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Author

O'Geen, Anthony T

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Do Constructed Flow-Through Wetlands Improve Water Quality in the San Joaquin River?

Anthony T. O'Geen: Dept. of Land, Air and Water Resources, UC Davis
atogeen@ucdavis.edu
One Shields Avenue
Davis, CA 95616

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Abstract

The efficacy of using constructed wetlands (CW) to improve water quality of irrigation tailwaters was studied in the San Joaquin Valley, California. Two CWs were monitored during the 2004 and 2005 irrigation season, a new CW (W-1) and 12-year-old CW (W-2). Input/output waters from CW were collected weekly and analyzed for a variety of water quality contaminants. Organic carbon, nutrient and sediment retention efficiencies were evaluated from input/output concentrations. Results indicate that CW-2 was more a more efficient contaminant removal system for most water quality constituents. CWs were most effective at removing total suspended solids (TSS). Average TSS removal at CW-2 was 98% in 2004 and 83% in 2005. At CW-1, mean TSS removal was 90% in 2004 and 87% in 2005. Average total N removal efficiency was 41% in 2004 and 29% in 2005 for W-2, compared to 31% in 2004 and 21% in 2005 at W-1. Total P removal efficiency was 63% in 2004 and 24% in 2005 at W-2, compared to 27.5% in 2004 and 11% in 2005 at W-1. Chlorophyll-a, a measure of algal biomass, was higher at W-1, especially in input waters. Initially, in 2004, output concentration of chlorophyll-a increased, however over time, as emergent vegetation established, chlorophyll-a decreased to 35% of input levels. In 2005, CW-2 was a large source of algal biomass because vegetation was not present. Results demonstrate that CWs are effective at capturing sediment and nutrients from irrigation tailwaters, but may be a source of algae if not managed carefully.

Introduction and Problem Statement

The San Joaquin River (SJR) is a hypereutrophic tributary of the Sacramento-San Joaquin Delta, the hub of California's water supply system. Low dissolved oxygen (DO) conditions, frequently occurring between July and October (>50% of the time), often violate the water quality objectives for DO in the lower SJR: 6.0 mg L^{-1} from September through November to facilitate salmon migration and 5.0 mg L^{-1} during the remainder of the year. The oxygen deficit can stress and kill aquatic organisms and has delayed the upstream migration of fall-run Chinook salmon (*Oncorhynchus tshawytscha*). An important component of the oxygen demand originates from high algal biomass loading from upstream sources. Algal loads are a result of excess nutrient supply, largely from non-point sources associated with irrigated agriculture. In the lower SJR, summer concentrations of mineral nitrogen ($NH_4^+ + NO_3^-$) range between 2.0 to 2.5 mg N L^{-1} and soluble reactive phosphorus range between 0.10 and 0.15 mg P L^{-1}.

New regulations are requiring that all irrigated land managers develop and implement water quality management and water quality monitoring plans in order to obtain a waiver to discharge irrigation return flows from their properties. As a result, agricultural land managers are searching for cost-effective management practices to improve irrigation tailwaters before disposal to waterways. One possible solution is the use of flow-through wetlands, which have been shown in other regions to be effective for improving water quality. If effective in the San Joaquin Valley, constructed wetlands would provide an important best-management practice for enhancing water quality of tailwaters. Wetland treatment of irrigation tailwaters could provide a valuable tool for addressing the downstream hypoxia problem and the needs of land managers to address the agricultural discharge waiver.

Objectives

Examine the retention efficiencies of these wetlands for particulate organic carbon, dissolved organic carbon, major nutrients (total N and P), chlorophyll-a, and total suspended solids.

Procedure

The San Joaquin River has a perennial drainage area of 19,158 km^2 in California's Central Valley, including portions of the Sierra Nevada (11,192 km^2), Coast Ranges (2,078 km^2) and Valley Basin (2,273 km^2). The valley basin is among the most productive agricultural regions of California, in large part due to the availability of irrigation water. The intensive utilization of tributary runoff for irrigation commonly results in 40 to 50% of the summer flows in the San Joaquin River originating from surface and subsurface agricultural drainage.

Two sites were selected to compare differences in wetland design and age on wetland biogeochemistry. The CWs are located along the SJR between the confluences of the Merced and Tuolumne Rivers. A newly constructed wetland CW (CW-1) having an area of 1.3 ha and receiving irrigation tailwaters from about 450 ha was compared to a 12-year-old CW (W-2) wetland with an area of 7.3 ha and receiving tailwaters from about 2,300 ha. Both wetlands receive tailwater ultimately destined for the San Joaquin River.

Input and output water samples were collected on a weekly basis during the 2004 and 2005 irrigation seasons (April-Sept.) and analyzed for several water quality constituents, including total nitrogen (TN), nitrate (NO_3) total phosphorus (TP), dissolved reactive phosphate (DRP), dissolved organic carbon (DOC), total suspended solids (TSS), and chlorophyll-a (a measure of algal biomass). No analysis was accomplished in 2006 due to flooding of the San Joaquin River.

Results

Monitoring results for the newly constructed CW (CW-1) and 12-year-old (CW-2) indicated that CWs trap a variety of constituents present in agricultural return flows. The CWs were particularly efficient at removing TSS, but also removed a large percentage of nitrogen and phosphorus.

Table 1. Seasonal mean concentration of water quality constituents at input and output locations at CW-1 and CW-2 (standard deviation in parentheses).

	Total Nitrogen	Nitrate	Total Phosphorus	Dissolved Reactive Phosphorus	Dissolved Organic Carbon	Chloro-phyll-a	Total Suspended Solids
	TN	NO_3	TP	DRP	DOC	Chyll-a	TSS
				$mg\ L^{-1}$			
CW-1 Input							
2004	14.4 (10.5)	8.8 (3.6)	0.432 (0.246)	0.382 (0.181)	4.3 (2.3)	0.0211 (0.0181)	469 (301)
2005	8.4 (6.1)	4.3 (2.8)	0.357 (0.159)	0.223 (0.154)	3.3 (0.8)	0.0187 (0.0076)	269 (243)
CW-1 Output							
2004	10.0 (3.6)	7.7 (3.1)	0.313 (0.122)	0.277 (0.117)	3.7 (1.1)	0.0265 (0.0245)	47 (37)
2005	6.6 (4.3)	4.7 (3.9)	0.318 (0.278)	0.183 (0.230)	3.7 (1.3)	0.0225 (0.024)	34 (36)
CW-2 Input							
2004	5.8 (1.6)	4.2 (1.5)	0.275 (0.080)	0.188 (0.049)	4.9 (1.9)	0.0042 (0.0021)	305 (185)
2005	4.1 (2.2)	2.8 (2.1)	0.398 (0.164)	0.162 (0.063)	4.0 (1.0)	0.008 (0.0101)	516 (267)
CW-2 Output							
2004	3.4 (1.5)	2.1 (1.2)	0.103 (0.068)	0.043 (0.067)	5.1 (1.3)	0.0135 (0.0126)	7 (3)
2005	2.9 (1.2)	2.0 (3.3)	0.304 (0.217)	0.128 (0.143)	4.4 (1.2)	0.0695 (0.0424)	88 (41)

Total Suspended Solids

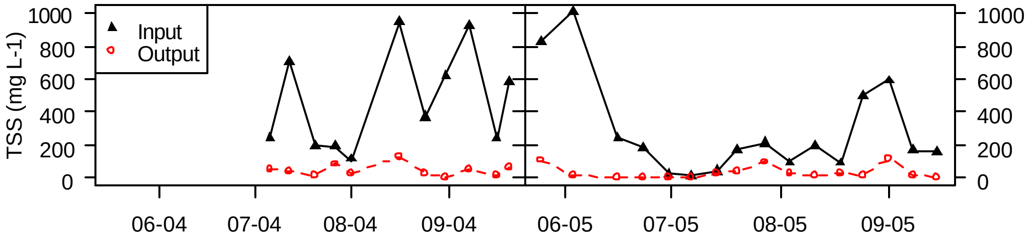

Figure 1. Total Suspended solids measured at CW-1 at input and output locations over the 2004 and 2005 irrigation seasons.

The TSS concentration in output water at CW-1 was consistently low over both irrigation seasons (Figure 1). Input levels of total suspended solids were very high throughout much of the irrigation season in 2004. Episodes of low TSS at the input in 2005 were observed to correspond with the presence of PAM (a soil aggregating agent) in the irrigation water. In 2004, average TSS concentration was 469±301 mgL^{-1} (mean ± standard deviation) at the input and 47±37 mgL^{-1} at the output. In 2005, average TSS concentration was 269±243 mgL^{-1} at the input and 34±36 mgL^{-1} at the output (Table 1). Corresponding seasonal TSS removal efficiencies were 90% for 2004 and 87% for 2005 (Table 2).

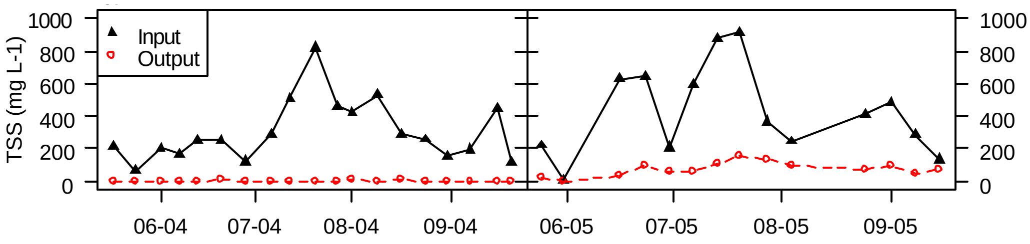

Figure 2. Total Suspended solids measured at CW-2 at input and output locations over the 2004 and 2005 irrigation seasons.

At CW-2, input levels of TSS were slightly lower than CW-1 for 2004, but higher in 2005. The TSS concentration in output water was very low throughout the 2004 season, but higher in 2005 (Figure 2). In 2004, average TSS concentration was 305±185 mgL^{-1} at the input and 7±3 mgL^{-1} at the output. In 2005, average TSS concentration was 516±267 mgL^{-1} at the input and 88±41 mgL^{-1} at the output (Table 1). Corresponding seasonal TSS removal efficiencies were 98% for 2004 and 83% for 2005 (Table 2).

Phosphorus

The phosphorus concentration was high at input locations and decreased modestly at the outputs due to the filtering capacity of the CWs.

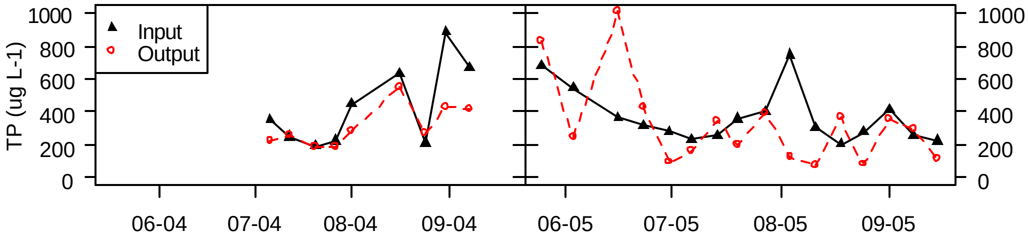

Figure 3. Comparison of total phosphorus in CW-1 at input and output locations over the 2004 and 2005 irrigation seasons.

TP concentration was highly variable at CW-1 at input and output locations (Figure 3). In 2004, average TP concentration was 0.432±0.246 mgL^{-1} at the input and 0.313±0.122 mgL^{-1} at the output. In 2005, average TP concentration was 0.357±0.159 mgL^{-1} at the input and 0.318±0.278 mgL^{-1} at the output (Table 1). Corresponding seasonal TP removal efficiencies were 27.5% for 2004 and 11% for 2005 (Table 2).

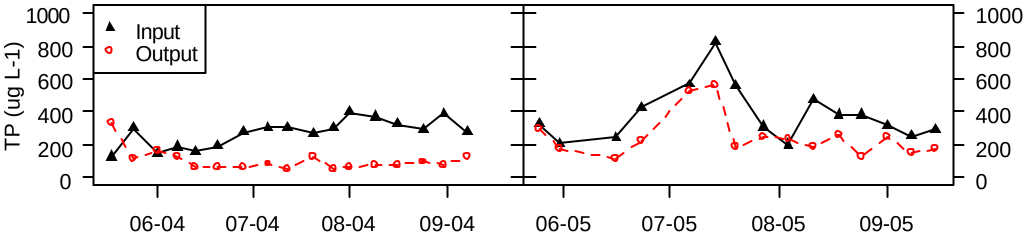

Figure 4. Comparison of total phosphorus in CW-2 at input and output locations over the 2004 and 2005 irrigation seasons.

In 2004, input TP concentration at CW-2 was more uniform and lower compared to CW-1. However, in 2005, the concentration and variability of TP were similar between CW-1 and CW-2 at input and outputs, although more P was removed by CW-2 (Figure 4). In 2004, average TP concentration was 0.275±0.080 mgL^{-1} at the input and 0.103±0.068 mgL^{-1} at the output. In 2005, average TP concentration was 0.398±0.164 mgL^{-1} at the input and 0.304±0.217 mgL^{-1} at the output (Table 1). Corresponding seasonal TP removal efficiencies were 63% for 2004 and 24% for 2005 (Table 2).

Similar results were observed for dissolved reactive phosphorus (DRP). At CW-1, DRP removal efficiency was 27.5% in 2004 and 18% in 2005. At CW-2 DRP removal efficiency was 77% in 2004 and 21% in 2005 (Table 2).

Nitrogen

Nitrogen levels were relatively high and variable in input waters. Encouraging reductions were achieved by the CWs, especially from CW-2. In most instances, much of the total N was in the form of nitrate.

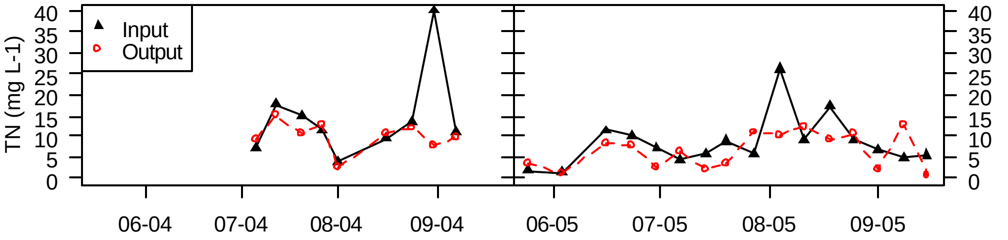

Figure 5. Total nitrogen measured at CW-1 at input and output locations over the 2004 and 2005 irrigation seasons.

Variability in TN concentration was highest at CW-1 and TN removal efficiencies were lower (Figure 5). In 2004, average TN concentration was 14.4±10.5 mgL^{-1} at the input and 10.0±3.6 mgL^{-1} at the output. In 2005, average TN concentration was 8.4±6.1 mgL^{-1}

at the input and 6.6±4.3 mgL^{-1} at the output (Table 1). Corresponding seasonal TN removal efficiencies were 31% for 2004 and 21% for 2005 (Table 2).

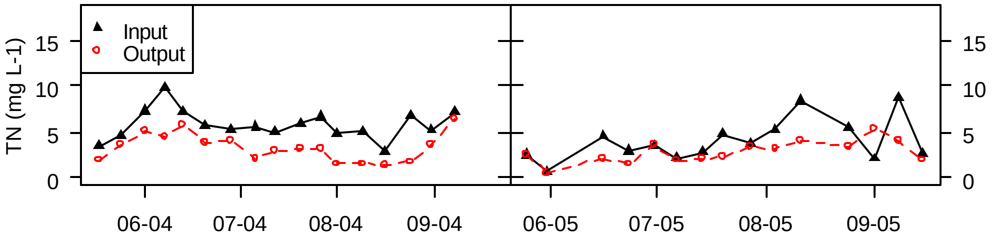

Figure 6. Total nitrogen measured at CW-2 at input and output locations over the 2004 and 2005 irrigation seasons.

The TN concentration at CW-2 was lower and less variable at input and output locations (Figure 6). In 2004, average TN concentration was 5.8±1.6 mgL^{-1} at the input and 3.4±1.5 mgL^{-1} at the output. In 2005, average TN concentration was 4.1±2.2 mgL^{-1} at the input and 2.9±1.2 mgL^{-1} at the output (Table 1). Corresponding seasonal TN removal efficiencies were 41% for 2004 and 29% for 2005 (Table 2).

Potential Adverse Impacts of CWS on Water Quality

Chlorophyll-a was used as a bio-indicator of for algae. High algal loads have been linked to low dissolved oxygen levels in the Stockton Ship Channel acting as a barrier to spawning fish. CWs could serve as a bioreactor for algae due to decreased residence time and high nutrient levels.

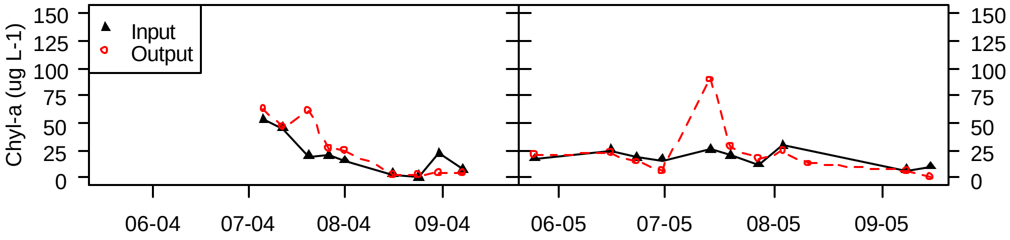

Figure 7. Chlorophyll-a, a bio-indicator of algae, measured at CW-1 at input and output locations over the 2004 and 2005 irrigation seasons.

In general, trends in chlorophyll-a concentration were similar at input and output locations at CW-1 with episodes in time where it was a source of algae (Figure 7). In 2004, average chlorophyll-a concentration was 0.021±0.0181 mgL^{-1} at the input and 0.0265±0.0245 mgL^{-1} at the output. In 2005, average chlorophyll-a concentration was 0.0187±0.0076 mgL^{-1} at the input and 0.0225±0.024 mgL^{-1} at the output (Table 1). When considering seasonal averages, CW-1 was a source of algae with seasonal removal efficiencies of -26% for 2004 and -20% for 2005 (Table 2).

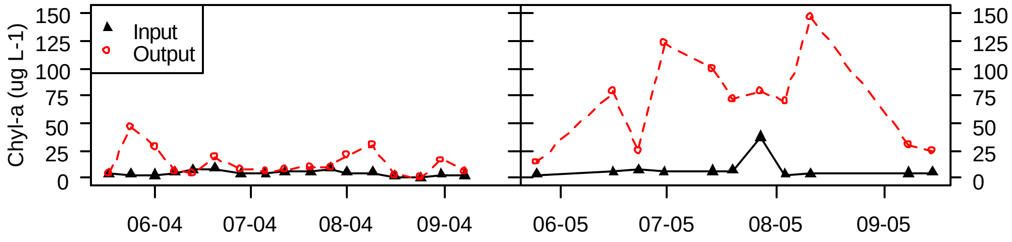

Figure 8. Chlorophyll-a, a bio-indicator of algae, measured at CW-2 at input and output locations over the 2004 and 2005 irrigation seasons.

Trends in chlorophyll-a concentration were even more variable at CW-2, particularly the output (Figure 8). In 2004, average chlorophyll-a concentration was very low, 0.0042±0.0023 mgL^{-1} at the input and 0.0135±0.0126 mgL^{-1} at the output. In 2005, average chlorophyll-a concentration was low at the input, 0.008±0.0101 mgL^{-1}, but much higher at the output 0.06955±0.0424 mgL^{-1} (Table 1). When considering seasonal averages, CW-2 was a major source of algae, increasing 2.2 fold at output locations in 2004 and almost 7.7 fold in 2005 (Table 2).

Dissolved organic carbon (DOC) was measured because some forms of DOC react with chlorine during the water purification process to form carcinogenic disinfection byproducts.

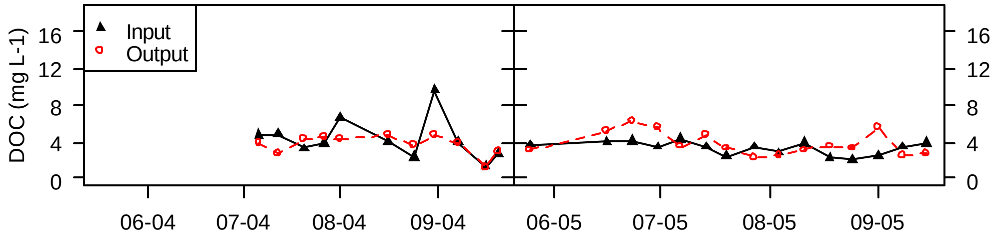

Figure 9. Dissolved organic carbon measured at CW-1 at input and output locations over the 2004 and 2005 irrigation seasons.

There were no clear trends in DOC concentration through the 2004 and 2005 irrigation season at CW-1 and [DOC] was relatively low for wetland systems (Figure 9). In 2004, average DOC concentration was 4.3±2.3 mgL^{-1} at the input and 3.7±1.1 mgL^{-1} at the output. In 2005, average DOC concentration was 3.3±0.8 mgL^{-1} at the input and 3.7±1.3 mgL^{-1} at the output (Table 1). Corresponding seasonal DOC removal efficiencies were 14% for 2004 and -12% for 2005 (Table 2).

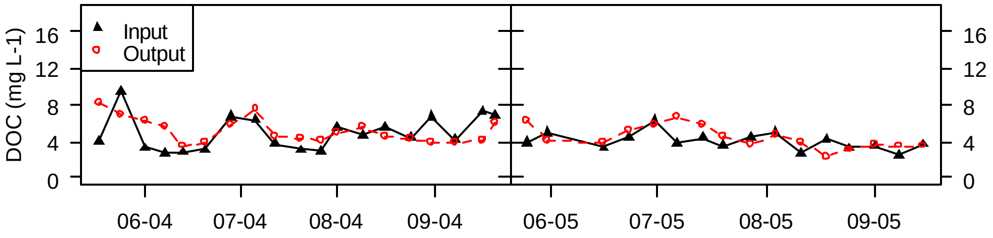

Figure 10. Dissolved organic carbon measured at CW-2 at input and output locations over the 2004 and 2005 irrigation seasons.

CW-2 showed no clear trends in DOC concentration over the 2004 and 2005 irrigation season (Figure 10). In 2004, average DOC concentration was 4.9±1.9 mgL^{-1} at the input and 5.1±1.3 mgL^{-1} at the output. In 2005, average DOC concentration was 4.0±1.0 mgL^{-1} at the input and 4.4±1.2 mgL^{-1} at the output (Table 1). Corresponding seasonal DOC removal efficiencies were -4% for 2004 and -10% for 2005 (Table 2).

Table 2. Seasonal removal efficiencies calculated from seasonal means at input and output locations at CW-1 and CW-2.

	Total Nitrogen	Nitrate	Total Phosphorus	Dissolved Reactive Phosphorus	Dissolved Organic Carbon	Chloro-phyll-a	Total Suspended Solids
	TN	NO_3	TP	DRP	DOC	Chyll-a	TSS
	---removal efficiency (%) ---						
CW-1							
2004	31	12.5	27.5	27.5	14	-26	90
2005	21	9	11	18	-12	-20	87
CW-2							
2004	41	50	63	77	-4	-221*	98
2005	29	29	24	21	-10	-769**	83

* corresponds to ~2 fold increase
** corresponds to 7.7 fold increase

Conclusions

Constructed wetlands are an effective management practice to reduce non-point source pollution in irrigated agriculture. CW-2, the older wetland, was most effective at removing nutrients. Sharp decreases in nutrient removal efficiencies were observed in both wetlands in 2005. This decrease in removal efficiency observed in each wetland likely has different explanations. CW-2 was did not have an extended dry period before the irrigation season in 2005, and as a result, dense vegetation did not emerge. Dense vegetation increases water residence time, which promotes particle settling and nutrient uptake. We attribute the decrease in removal efficiency at CW-1 to less than ideal flow regulation; in 2005 water residence time was observed to be much shorter than in 2004. The variation in nutrient removal from 2004 and 2005 indirectly suggests that wetland management can be optimized to enhance removal efficiencies.

CW-2 was a large source of algae in 2005. This drastic change from 2004 can also be explained by the lack of emergent vegetative canopy in 2005. We believe that the canopy plays an important role through light interception, limiting the amount of light available for algae growth in the wetland. Nearly 90% of the wetland had a dense canopy in 2004 when CW-2 was a minor source of algae. It is important the limit algae growth in CWs in order to reduce the algal seed source in the San Joaquin River to avoid hypoxic conditions in the Stockton Ship Channel.

While wetlands may be a major sink for nutrients and sediments, they may also be a source of algal biomass and sometimes DOC (Figs 7-10). Dissolved organic carbon (DOC) in the SJR/Delta system is a water quality concern because of production of mutagenic and carcinogenic disinfection by-products (DBP) during water treatment. In addition, these components contribute to biological oxygen demand (BOD) in wetland drainage waters and could add to the BOD load causing hypoxia in the lower SJR (e.g., Stockton Deep Water Ship Channel). The high hydraulic residence time coupled with warm water temperatures in the shallow wetlands could enhance algae production in wetlands. Similarly, removal of suspended solids by wetlands may result in less turbid conditions in the SJR that in turn could result in enhanced algal growth due to greater light availability. Therefore, processing of irrigation tailwaters in flow-through wetlands may conceivably enhance hypoxia through increased algal production both within wetlands (algae exported to river) and within the main stem of the river. Thus, flow-through wetlands could simply serve as an incubator, transforming nutrients to algal biomass, resulting in no beneficial effect on BOD loads and DO in the lower SJR. Wetland management strategies must be developed to limit algae growth and DOC export. Results of this monitoring indicate that mineral-dominated CWs (as opposed to organic-rich wetlands) are not a significant source of DOC. Other water quality contaminants such as excess salts and selenium were measured, and showed no increase at output locations in the wetlands (data not shown).

The conversion of flood plain agroecosystems to flow-through wetlands is becoming a popular land-use practice nation wide, yet little information exists to document how these systems function in California where CWs dry out in late winter and spring. This project directly addresses the needs of agricultural land managers who will be required to obtain a waiver for disposal of agricultural tailwaters and total maximum daily load (TMDL) efforts related water quality impairment in the lower SJR. Information gained from this research will allow us to identify factors that may improve the functionality of CWs as carbon sinks and water purifiers. Constructed wetlands have the potential to be excellent contaminant sinks and represent the last opportunity for treatment before tailwaters are discharged back to the SJR.