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Effects of vegetation management in constructed wetland treatment cells on water quality and mosquito production

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Abstract

The impact of three vegetation management strategies on wetland treatment function and mosquito production was assessed in eight free water surface wetland test cells in southern California during 1998–1999. The effectiveness of the strategies to limit bulrush *Schoenoplectus californicus* culm density within the cells was also investigated. Removing accumulated emergent biomass and physically limiting the area in which vegetation could reestablish, significantly improved the ammonia–nitrogen removal efficiency of the wetland cells, which received an ammonia-dominated municipal wastewater effluent (average loading rate = 9.88 kg/ha per day NH_4-N). We determined that interspersing open water with emergent vegetation is critical for maintaining the wetland's treatment capability, particularly for systems high in NH_4-N. Burning aboveground plant parts and thinning rhizomes only temporarily curtailed vegetation proliferation in shallow zones, whereas creating hummocks surrounded by deeper water successfully restricted the emergent vegetation to the shallower hummock areas. Since the hummock configuration kept open water areas interspersed throughout the stands of emergent vegetation, the strategy was also effective in reducing mosquito production. Decreasing vegetation biomass reduced mosquito refuge areas while increasing mosquito predator habitat. Therefore, the combined goals of water quality improvement and mosquito management were achieved by managing the spatial pattern of emergent vegetation to mimic an early successional growth stage, i.e. actively growing plants interspersed with open water. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Wetland plant management; Constructed treatment wetland; Free water surface wetland; California bulrush (*Schoenoplectus californicus* or *Scirpus californicus*); Mosquito production; Hemi-marsh; Ammonia–nitrogen removal

1. Introduction

Vegetation management has been a controversial topic within the treatment wetlands profession. Since the idea of treating wastewater with natural systems gained acceptance, scientists around the world have studied the various roles

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that plants play (Seidel, 1976; Gersberg et al., 1986; Wolverton, 1987; Rogers et al., 1991; Brix, 1994; Verhoeven and Meuleman, 1999; Greenway and Woolley, 2000). Aquatic plants in treatment wetlands act as filters (Hammer, 1989; Brix, 1994), take up nutrients (Yount and Crossman, 1970; Shaver and Melillo, 1984; Reddy and DeBusk, 1985; Breen, 1990; Greenway and Woolley, 1999; Liu et al., 2000), provide a substrate for microbiota (algae, bacteria, fungi, protists) (Kadlec and Knight, 1996; Yakushin, 1998; USEPA, 2000; Wetzel, 2000), and provide a carbon source for denitrification (Stefan et al., 1994; Reed et al., 1995; Mann and Wetzel, 1996; Ingersoll and Baker, 1998; USEPA, 1999).

Arguments against wetland vegetation management typically state that the regular harvest of treatment systems is too costly, unsustainable, or impractical (Reed et al., 1995; Kadlec and Knight, 1996; USEPA, 1999), that management does little to improve water treatment (Tchobanoglous, 1987; USEPA, 2000; Wetzel, 2000), and it reduces the readily available carbon source necessary for denitrification (USEPA, 1999). Those in support of wetland plant harvesting agree that not only is it an effective way to remove the accumulated nutrients within the plants (Reddy and DeBusk, 1987; Breen, 1990; Rogers et al., 1991; Gearheart, 1992; Gumbricht, 1993; Verhoeven and Meuleman, 1999; Asaeda et al., 2000), but by opening up dense vegetated areas it encourages an abundance of mosquito predators while reducing mosquito habitat (Tchobanoglous, 1987; Batzer and Resh, 1992; de Szalay et al., 1995; Russell, 1999). It also reduces densely shaded areas, thereby promoting the photosynthetic periphyton in the system (Grimshaw et al., 1997; Wetzel, 2000), and is important for keeping areas open for wildlife use (Moore et al., 1994; Creighton et al., 1997; Gray et al., 1999; de Szalay and Resh, 2000).

Westoby (1984) promoted the idea that with time, a densely crowded even-aged plant population will 'self-thin' to maintain the population's overall health. His self-thinning rule predicts the natural selection of biomass accumulation phases. Some argue that a wetland, even a wetland constructed for wastewater treatment, should be left alone for nature to follow its natural course (Mitsch and Wilson, 1996). However, wastewater is not a 'natural' water source and can contain abundant nutrients readily available to plants (Vymazal, 1995). In favorable climatic areas, maximum plant growth rates and biomass development are amplified by the abundant nutrients in the system.

Constructed treatment wetlands in the southwestern United States supplied with municipal wastewater often provide ideal environmental conditions for growth of emergent wetland plant species. Although, emergent vegetation contributes to the improvement of water quality in most treatment systems (Reed et al., 1995; Hammer, 1997; USEPA, 1999), dense vegetation can actually become the source of several problems. Our previous investigations have shown that as stands of California [*Schoenoplectus* (formerly *Scirpus*) *californicus* (C.A. Meyer)] or hardstem [*S. acutus* (G.H.E. Muhlenberg ex J. Bigelow)] bulrushes reach maturity, they can contribute significantly to the internal loading of nitrogen in the system (Sartoris et al., 2000). Both mature and standing dead plants shade the attached microbial communities, thus reducing the nutrient retentive capacities of those communities (Wetzel, 2000); provide abundant mosquito habitat (Walton et al., 1998); cause low dissolved oxygen levels (Sartoris et al., 2000; Smith et al., 2000); contribute to short-circuiting of the water flow (Groeneveld and French, 1995) which can encourage stagnant water areas where avian botulism or avian cholera can thrive (Locke and Friend, 1987), and reduce the diversity of wildlife habitat (Weller, 1978).

Problems associated with the rapid accumulation of emergent vegetation biomass in constructed municipal wastewater wetlands have been documented at several sites in the southwestern US. Accumulated emergent biomass in the Kingman, Arizona, treatment wetlands was burned in 1997, 5 years after the wetlands were constructed (Pinney et al., 2000). Only 2.5 years following full operation, both mechanical removal and burning were used at the Sweetwater Wetlands in Tucson, Arizona, to clear emergent biomass to maintain flows and reduce mosquito-breeding habitat (Prior, 2000). The Tres Rios Constructed Wetlands Demonstration Project near Phoenix, Arizona, mechanically removed dense bulrush vegetation about 3 years following full operation to reduce mosquito habitat and improve waterfowl and fish habitat (Wass et al., 1999). At the Sacramento Constructed Wetlands Demonstration Project in Sacramento, California, various types of vegetation management were performed annually following the first year of operation (SRWTP, 2000). In wildlife management areas, mechanical removal such as discing, mowing and prescribed burning are often used to remove dense areas of vegetation and create open water areas accessible to waterfowl (Gray et al., 1999; de Szalay and Resh, 2000).

We have been investigating vegetation community development and nitrogen dynamics since 1992 at the Hemet/San Jacinto Wetland Research Facility located in Riverside County, California. Three years following the planting of a 9.9 ha demonstration wetland, we concluded from our investigations (Sartoris et al., 2000) that vegetation management was necessary to maintain the N removal capabilities of a newly constructed treatment wetland. Additionally, a review of the literature on emergent vegetation management in wildlife refuges led us to the hypothesis that a hemi-marsh configuration, in which approximately equal areas of emergent marsh and deep open water are interspersed (Weller and Spatcher, 1965; Sojda and Solberg, 1993), would improve and maintain the treatment function of a constructed wastewater treatment wetland (Sartoris and Thullen, 1998). In addition to improving the water quality of a treatment wetland, a hemi-marsh configuration would improve the quality of the wildlife habitat by increasing aquatic invertebrate populations for food (Murkin et al., 1982; Batzer and Resh, 1992; de Szalay and Resh, 1997, 2000) and by creating the structure needed by waterfowl for access, nesting, and loafing (Beecher, 1942; Weller, 1978). Wetland systems with more open areas also minimize mosquito populations (Batzer and Resh, 1992; de Szalay et al., 1995; Walton et al., 1999a; de Szalay and Resh, 2000). From November 1997 through September 1999, we tested our hypothesis with an experiment in the eight research cells adjacent to the demonstration wetland. In this paper, we describe the three vegetation management techniques we tested and their effects on plant reestablishment, water treatment, and mosquito production. In addition to evaluating the effect of the hemi-marsh configuration on water treatment and habitat quality, the sustainability of the desired configuration was another issue that needed further study.

2. Methods

2.1. Site configuration

The eight research cells (each 68.6×13.7 m or about 0.1 ha) are part of the Hemet/San Jacinto Wetland Research Facility located at Eastern Municipal Water District's (EMWD) Hemet/San Jacinto Regional Water Reclamation Facility (RWRF) 6.4 km north of Hemet, California (33°48′ N, 117°1′ W). In September 1992, four of the cells were constructed as fully vegetated marshes (one-phase cells) while the other four were constructed as 70% vegetated marsh–pond–marsh systems (three-phase cells) (Stiles, 1994; USBR/NBS/EMWD, 1994; Walton and Workman, 1998). California bulrush root/rhizome clumps 30.5 cm in diameter were transplanted from the adjacent nursery (planted with locally collected plants) and staked with wooden lathe in rows on 1.2 m centers. When effluent from the RWRF was added to the newly constructed cells, the plants grew hydroponically until they affixed themselves to the sediment. Virtually 100% of the transplants survived and thrived for the next 4 years (USBR/NBS/EMWD, 1994). During the fall of 1996, flow to the cells was eliminated and the cells were allowed to dry out. In November 1997, the dried aboveground vegetation in the research cells was burned. Fresh bulrush samples from the adjacent nursery and newly burnt ash samples from each cell were collected and analyzed for C, H, N, S, ash and 30 additional elements (unpublished data).

In June 1998, the bottom topography of the eight wetland research cells was reconfigured by excavating two approximately 1.8 m deep ponds

(13.7 × 13.7 and 13.7 × 21 m) in each cell. The smaller pond was excavated at the influent end; the larger pond was located about two third of the distance downstream. The emergent marsh areas remained at the previously designed 46 cm water depth. These modifications created a 50:50 ratio of vegetated emergent marsh to deep open water. Subsequent to the cell reconfiguration, three vegetation management techniques were tested: (1) three 'control' cells which were left unmanipulated after the burn and the reconfiguration, (2) three 'thinned' cells in which approximately 50% of the bulrush roots and rhizomes were mechanically removed from the emergent marsh zones using a backhoe with a rock bucket attached to sieve out large materials, and (3) two 'hummock' cells in which 36 hummocks (3.7 × 1.5 × 0.4 m tall) were constructed on the surface of the emergent marsh zones in staggered rows across the cell perpendicular to the water flow (Fig. 1a). Bulrush sprouts and exhumed rhizomes from the cells were transplanted on the hummock tops. The operational water depth over the top of the hummocks was about 30 cm (Fig. 1b) and the areas vegetated (hummock tops) comprised about 20% of the total cell area.

The RWRF supplied ammonia-dominated, secondary-treated municipal effluent to the research cells beginning on 13 July 1998. The total inflow rate was monitored by means of a propeller meter installed in the supply pipe, and was maintained at 454 l/min (120 gpm) throughout the entire period of these investigations. The total inflow was divided equally among the eight research cells by manually adjusting the valves supplying the individual cells. This equalization of flow among the cells resulted in a common inflow rate of approximately 56.8 l/min (15 gpm) to each cell. Nominal hydraulic residence time (HRT) was approximately 13 days in the control and thinned cells. Due to their greater water volume, the hummock cells had an HRT of about 18 days.

Since no flow metering devices were installed on the effluent ends of the research cells, outflow rates were estimated by means of the following hydraulic balance:

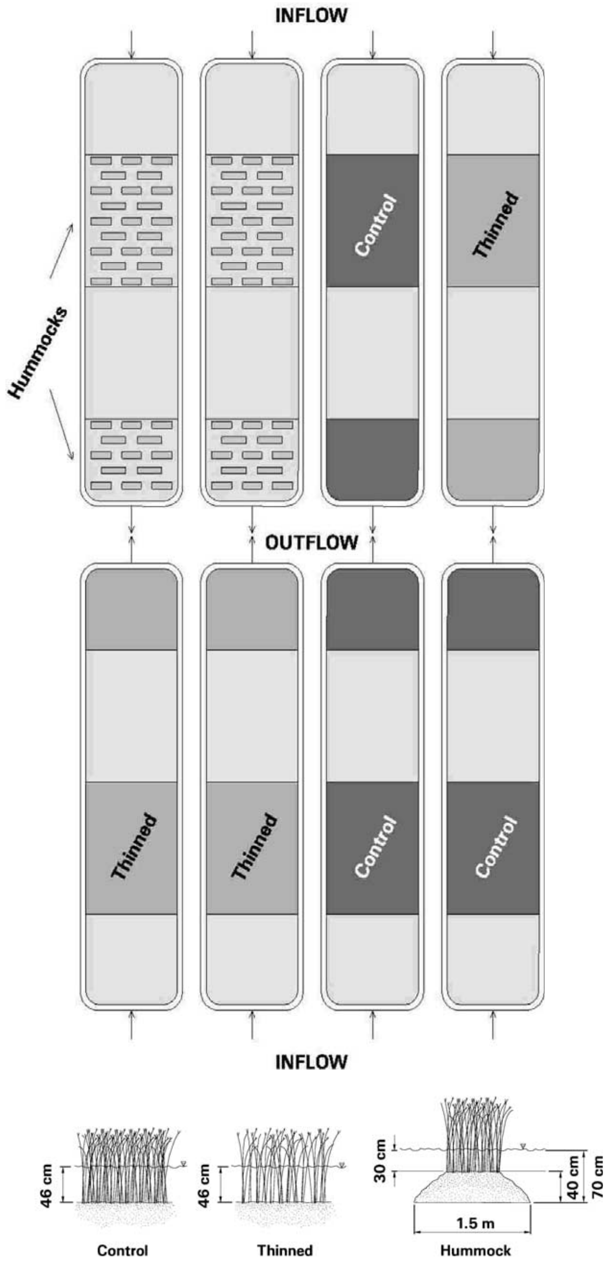

Fig. 1. (a) Schematic of the research cells' configuration. The hummocks (small rectangular islands) were built up on top of the original emergent marsh zones using a backhoe. They were oriented in staggered rows across the cell perpendicular to the water flow as depicted in the schematic. Unlabeled, very light shaded areas illustrate open water. All darker shades illustrate vegetated areas. (b) Cross section schematic of each of the vegetation management strategies with associated water depths.

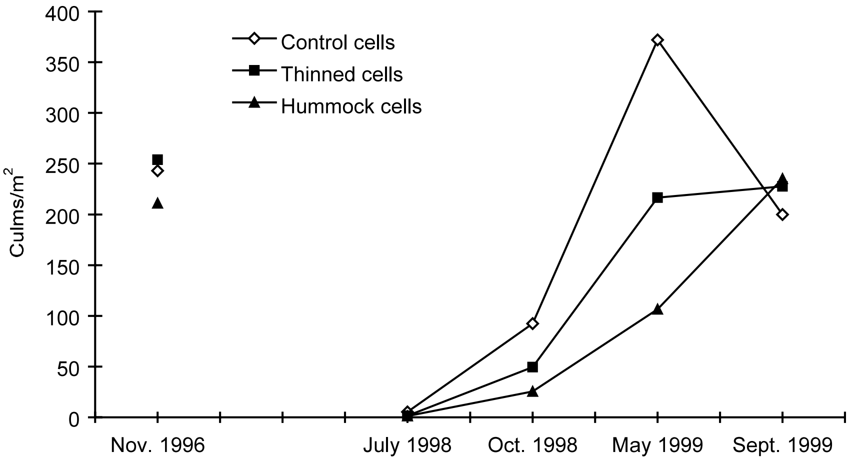

Fig. 2. ECD of the California bulrush (culms per m^2). Data are pooled by vegetation management strategy for each sampling date. November 1996 data are baseline density data collected prior to drying out the wetland cells for the burn and reconfiguration.

$$\text{Outflow} = \text{Inflow} + \text{Precipitation} - \text{Evapotranspiration} \pm \text{Groundwater} \quad (1)$$

Outflow rates were estimated only for the periods: 12 August through 29 October 1998, and 8 April through 23 September 1999. Precipitation records at the RWRF showed no measurable rainfall during either of these periods, so the precipitation term was set at zero in the hydraulic balance. Geotechnical investigations conducted prior to construction of the research cells indicated that the types of soils and the depth to the water table on the site precluded any significant infiltration from or seepage to the groundwater (USBR/NBS/EMWD, 1994). Evapotranspiration was estimated at 80% of pan evaporation (Kadlec and Knight, 1996), using mean monthly pan evaporation rates, based on 51 years of record, from the US Department of Commerce San Jacinto station (USBR/EMWD, 1991). The resulting estimates of mean monthly evapotranspiration rate were converted to flow units and subtracted from the common inflow rate to calculate mean monthly outflow rates for the research cells.

2.2. Vegetation monitoring

To estimate the baseline culm (i.e. stem) density of the mature California bulrush prior to our vegetation management investigations, we counted and recorded individual bulrush culms within twelve 0.25 m^2 quadrats distributed throughout the research cells during 12–13 November 1996, just prior to the cells being dried for reconfiguration. By placing quadrats at two random locations in each of six cells, we obtained a random sample of culms. All plants came from the same plant source and their environmental conditions had been virtually identical for 4 years. For ease of comparison with the 1998–1999 data, the 1996 data are displayed in Fig. 2 according to how the cells were later reconfigured.

During 27–28 July 1998 (July 1998), 2 weeks after flooding the modified cells, we performed our first vegetation survey to record the rate of reestablishment of the emergent vegetation zones. In addition to counting the individual culms to estimate density within five 0.25 m^2 random quadrats per research cell, we measured the diameters and heights of ten random bulrush culms within each quadrat. We also estimated the percent areal vegetation coverage of each of the cells and documented the estimates using drawings and photographs. During 29–30 October 1998 (October 1998), 4–6 May 1999 (May 1999), and 13–15 September 1999 (September 1999) we repeated the entire vegetation survey.

In comparing the percent areal vegetation coverage data with the mean density measurements, it became clear that the patchy distribution of the bulrush was difficult to quantify. To present a more accurate representation of the plant density within each of the vegetation management strategy tests, we calculated an effective culm density (ECD) for our comparisons:

$$ECD = D \times AC_{veg} \quad (2)$$

where D, the average culm density (culms per m^2) and AC_{veg}, the percentage of the shallow emergent zone covered by vegetation within a given research cell. The ECD, therefore, incorporates the spatial variation of plant distribution with the mean plant density measurements.

2.3. Water quality monitoring

During each vegetation survey, three Hydrolab Recorder™ Water Quality Multiprobe Loggers were deployed at representative locations within a control cell, a thinned cell, and a hummock cell to record hourly measurements of water temperature, dissolved oxygen concentration (DO), and pH over the vegetation survey period. These hourly data provided a framework of ambient conditions for interpreting the water quality analytical results.

We collected water samples synoptically across three transects within each of three cells representing the three vegetation management strategies in May and September 1999. The samples were analyzed within 24 h of collection for total NH_4-N, total Kjeldahl-N (TKN), nitrite-N (NO_2-N), nitrate-N (NO_3-N), total phosphorus (TP), total suspended solids (TSS), total coliforms, 5 day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and carbonaceous biochemical oxygen demand (CBOD) according to EPA protocols (USEPA, 1984). NH_4-N was determined by the titrimetric distillation procedure (EPA Method 350.2), TKN was determined by the semi-automated block digester, autoanalyzer method (EPA Method 351.2), NO_2-N data were determined by spectrophotometry (EPA Method 354.1), and NO_3-N data were determined by ion chromatography (EPA Method 300.0).

Weekly water samples were collected from the effluent of three of the cells (one from each of the three management strategies) from 12 August through 29 October 1998 and 8 April through 23 September 1999. The samplings were rotated so that each cell was sampled at least every 21 days. A common influent sample also was collected weekly and all samples were analyzed for total NH_4-N, TKN, NO_2-N, NO_3-N, TP, TSS, total coliforms, and BOD_5.

Inflow and outflow rates (described above) were combined with the temporally corresponding laboratory concentration data to calculate mass loading and export rates for the various nitrogen species, in kg per day. Removal efficiencies (RE) for the various constituents were calculated as percent of inflow load removed.

Since the inflow rate to all the cells was the same, the mass loading rates of the various constituents were also equal among the three cell types. Treatment results were, therefore, normalized for constituent loading rate, rather than for hydraulic retention time.

2.4. Mosquito production

Temporal and spatial trends of mosquito production from the wetlands were determined using 0.25 m^2 emergence traps (Walton et al., 1999b) and dipping (Service, 1993). Eight emergence traps were placed into each research cell and emerging insects were collected either weekly (1998) or biweekly (1999). Immature mosquitoes were sampled by dipping at 16 stations positioned equidistantly along the research cell periphery and at four stations along two transects through the cell interior. At each station, three (peripheral samples) or five (interior samples) dips were taken within a 2 m zone and combined. Dense emergent vegetation precluded dipping along the interior transects in the control and thinned treatments on most dates during 1999. Developmental stage and abundance of immature mosquitoes were determined at 25–50 $\times$ magnification using a stereo dissecting microscope.

Mosquito production during each of the 2 years of the study was compared statistically among the three vegetation management treatments using Friedman's method (Sokal and Rohlf, 1995) by ranking mosquito abundance in each treatment within each date. Differences in immature mosquito abundance among vegetation management treatments were also compared using Friedman's method. This nonparametric statistical test was used because mosquitoes were undetectable by our sampling methods in some vegetation management treatments on many sampling dates during 1998. Comparisons between the treatment means were carried out using the Mann–Whitney U-test. Mosquito abundance in the eight research cells was compared between years using a repeated measures ANOVA followed by a contrast for repeated measurements on four dates representing a comparable period within each year (22 July, 5 August, 13 August, 25 August 1998 vs. 20 July, 2 August, 16 August, 31 August 1999). Mosquito abundance was $\log(x+1)$ transformed prior to analysis by ANOVA.

3. Results

3.1. Vegetation monitoring

Bulrush coverage increased in all the cells, but reestablishment in both the control and thinned cells was more rapid than in the cells with hummocks (Table 1). By September 1999 (14 months after reconfiguration), vegetation in the control and thinned cells covered 95 and 93% of their emergent marsh areas, respectively, (48 and 47% of the total cell areas). Vegetation in the hummock cells covered only 58% of the emergent marsh area (29% of the total cell area).

As the new bulrush sprouts propagated from rhizomes left in place after the burn and cell reconfiguration, the emergent vegetation developed a patchy spatial distribution pattern. Initially the patches were small, but later coalesced and eventually spread across the entire emergent zone areas in the control and thinned cells. Areas not yet colonized by the laterally expanding bulrush are referred to here as vegetation voids between the bulrush clumps. As the bulrush plant communities approached maturity, the voids became smaller and fewer, particularly in the control and thinned cells. In the hummock cells, on the other hand, even as the bulrush spread across the hummock tops and down the slopes, the hummock configuration maintained vegetation patches interspersed with large voids.

The patchy distribution pattern of bulrush led to within-cell culm density measurements varying from 0 to 992 culm per m^2 during the second growth season. This large variation, plus the small sample size per cell ($n = 5$), contributed to large standard deviations (42–91% of the means). To better illustrate this spatial variation, we used the ECD equation [see (Eq. (2))] to compare plant reestablishment among the vegetation management strategies. The ECDs are plotted through the study period in Fig. 2.

Immediately after flooding the bulrush began to reestablish in the research cells. Since the sediments of the emergent marsh zones of the control cells were left undisturbed following the burn, the control cells began with an ECD 1.6 times that of the thinned or hummocked cells. Between July and October 1998, the ECDs increased 5.6 times in the control cells, 7.1 times in the thinned cells, and 4.9 times in the hummock cells (Fig. 2). During this first growing season, the rate of revegetation in the thinned cells was rapid even though the rhizomes had been thinned by about 50%. The slowest rate of revegetation was in the hummock cells due to the heavy disturbance during construction and the high percentage of deeper water.

Table 1
Mean percent areal coverage of California bulrush within the shallow emergent zones of the vegetation management test cells

	July 1998	October 1998	May 1999	September 1999
Control cells	16.7	53	82	95
Thinned cells	8.3	38	72	93
Hummock cells	6.5	25	40	58

Table 2
Mean daily areal nitrogen loading rates and load RE

	Organic N	Total NH_4-N	NO_2-N	NO_3-N	Total N	Total IN
5 May–3 November 1993[a]						
Three-phase cells loading rate (kg/ha per day)	0.77	5.77	0.95	0.38	9.11	7.10
Three-phase cells RE (%)	−22	58	73	14	63	57
One-phase cells loading rate (kg/ha per day)	0.56	4.14	0.68	0.27	6.54	5.09
One-phase cells RE (%)	−6	6	87	35	30	18
12 August–29 October 1998						
Common loading rate (kg/ha per day)	2.27	10.29	1.16	0.18	13.89	11.63
Control cells RE (%)	−15	63	93	38	52	66
Thinned cells RE (%)	2	65	67	−41	54	64
Hummock cells RE (%)	27	70	49	−206	58	64
8 April–23 September 1999						
Common loading rate (kg/ha per day)	1.80	9.47	1.21	0.83	13.31	11.52
Control cells RE (%)	14	23	87	17	27	29
Thinned cells RE (%)	7	15	71	−72	14	15
Hummock cells RE (%)	21	47	74	−100	36	39

[a] Data from USBR/NBS/EMWD (1994).

By May 1999, the ECD across all of the cells averaged 231.6 culms per m^2 and was similar to the November 1996 mean baseline bulrush density of 236.0 culms per m^2. ECDs increased from the October 1998 survey by four times in the control cells, by 4.4 times in the thinned cells, and by 4.2 times in the cells with the hummocks (Fig. 2). By the end of the second growing season, the bulrush growth curve in the control and thinned cells leveled out as the plants approached maximum density and maximum culm diameters (maximum diameter during September 1999 = 4.14 cm; mean = 2.07 cm; S.D. = 0.51; $n = 375$). The ECDs within the hummock cells were still increasing through the second growth season because they still contained open areas to allow the vegetation to spread.

3.2. Water quality monitoring

Mean daily RE and areal loading rates for the nitrogen series are listed in Table 2. The daily loading into each of the cells during the first growing season following the reconfiguration (12 August–29 October, 1998) averaged 13.89 kg/ha per day TN. Total NH_4-N made up approximately 74% of the influent load. During the first growing season, NH_4-N removal percentages were similar between the three vegetation management techniques. The control cells removed 63%, the thinned cells removed 65% and the hummock cells removed 70% NH_4-N. Between 8 April–23 September 1999, the TN loading averaged 13.31 kg/ha per day, with total NH_4-N making up approximately 71% of the influent load. During this second growing season, NH_4-N RE declined on average to 23, 15 and 47%. NO_3-N, on the other hand, was produced during both growing seasons in the thinned (RE = −41, −72%) and hummock (RE = −206, −100%) cells indicating nitrification. NO_3-N was removed from the control cells (RE = 38, 17%) in both years. Throughout our study, the hummock cells provided the highest levels of NH_4-N removal and NO_3-N production.

During October 1998, when NO_3-N doubled in the hummock cells, the mean DO was over four times higher than in the other cell types (Table 3). Likewise, the pH was higher during daylight, indicating algal photosynthesis. The following year, the diurnal patterns were not as divergent as the previous year; however, DO and pH remained higher in the hummock cells than in the thinned or control cells.

Table 4 compares the three vegetation management strategies in their abilities to meet wastewater constituent discharge limits in removing BOD_5, total coliforms, TSS, total inorganic N (TIN), and TP. We included data from our initial 1993 study for comparison. Total coliform and BOD_5 removals were not substantially different among the cell types. Total coliform numbers were reduced by at least 97% in all cells following reconfiguration. BOD_5 concentrations were reduced in all cells to near background levels and TSS influent concentrations were below background levels making further removal difficult (Kadlec and Knight, 1996). While algal blooms occasionally increased TSS concentrations, they aided in TIN removal through assimilation and by providing the dissolved oxygen necessary for nitrification. TP concentration increased slightly as the wastewater moved through the control and thinned cell types during both growing seasons, but was virtually unchanged in the hummock cells.

3.3. Mosquito production

Adult mosquito production differed significantly among the vegetation management treatments (Friedman's method: $\chi^2_2 = 15.27$; $P < 0.001$) during 1998. The number of *Culex* spp. emerging from the control cells was 100- and ten-fold per m^2 of water surface greater than from the hummock and thinned cells, respectively, during the second week after flooding. Thereafter during 1998, mosquitoes were not found in emergence trap samples from the hummock cells. Adult production declined 4–6 weeks after initial flooding in the control and thinned treatments, and a low level of emergence (< 2 individuals per m^2) occurred until emergence traps were removed from the ponds in mid-October 1998. *Culex tarsalis* constituted 71% of the emerging mosquitoes, and adult production from the control cells was significantly greater than from the thinned or hummock cell types (Mann–Whitney *U*-tests, $P < 0.05$). *C. stigmatosoma*, *C. quinquefasciatus* and *C. erythrothorax* were 27, 1 and $< 1\%$, respectively, of the emerging adult mosquitoes. After correcting for vegetation coverage, the per cell mosquito production from hummock cells and thinned cells was 2 and 25%, respectively, that of the control cells during 1998 (Fig. 3).

The trends for abundance of mosquito larvae in dip samples among the treatments (Fig. 4) were similar to those observed for the emergence traps during 1998. Declines in larval mosquito populations preceded those for emergent adults by 1–2 weeks. Significantly more *C. tarsalis* larvae were collected from control cells than from thinned and

Table 3
Mean, maximum, and minimum hourly dissolved oxygen (DO) concentrations and pH values

	DO (mg/l)			pH		
	Minimum	Mean	Maximum	Minimum	Mean	Maximum
28–30 October 1998						
Control cells	0.2	0.8	2.0	7.2	7.3	7.4
Thinned cells	0.7	1.4	2.5	7.4	7.4	7.5
Hummock cells	3.1	6.1	9.8	7.4	7.6	7.9
10–13 May 1999						
Control cells	1.1	2.1	3.7	7.3	7.4	7.5
Thinned cells	0.3	1.8	6.7	7.1	7.2	7.3
Hummock cells	1.3	4.1	7.2	7.4	7.5	7.6
20–24 September 1999						
Control cells	No data	No data	No data	No data	No data	No data
Thinned cells	0.2	1.5	5.9	6.9	7.1	7.5
Hummock cells	0.2	4.3	8.1	6.9	7.3	8.4

Table 4
Comparison of mean inflow and outflow wastewater constituent concentrations

	BOD_5 (mg/l)	Total coliforms (MPN per 100 ml)	TSS (mg/l)	Total inorganic N (mg/l)	Total P (mg/l)
5 May–3 November 1993[a]					
Inflow	5	363 600	10	14.41	4.0
Three-phase cells outflow	6	6417	8	7.05	5.4
One-phase cells outflow	5	25 573	5	14.33	4.9
12 August–29 October 1998					
Inflow	19	1 035 000	6.5	13.38	2.4
Control cells outflow	8	28 877	6.1	4.97	3.5
Thinned cells outflow	9	14 162	10.3	5.24	3.0
Hummock cells outflow	6	10 685	4.2	5.22	2.2
8 April–23 September 1999					
Inflow	10	766 174	5.9	13.25	1.2
Control cells outflow	5	3809	7.3	10.12	1.7
Thinned cells outflow	5	5361	4.5	12.18	1.6
Hummock cells outflow	6	17 493	5.7	8.73	1.3
H/SJ RWRF discharge limits	30	2.2 (after disinfection)	30	10.00	N/A

[a] Data from USBR/NBS/EMWD (1994).

hummock cells (Friedman's method: $\chi^2_2 = 11.56$, $P < 0.003$; control > thinned, hummock, Mann–Whitney U-tests, $P < 0.05$).

Mosquito larvae were associated with vegetation and were rarely found in open water. On the first sampling date in 1998 all larvae were collected in emergent vegetation along the periphery of the research cells. Median larval mosquito abundance in the perimeter vegetation of one hummock cell differed significantly from that in the open water in the interior of the cell (median in edge vs. interior samples = 3.5 vs. 0; Mann–Whitney Rank Sum test: $T_{4.16} = 16$; $P = 0.016$). Even though the median abundance of mosquito larvae in perimeter versus interior samples did not differ significantly for the second hummock cell (medians in edge and interior samples = 0; Mann–Whitney Rank Sum test: $T_{4.16} = 28$; $P =$ 0.199), the comparatively few mosquito larvae collected in this hummock cell were found only in samples from the perimeter vegetation. Thereafter, mosquitoes were either not present or were collected from samples taken in emergent vegetation.

As vegetation coverage increased during the second year, summer mosquito abundance in the research cells increased significantly ($F_{7.35} = 9.70$, $P < 0.001$; contrast 1998 vs. 1999: $F_{3.5} = 6.61$, $P < 0.034$). During summer 1999, mean larval mosquito abundance was approximately six *Culex* larvae per dip. Larval mosquito abundance (Friedman's method: $\chi^2_2 = 3.81$; $P > 0.05$) and adult mosquito production per m^2 of vegetated water surface (Friedman's method: $\chi^2_2 = 2.67$; $P > 0.05$) did not differ significantly among the treatments on most dates during 1999 (Figs. 3 and 4). However, after correcting for vegetation coverage, annual adult mosquito production per pond remained lowest in the hummock cells and was approximately 50% that of the other treatments (~ 92 000 mosquitoes per hummock cell per year vs. 174 000 mosquitoes per control cell per year and 182 000 mosquitoes per thinned cell per year). About 89% of the emerged mosquitoes in 1999 were *C. tarsalis*. *Culex erythrothorax*, *C. quinquefasciatus* and *C. stigmatosoma* constituted, respectively, 8, 2 and 1% of the emerged mosquitoes.

4. Discussion

Our investigations within 0.1 ha wetland research cells receiving ammonia-dominated, secondary-treated effluent suggest that managing bulrush vegetation by keeping it interspersed with open water significantly improves the NH_4-N and TN removal capabilities of a free water surface wetland. The interspersion of open water areas, or vegetation voids, in the hummock cell configuration maintained a consistently higher level of treatment than did the solid bands of dense vegetation in the thinned and control cells. A 50% vegetated to 50% open water ratio in the wetlands without hummocks did not maintain the early successional plant growth treatment success into the second growing season. The hummock configuration, on the other hand, maintained a more interspersed pattern of open water and vegetation as well as a higher level of nitrogen removal. Our data indicate that this interspersion effect was also effective in removing other wastewater constituents.

These results confirm earlier results obtained at the Hemet/San Jacinto Wetland Research Facility. In 1993, during the first year of operation, the one-phase (fully vegetated) research cells reduced NH_4-N by an average of only 6% while the three-phase (marsh–pond–marsh, 70% vegetated) cells removed 58% on average (Table 2, USBR/NBS/EMWD, 1994). Likewise, in 1996, during the first growing season the adjacent 9.9 ha demonstration wetland was in operation, an average of 76% of NH_4-N was removed from the marsh–pond–marsh configuration. At that time, the plant clumps were discrete and vegetation voids were large, effectively interspersing the planted zones with open water. Sixteen months later as the demonstration wetland's vegetation stands became more dense, an average of only 4% NH_4-N was removed (Sartoris et al., 2000). In both cases, as the vegetation reached maximum density and biomass (which contributed to internal nutrient loading and large anaerobic zones) and was no longer interspersed with open water (further limit-

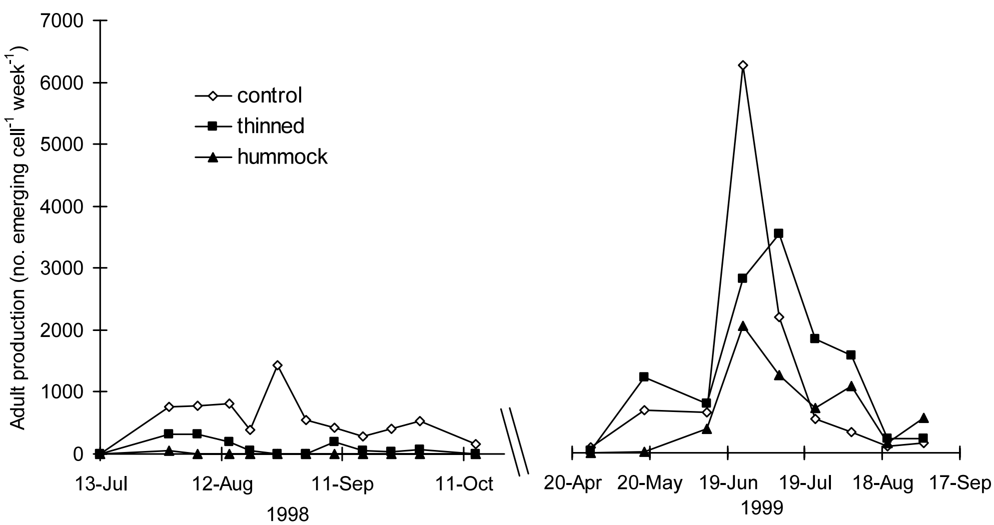

Fig. 3. Adult mosquito (*Culex* spp.) production from the vegetated regions of wetland research cells under the three vegetation management strategies.

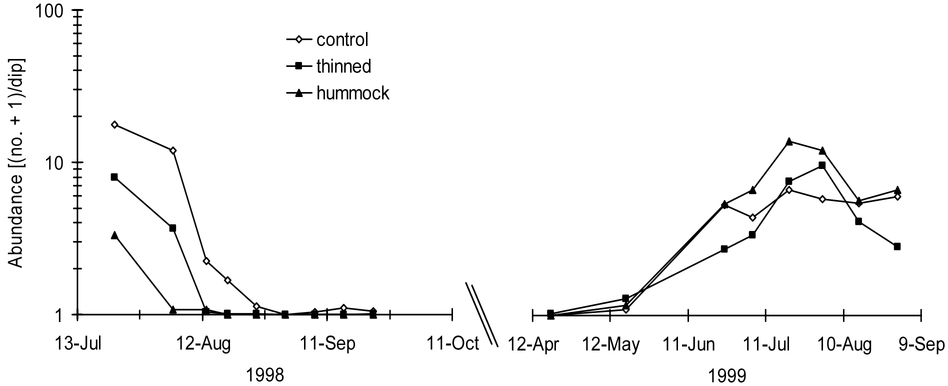

Fig. 4. Abundance of *Culex* spp. larvae in dip samples from wetland research cells under the three vegetation management strategies.

ing DO in the water column by restricting mixing and algal photosynthesis), lower NH_4-N RE resulted.

The consecutive processes of nitrification and denitrification are well understood by treatment wetland scientists. Wastewater high in NH_4-N must have oxygen available for the nitrifying bacteria to convert it sequentially to NO_2-N and NO_3-N, and then carbon and anoxia are necessary for the denitrifying bacteria to convert the NO_3-N to N_2. The combination of the aerobic and anaerobic zones within a wetland system is thus required for effective N removal (Mitsch and Gosselink, 2000; Kadlec and Knight, 1996; USEPA, 2000). Hammer and Knight (1994) stated that open water areas totaling 10–20% of a wetland system, arranged intermittently along its length, appeared to be beneficial for N treatment. However, the 50% open water ratio in the pond–marsh–pond–marsh control and thinned cells alone was not open enough to maintain the treatment benefits in this Californian coastal scrub climate (Pase and Brown, 1994) where the 3.5 m tall bulrush can produce up to 992 culms per m^2. The critical component in controlling REs in a treatment wetland receiving high loads of NH_4-N is the degree of interspersion of vegetation with open areas large enough for light penetration. This interspersion effect appears to mimic an early successional plant growth stage, such as the first growing season of a typical free water surface wetland.

Busnardo et al. (1992) pointed out that the nutrient assimilation of emergent plants (*S. californicus*) that have reached maximum density within a large, mature wastewater wetland with a low ratio of edge to surface area, would be lower than what they observed in their 1.22×1.65 m mesocosms. On the other hand, they concluded that a treatment wetland designed to maintain a high ratio of edge to surface area would enable the vegetation to assimilate and remove the bulk of the wastewater nutrients. Their ratio of edge to surface area theory appears to be related to the benefits derived from the interspersion of vegetation and open water, however, the benefits of the interspersion are more varied and complex.

Early in a successional growth period when the emergent plants are interspersed with open water, numerous processes are concurrent:

- The young, actively growing plants are absorbing nutrients from the wastewater. During this time, they contribute little senesced plant material into the water column (Shaver and Melillo, 1984; Breen, 1990; Rogers et al., 1991; Vymazal, 1995; Asaeda et al., 2000; Liu et al., 2000).
- The plants are providing suitable substrate for various types of microbiota (Brix, 1994; Weisner et al., 1994; Kadlec and Knight, 1996; Wetzel, 2000).
- The interspersed open water allows penetration of sunlight and mixing at the air/water interface producing higher DO concentrations and conditions necessary for algal and periphyton

uptake (Hansson and Granéli, 1984; Moore et al., 1994; Grimshaw et al., 1997; Wetzel, 2000; Présing et al., 2001).

- The open areas also enhance photolysis, which is necessary to detoxify pathogens and many other contaminants (Barber et al., 1999).
- The open configuration creates better habitat for aquatic invertebrates, including mosquito predators, especially when water depths are ≥ 60 cm (Batzer and Resh, 1992; Walton and Workman, 1998; Russell, 1999; de Szalay and Resh, 2000).
- The open configuration reduces mosquito refuges, especially when water depths are ≥ 60 cm (Batzer and Resh, 1992; Russell, 1999; Walton et al., 1999a; de Szalay and Resh, 2000).
- The open configuration provides more diverse wildlife habitat (Weller, 1978).

These characteristics are all desirable in maintaining an effective ammonia-dominated free water surface treatment wetland and a high quality wildlife habitat.

While more than 50% open water was maintained in all the cells, and the hummock cells maintained an additional 42% interspersion of open water throughout the vegetation, N RE declined by the end of the second growing season (September 1999). We suspect this was due to the small area of the research cells. As the emergent marsh areas quickly revegetated following the burn and reconfiguration, dense stands of bulrush grew to line the cell perimeters, reducing the openness of the deep-water areas within each cell more than anticipated. The additional vegetation appeared to impact the treatment results. The impact from the dense vegetation growth around the cell peripheries would be minimized in a full-scale treatment wetland. Nevertheless, our data have shown that nitrification occurred in the areas where adequate DO was available. NO_3-N was consistently produced in the hummock cells throughout the study.

Physically limiting the area in which vegetation could reestablish reduced mosquito refuge areas compared with burning and rhizome thinning or burning alone. During the first season, mosquito production from the control cells was 50- and four-fold greater than from the hummock and the thinned cells, respectively. During 1999 as the vegetation growth increased, mosquito production increased concurrently. Even though larval abundance and adult production per m^2 of vegetated water surface did not differ significantly among the treatments during 1999, the hummock cells maintained comparatively more open water than did the other treatments and produced fewer mosquitoes.

The open water between small stands of emergent vegetation in the hummock cells will also enhance supplemental mosquito abatement utilizing biological control agents and nonchemical methods of mosquito control such as mosquito-specific bacteria by promoting contact between the control agents and mosquito larvae. Implementation of mosquito abatement in seasonally-flooded and treatment wetlands has occurred at larval mosquito abundance of ≤ 1 larva per dip (Tennessen, 1993; Knight et al., 2000). A mean mosquito abundance of three to 12 larvae per dip observed during summer 1999 is comparatively high and depending on other factors such as size of the wetland, proximity to human development, and activity of pathogens and vectors of public health concern, supplemental mosquito control measures might be required. Problems for mosquito control in some treatment wetlands include penetration of thick emergent vegetation by aerial application of control agents or delivery of sufficient doses of mosquito control agents by water flow to immature mosquitoes inhabiting dense vegetation (Walton et al., 1998; Wass et al., 1999; Prior, 2000). While anaerobic zones are necessary for denitrification and effective NO_3-N removal, large areas of dense vegetation might also reduce movement of important mosquito predators into zones with low DO concentrations, particularly for biota with limited abilities to utilize atmospheric oxygen.

The results from this study demonstrate that proper vegetation management can improve the N removal of a treatment wetland while minimizing mosquito production. We have demonstrated that these two goals can be compatible and sustainable with appropriate wetland design and management. However, wetland designs and management plans must be tailored appropriately to individual settings, since they are natural biological systems (Batzer and Resh, 1992), and designed to remove the specific water constituents of concern entering the treatment wetland.

5. Conclusions

Interspersion of emergent wetland vegetation with open water areas enhanced treatment of ammonia-dominated, secondary-treated effluent in wetland research cells in southern California. Cells in which the emergent vegetation zones were configured as a series of hummocks surrounded by deeper water mimicked a natural early successional plant growth stage by maintaining an interspersion of vegetation with open areas large enough for light penetration. The hummock cells removed 70% of the NH_4-N during the first year, and maintained a 47% removal efficiency during the second year in spite of the fact that the small scale of the cells and hummocks allowed some bulrush encroachment into the deeper open areas.

Mosquito production remained lowest in the hummock cells where vegetation cover was the lowest. Mosquito populations increased directly with vegetation coverage. Delivery of mosquito control agents to the water surface and supplemental control by biological agents such as larvivorous fish will be enhanced in the comparatively open water configuration of the hummock cells.

The hummock configuration was successful in limiting vegetation coverage to specific areas, though the hummocks must rise high enough above the wetland floor to provide adequate water depth to maintain this success. A water depth sufficient to completely limit emergent vegetation propagation (0.7–1.8 m depth at this site) proved to be the most effective method of maintaining the desired vegetation coverage. Aboveground burning and thinning the rhizomes proved to be only temporary (less than 1 year) methods of curtailing the vegetation.

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