (Mildred Island) was opposite and unexpected: bottom salinity increased steadily at the northern opening of Mildred Island (Figure 4B) and at all other sampled locations in/around Mildred Island between 7-31 October 2001. Flow measurements and model simulations indicate that this salinity increase was caused by a shift in dominant freshwater source from the low-conductivity Sacramento (Table 1) to the high-conductivity San Joaquin.

The SWP and CVP pumps draw water from both the south Delta and the central mixing zone (Figure 3A). The draw of the pumps is large enough to redirect the net flow in nearby channels toward the export facilities, altering regional circulation patterns. Mildred Island is bounded by two north-south channels (Middle River and Latham Slough) and two east-west channels. It is separated from these deeper channels by (leaky) levees with discrete openings at the north and south. Flow measurements revealed an altered circulation pattern throughout the Mildred Island region as a result of altered pump operations. During the September period of high SWP export, the mean net (tidal residual) north-to-south flow via Middle River just north of Mildred Island was 100 $m^3 s^{-1}$. In October when exports were curtailed, the mean flow fell to 56 $m^3 s^{-1}$. Because less water was drawn toward the pumps, the net southerly residual flow was reduced in the Mildred Island region. In some locations, the direction of net flow reversed.

The shift in net north-to-south flow around Mildred Island was primarily due to changes in pump operations rather than significant changes in Delta hydrology. During September and early October 2001, the tidally averaged Sacramento inflow (at Freeport, Figure 2) ranged from 350-380 $m^3 s^{-1}$ and the San Joaquin inflow (at Vernalis) ranged from 35-45 $m^3 s^{-1}$. During the period of pump reduction, the tidally averaged Sacramento inflow (at Freeport) ranged from 200-300 $m^3 s^{-1}$ and the San Joaquin inflow (at Vernalis) had a pulse inflow that peaked at 82 $m^3 s^{-1}$ on 28 October.

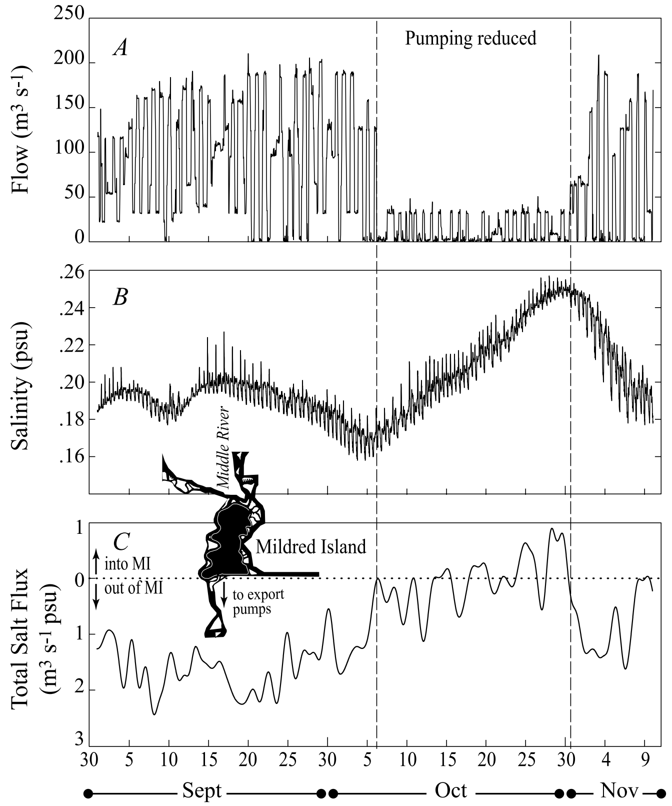

Figure 4. State Water Project exports alter salinity in Mildred Island (central Delta) in autumn 2001. (A) SWP export rate from 1 September–14 November 2001. (B) Salinity 1 m above the channel bottom at the northern opening of Mildred Island. (C) Advective salt flux at the southern opening of Mildred Island. Inset: map of Mildred Island and the surrounding channels. Data sources: State Water Project pump operation data: IEP database station CHSWP003. Salinity and flow data (22 Aug 2001–14 Nov 2001) from Lucas et al. (2006).

Simulations with Delta TRIM show how this modification of circulation altered water composition as a shift in dominance from Sacramento to San Joaquin water. Sacramento water can be transported toward the export pumps through either Old or Middle River (Figure 2). When export pumps operate at high capacity, Old and Middle Rivers become a freshwater corridor of

Sacramento-derived water. On 6 October 2001, immediately prior to pumping reduction, the Mildred Island region was dominated by Sacramento-derived water (Figure 5a). However, San Joaquin source water dominated the region on 6 November, after a month of pump curtailment when the Sacramento freshwater corridor was constricted to Old River (Figure 5b). The San Joaquin source of water increased inside Mildred Island (Figure 5d) because the regional mass balance changed: less Sacramento-derived water entered from the north and more San Joaquin derived water exchanged with Mildred Island from the channel at its southeast corner.

Pumping curtailment also altered the exchange rate between Mildred Island and its surrounding channels. Total salt flux (<qc>) was computed for the south opening of Mildred Island as the tidally filtered product of flow (q) and salinity (c) (Fischer et al. 1979). During peak SWP exports in late September, the salt flux was directed out of Mildred Island toward the export pumps (Figure 4C). After pumping was curtailed, the salt flux was significantly reduced and, during some short periods, it reversed as salt entered Mildred Island from the channels adjacent to its southeast corner.

The coherent changes in flow and salinity around Mildred Island with pump operations illustrate how exports generate regional responses. Salinity in the central Delta changed almost instantaneously with changes in export diversions occurring 25 km away. Simulations with a hydrodynamic model reveal how pump curtailment altered local exchanges and regional flows such that low-conductivity Sacramento water was gradually replaced with high-conductivity San Joaquin water. However, this shift in source mixture was not spatially uniform (Figure 5) because the routing of Sacramento-derived water was modified differentially within Old River and Middle River. Hydrodynamic models provide a tool for discovering and understanding the spatial complexity of water quality dynamics and their responses to diversions.

Delta Cross Channel Diversions Alter Source Water Distributions

The Delta Cross Channel (DCC), a 1,100 m long, 8 m deep trapezoidal channel in the north Delta (Figure 2), diverts high-quality Sacramento River water into the central Delta. Flows are controlled by gates that are normally kept open to maintain cross-Delta flows. The DCC gates are closed in late summer and autumn, when inflows are low and estuarine salinity intrusion peaks, to facilitate salmon emigration. During an extreme salinity intrusion event in November 1999, low river flow and high pump exports co-occurred and created a conflict between DCC operations to (a) repel salt intrusion to meet salinity standards (gates open, Figure 3A) and (b) route flows and juvenile salmon down the Sacramento River (gates closed, Figure 3B). Salinity across the western Delta changed rapidly in response to DCC operations during this period (Figure 6A-C).

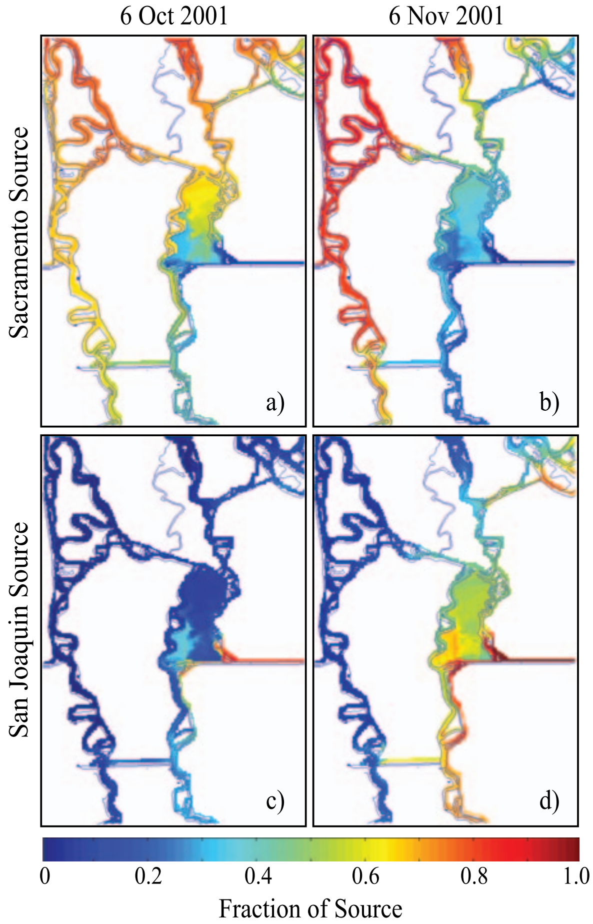

Figure 5. Model-computed fractions of Sacramento (a, b) and San Joaquin River (c, d) source water at each grid cell around Mildred Island on 6 October 2001 (a, c), immediately prior to reduced pump operations, and on 6 November 2001 (b, d) after a month of pump curtailment.

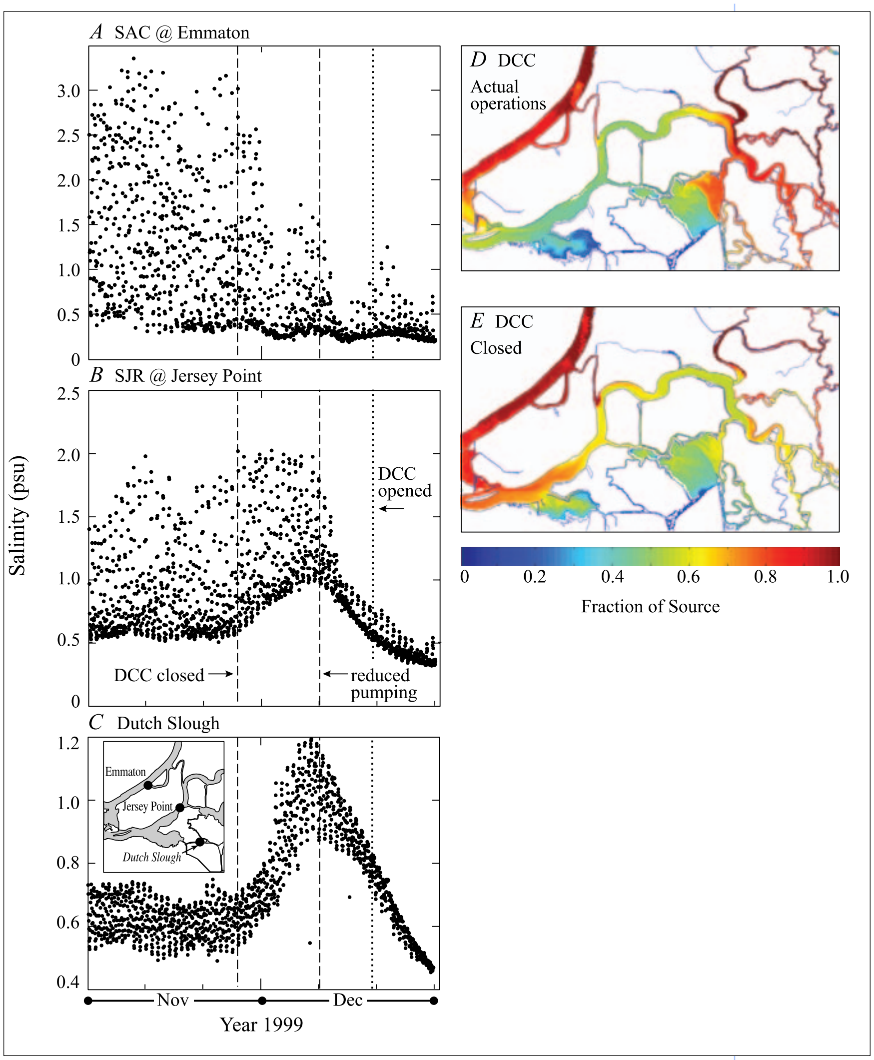

Figure 6. Influence of Delta Cross Channel gate operations on salinity intrusion during November-December 1999 at (A) Emmaton, (B) Jersey Point, and (C) Dutch Slough (inset: map of the region). Data source: IEP Database: electrical conductivity (Station: RSAC092, RSAN018, SLDUT007), water temperature (Station: RSAC101, RSAN007), Delta Cross Channel gate operations (Station: RSAC128), and export pump operations (Station: CHSWP003, CHDMC004). (D) Color maps show the distribution of modeled Sacramento source water on 13 September 2001, comparing simulations with (D) actual operation of the Delta Cross Channel and (E) Delta Cross Channel gates closed for the entire simulation.

The DCC gates were closed on 26 November as the salmon migration began. This closure altered the circulation pattern in the north Delta by directing more Sacramento water down the main stem of the Sacramento away from the central Delta (see Figure 3B). As a result, less fresh water was available in the central Delta to prevent salinity intrusion on the San Joaquin stem of the western Delta. Salinity decreased at Emmaton on the Sacramento River, but tidally-averaged salinity increased almost immediately on the San Joaquin at Jersey Point and Dutch Slough (Figure 6A-C). Salt intrusion into the San Joaquin progressed until export pumping was curtailed on 10 December in an effort to prevent chloride concentrations from exceeding the 250 mg L^{-1} chloride standard at Rock Slough (CDWR 2001). Export pump curtailment resulted in more San Joaquin-derived fresh water entering the western Delta, repelling intrusive sea water and reducing salinities at both Jersey Point and Dutch Slough. Despite reduced export pumping, the chloride level continued to rise at Rock Slough eventually averaging 258 mg L^{-1} on 20 December. Although the salmon emigration was still in progress, DCC gates were re-opened on 15 December to repel salt intrusion on the San Joaquin stem of the western Delta, further lowering salinity at Jersey Point and Dutch Slough (Figure 6B,C).

To investigate how regional circulation patterns are altered by DCC gate diversions, we compared two modeling simulations using autumn 2001 hydrologic conditions to represent typical autumn inflows and exports. Delta hydrodynamics were simulated for 9 August-13 September 2001, under scenarios of: (a) actual DCC operations in which the gates were open except for short (4-6 h) closures during 2 weeks in August; and (b) closure of DCC gates for the entire period. We then mapped the fractions of Sacramento River water after 35 days of simulation, when the model attained a quasi-steady state.

When the gates were open, the eastern central Delta, including northeast Franks Tract, was dominated by Sacramento water (Figure 6D). In contrast, when the DCC gates were closed, less Sacramento water reached the eastern side of the central Delta because less Sacramento water was transferred to this region via the Mokulemne channels (Figure 6E). Since the Sacramento and San Joaquin rivers have different electrical conductivity (Table 1), changes in DCC operations altered salinity across the central Delta including the large shallow habitat of Franks Tract.

This second example illustrates how a localized diversion in the north Delta can influence regional-scale water quality through its modification of the flow paths of Sacramento- and San Joaquin-derived river water. The spatial complexity of this response is evident in monitoring records showing concurrent salinity decreases in the lower Sacramento River and salinity increases in the lower San Joaquin River (Figures 6A-C). Simulations of scalar transport provide a clear visualization of the hydraulic response to DCC gate closure. These visualizations reveal the fine-resolution spatial complexity underlying the differential salinity responses measured at a few fixed locations (Figure 6D,E). The Delta is subjected to multiple diversions and this example highlights the compounding effect of gate and export operations on salinity distributions (Figures 6A-C).

Old River Barrier Diversions Alter Flushing and Dissolved Oxygen

The San Joaquin River splits into two channels as it enters the Delta: Old River carries flows west toward the export pumps, and the San Joaquin River carries flows north toward the central mixing zone (Figure 3A). The head of Old River barrier (HORB), a temporary rock wall (~ 70 m x 5 m), is constructed at this branch twice a year. In spring this barrier directs emigrating salmon seaward via the San Joaquin River, and in autumn it amplifies flows through the Stockton Ship channel to preclude oxygen sags that occur under stagnant hydraulic conditions (Figure 3C, Jones and Stokes 2005b). This barrier is removed each year during the wet season to protect local levees from flooding.

The linkage between barrier operations and oxygen dynamics is illustrated with monitoring data showing the progressive decrease of DO concentration in the Stockton ship channel, a deep section of the San Joaquin River downstream of the HORB, immediately after the barrier was removed on 15 November 2001 (Figure 7A). San Joaquin flows above and below the Old River junction during autumn 2002 illustrate the effect of this barrier on the routing of river inflow. The San Joaquin inflow (at Vernalis, Figure 2) was relatively steady (~45 $m^3\ s^{-1}$) from mid-October to mid-December (Figure 7B). Similar-magnitude flows below the Old River branch (at Stockton, Figure 2) show that most of the San Joaquin inflow was, as intended, routed along the northerly transit when the HORB was in place. After the barrier was removed on 15 November, most San Joaquin inflow was routed into Old River and, as a result, the net flow at Stockton fell near or below zero (Figure 7B). These records reveal barrier-controlled modification of south Delta circulation, dominated by northerly San Joaquin flow (Figure 3C) when the head of Old River barrier is present, and westerly flow (Figure 3A) when it is absent.

The Stockton ship channel has chronic problems of DO depletion below 6 mg L^{-1}, the regulatory level set to protect biota sensitive to hypoxia (CVRWQCB 1998). Several studies have identified residence time as a key mechanism of hypoxia (Jassby and Van Nieuwenhuyse 2005, Jones and Stokes 2005a), but none have explicitly calculated transport time scales in the Stockton ship channel and their sensitivity to barrier placement and removal. Model simulations provide a tool for quantifying the hydraulic flushing rate of water in the Stockton Ship Channel under scenarios of HORB emplacement and removal.

We used Delta TRIM simulations driven with autumn 2001 and 2002 hydrologic conditions to compute flushing times in Stockton ship channel when the HORB is in place and removed. Neutrally buoyant particles were released in the Stockton ship channel. Particle trajectories and the number of particles remaining within the Stockton ship channel were recorded each hour. Because the phase of the tide at release time influences particle trajectories, 24 different initial release times were simulated for each day. Three hundred and fifteen particles were introduced at the beginning of each release time. We recorded the number of particles remaining in the Stockton ship channel hourly for 145 hours after release on 14 August 2002 (barrier in, Figure 7C) and 5 December 2002 (barrier out, Figure 7D).

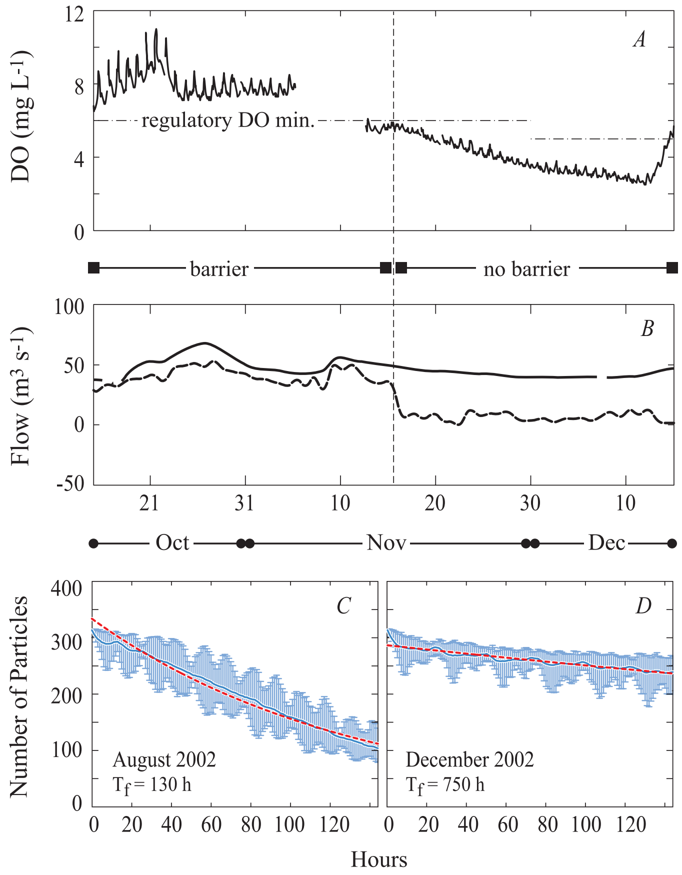

Figure 7. Influence of head of Old River barrier removal on DO concentrations in the Stockton Ship Channel during autumn 2002. (A) Dissolved oxygen 1 m below the surface in the Stockton Ship Channel at Rough and Ready Island; (B) San Joaquin flow at Vernalis (solid line) and tidally-averaged flow at Stockton (dashed line). (C-D) Model-based calculations of flushing time Tf for (C) August 2002 (Tf = 130 h) and (D) December 2002 (Tf = 750 h). Vertical bars represent the range of particle numbers remaining after t hours for all 24 simulations. The solid line represents the mean number of particles each hour. The dotted lines are time series of mean particle numbers from equation (4). Data sources: IEP database: dissolved oxygen (CDWR; Station: RSAN058) and San Joaquin flow (USGS; Station: RSAN063, RSAN112) and, CDWR Bay-Delta Office: Temporary barrier operating schedule (http://sdelta.water.ca.gov/web_pg/tempmesr.html).

These simulations showed > 5-fold increase in flushing time in the Stockton Ship Channel after the HORB was removed: in August 2002 (HORB in) the mean flushing time Tf was 130 h; in December 2002 (HORB out) Tf was 750 h. During early December, the tidally-averaged flow at Stockton was almost zero (Figure 7B). As a result, Tf calculated by the model during this period are highly sensitive to the model representation of tidally-averaged flow, which is underestimated by Delta TRIM because of poorly resolved bathymetry and model representation of the Old River-San Joaquin River junction. Therefore, Tf calculated for 5 December 2002 (Figure 7D) is best interpreted as an upper bound on the flushing time for this December 2002 period.

To test the sensitivity of model representation of flushing time with respect to San Joaquin flow, we did a second series of simulations forced with autumn 2001 hydrology when inflow at Vernalis was more variable, ranging from 40-60 $m^3 s^{-1}$. The flushing time for 8 August 2001 (HORB in) was 100 h, similar to the August 2002 simulation result. The flushing time for 5 December 2001 (HORB out) was 400 h, approximately half the value calculated for December 2002. In the December 2001 simulation, the tidally-averaged flow represented by the model at Stockton was close to the tidally-averaged flow measured in the December 2002 case. Therefore, T_f calculated for December 2001 by the model is an estimate of the lower bound on flushing time in the Stockton Ship Channel for December 2002 hydrology when the HORB is removed.

Based on these simulations, we concluded that, as a rule of thumb, the flushing time for the Stockton Ship Channel during autumn periods is on the order of days when the HORB is in place, and on the order of weeks when this barrier is removed. The calculation of flushing time was highly sensitive to the model representation of tidally-averaged flow, especially in low flow conditions. As with any calculation of transport time, the specific values calculated by a model are only applicable to the specific time period simulated and should not be assumed as absolute values for all periods (Monsen et al. 2002).

CONCLUSIONS: IMPLICATIONS FOR THE DELTA ECOSYSTEM

Diversions to meet society's demand for reliable water supply have often had surprising consequences. The Egyptian High Aswan Dam reduced nutrient inputs from the Nile to the Mediterranean Sea, resulting in collapse of sardine and prawn fisheries (Nixon 2003). Diversions exposed the Aral Sea bed, creating salt and dust storms with catastrophic effects on human health and agricultural production (Micklin 1988). Levee construction around Colombia's Ciénaga Grande de Santa Marta cut off freshwater supplies and killed extensive areas of mangrove forest (Perdomo et al. 1998). Diversions along China's Yellow River caused the river to dry up approximately 600 km from the river's mouth, with no outflow for 226 days in 1997, causing seawater intrusion and wetland recession in the delta area (Cai and Rosegrant 2004).

Tools are available to anticipate environmental consequences of flow diversions, and our purpose here is to illustrate the application of hydrodynamic models to understand how different diversion types modify water source mixtures, flow paths, and rates. Each hydraulic effect has consequences for water quality, and we conclude with a discussion of how each might also drive changes in the capacity of the Delta ecosystem to sustain communities of native biota.

Source Mixtures

Water quality in the Sacramento-San Joaquin Delta has an unusually large spatial heterogeneity because its subregions contain different mixtures of water from multiple origins, each having distinct chemical composition. We used monitoring data and a hydrodynamic model to illustrate how patterns of spatial heterogeneity change in response to gate and export diversions, using salinity as a tracer of river water from different sources. This approach can be expanded to learn how diversions alter the concentration fields of other chemical constituents such as land-derived pollutants. Selenium is a priority pollutant in San Francisco Bay, originating from mobilization of Se-enriched soils by irrigation in the San Joaquin River basin and accumulating in food webs downstream, leading to potentially toxic levels in consumers, including white sturgeon and Sacramento splittail (Stewart et al. 2004). Selenium concentrations are 8-85 times higher in the San Joaquin than the Sacramento River (Cutter and Cutter 2004), so the concentration of dissolved selenium across the Delta waterscape is expected to vary with the ratio of San Joaquin:Sacramento water. We can hypothesize that as diversions modify this ratio they alter selenium concentrations, just as they alter salinity distributions.

Processes that change concentration fields of pollutants are ecologically important because the toxicity and accumulation of pollutants in food webs are concentration dependent. The new pyrethroid pesticides are extremely toxic to invertebrates with sublethal effects at concentrations measured in parts per trillion (Oros and Werner 2005); the herbicide diuron inhibits phytoplankton photosynthesis in the Delta at concentrations $> 2\ \mu g\ L^{-1}$ (Edmunds et al. 1999); phytoplankton accumulate methyl mercury at concentrations 10,000 times those in water (Davis et al. 2003); bioaccumulation of toxic metals (e.g. copper, cadmium, silver, chromium) in invertebrates and fish depends on concentrations of those elements in water and prey (Luoma and Rainbow 2005). We have learned empirically how individual diversions modify salt concentrations across the Delta, but we have not yet considered how they modify distributions of land-derived pollutants and their threats to wildlife or human health.

Transport Routes

The Delta is an exceedingly complex network of channels, sloughs, and shallow open waters connected to a tidal estuary and large rivers. We used flow measurements and hydrodynamic simulations to illustrate how diversions, as intended, modify the routing of water through this network to meet multiple objectives. Pumped exports deliver fresh water to agricultural and municipal consumers; the Delta Cross Channel moves low-salinity Sacramento water into the central Delta and improves water quality delivered to exports and municipal intakes; seasonal barriers alter the routing of San Joaquin River water to facilitate fish migrations and prevent anoxia. The consequences of these altered flow routings are known for salinity and DO, but the broader suite of ecological consequences has not been explored systematically. This knowledge gap constrains our capacity for designing effective strategies to sustain or rehabilitate native species and their supporting ecological functions.

Some diversions, such as the HORB and DCC, are operated to direct the seaward or landward migrations of salmonids. However, other biological and ecological responses to diversion-induced flow routings are poorly known and most have not yet been considered. Pumped exports and within-Delta diversions cause entrainment loss and increased predation of endangered/threatened species of fish such as Delta smelt (Bennett and Moyle 1996). A key uncertainty of the Delta ecosystem is the extent to which diversion-induced mortality contributes to population declines of native biota. Recent analyses show that routing paths matter: entrainment (salvage) of juvenile and adult Delta smelt at the SWP and CVP are strongly correlated with combined flows in Old River and Middle River (Smith et al. 2006).

Flow routings have potentially large impacts on ecosystem functions, such as primary and secondary production in pelagic food webs that sustain native fish. Agricultural diversions and pumped exports remove phytoplankton biomass equivalent to 30% of annual within-Delta primary production (Jassby et al. 2002). This loss at the food web base reduces the Delta's carrying capacity for consumers in this low-productivity ecosystem where food limitation is pervasive across trophic levels (Lopez et al. 2006), and it significantly reduces the supply of algal-derived organic matter from the Delta to the San Francisco Estuary (Jassby et al. 2000). Diversion-induced alterations of hydraulic exchange across habitats (Figure 4c) may also alter production efficiency. Modeling analyses indicate that overall ecosystem primary and secondary production increase in proportion to the transport rate of algal food supplies from shallow donor habitats, such as Mildred Island to deep recipient channel habitats (Cloern 2007).

Flushing Time

We also used the hydrodynamic model to illustrate how diversions modify flushing time, an index of water replacement rate within individual habitats. The seasonal depletion of dissolved oxygen in the San Joaquin River at Stockton shows how water quality is influenced by the balance between rates of competing processes: microbial metabolism that removes oxygen and advective-dispersive replacement of oxygen-deficient water with oxygenated water. Model simulations show that DO depletion occurs in the Stockton Ship Channel when the flushing time is longer than several weeks, but not when the flushing time is less than one week (Figure 7). This result is consistent with BOD measurements indicating that the half life of oxygen-consuming constituents is about 12-15 days in the lower San Joaquin River (Volkmar and Dahlgren 2006). Flushing times longer than this characteristic time of oxygen consumption lead to local oxygen depletions. DO depletions are critical habitat degradations because they can be direct causes of mortality or impede migrations of salmonids (Jassby and Van Nieuwenhuyse 2005).

The DO example illustrates how the dynamics of reactive constituents are determined by time scales of both transport and biogeochemical reactions, and how these dynamics become dominated by biogeochemical transformations as transport time scales are lengthened by water diversions. Transport time scales are critical attributes of aquatic ecosystems (Monsen et al. 2002) and we expect that many other components of water quality respond when diversions alter transport rates. Massive algal blooms develop in the lower San Joaquin River under low-flow conditions of long flushing time (Jassby 2005). Detailed mapping across Mildred Island revealed significant spatial variability characterized by highest water temperatures and highest phytoplankton biomass within side embayments isolated from strong tides and having long residence time (Lucas et al. 2006). These retentive, high-biomass subhabitats are zones of enhanced algal and bacterial assimilation of dissolved selenium and transformation into particulate forms available to consumers (Baines et al. 2004). The Delta functions as a biogeochemical transformer of reactive substances as they are transported from land runoff to San Francisco Bay. For example, the Delta removes 60-80% of the river input of dissolved selenium, and this removal efficiency decreases as the water residence time decreases (Meseck and Cutter 2006). Therefore, hydraulic manipulations that lengthen (shorten) flushing time will amplify (diminish) the magnitude of biogeochemical transformations, and therefore modify the net downstream transport of contaminants and other reactive constituents to San Francisco Bay.

Toward a Vision of the Delta's Future

Ecosystem frameworks for water management consider the full suite of costs and benefits of flow manipulation, and these frameworks become more urgent as the world population and scale of water development continue to grow. Water withdrawals for food production are projected to increase 14% in the next 30 years, expanding irrigated land by 450,000 km^2 in 93 developing countries (World Water Assessment Programme 2003). Allocations of water for agriculture will also increasingly compete with municipal demands and water allotments for ecosystem sustainability in California, with particular focus in the Sacramento-San Joaquin Delta. Innovative resource managers are searching for means to implement Integrated Water Resources Management in which development of water, land, and related resources are coordinated to maximize economic and social welfare "without compromising the sustainability of vital ecosystems" (World Water Assessment Programme 2003). Our purpose here is to highlight the critical importance of understanding how flow manipulations alter hydraulics, water quality, habitat quality, and sustainability of the Delta ecosystem, and to illustrate how hydrodynamic models can be used as one tool set to assess the ecosystem-scale consequences of scenarios as we produce a vision for the twenty-first century Delta (Mount et al. 2006).

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