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THE EFFECTS OF BIRD USE ON NUTRIENT REMOVAL IN A CONSTRUCTED WASTEWATER-TREATMENT WETLAND

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Abstract: A 9.9-ha constructed wetland designed to reduce nitrogen in municipal wastewater following conventional secondary treatment began operating in southern California's San Jacinto Valley in September 1994. The wetland incorporated zones of bulrush (*Schoenoplectus acutus* and *S. californicus*) for effluent treatment, plus areas of 1.8-m deep open water and other features to benefit wintering waterfowl. A one-year long program to monitor bird use and evaluate their contribution to loadings of nitrogen and phosphorus was initiated seven months later and a second, four-month long period of monitoring was initiated after a 20-month hiatus. Daily bird use peaked at nearly 12,000 individuals during the second period. Estimates of maximum daily nitrogen and phosphorus input by birds were 139 g N ha^{-1} day^{-1} and 56 g P ha^{-1} day^{-1}. Following a reconfiguration of the wetland that increased the area of open water, a third year-long period of monitoring was initiated in September 2000. Estimated maximum daily loading attributable to birds during this period reached 312 g N ha^{-1} day^{-1} and 124 g P ha^{-1} day^{-1}. These levels represent only 2.6% and 7.0%, respectively, of the mean daily loads of N and P in inflow water from the wastewater-treatment plant. Wintering waterfowl contributed the most to nutrient loading, but the numerically dominant species was the colonial Red-winged Blackbird (*Agelaius phoeniceus*). The wetland's nutrient-removal efficiency was negatively correlated to bird loading. However, the greatest bird loading occurred during November to March, when winter conditions would reduce microbial nutrient-removal processes and plant uptake in the wetland. Multiple regression analysis indicated that variation in nutrient removal efficiency over a one-year period was best explained by wetland water temperature (R^2 = 0.21) and that little additional insight was gained by adding bird loading and inflow nutrient load data (R^2 = 0.22). This case study supports the concept that a constructed wetland can be designed both to reduce nutrients in municipal wastewater and to provide habitat for wetland birds.

Key Words: blackbirds, California, constructed wetland, nitrogen, nutrient removal, phosphorus, *Schoenoplectus acutus*, *S. californicus*, wastewater treatment, waterfowl

INTRODUCTION

The construction of wetland systems to mimic natural wetlands, with particular emphasis on their nutrient-removal capabilities, has become increasingly popular in the United States since the concept was introduced from Europe in the early 1970s as a low-cost alternative to conventional tertiary municipal wastewater treatment (USEPA 1984, Kadlec and Knight 1996, Cole 1998, Mitsch and Gosselink 2000). Most of the constructed wetlands presently used for treatment of municipal wastewater in the United States are ''surface flow'' systems; i.e., artificial marshes planted with emergent vegetation, in which the water surface is maintained above the sediment under normal operating conditions (Cole 1998, Mitsch and Gosselink 2000). A consideration of the physical nature of these constructed marshes, coupled with their known capacity to attract wildlife (Kadlec and Knight 1996, USEPA 1999), led Sartoris and Thullen (1998) to argue that the wetlands all provide habitat, although that habitat can vary greatly in quantity and quality.

Although many people view the ancillary wildlife habitat value generated by a constructed wastewater-treatment wetland as a social benefit (Kadlec and Knight 1996, Cole 1998, Hanson 2002), the intentional integration of wastewater treatment with habitat creation in a multipurpose constructed wetland (Stiles 1994) is not common and remains controversial. Wildlife biologists, beginning with Friend (1985), have noted the potential for a constructed municipal wastewater treatment wetland to become an attractive nuisance by

exposing birds to pathogens or harmful pollutants. On the other hand, many wastewater-treatment-plant operators and designers question the idea of intentionally encouraging bird use of a constructed treatment wetland because they view bird use as a threat to treatment efficiency (Knowlton et al. 2002). In particular, birds feeding outside a constructed wetland but depositing their excreta within it may add sufficient nutrients to replace any removed from the wastewater inflow through vegetation uptake and microbial processes. Bird-mediated transfers of nutrients from terrestrial to aquatic environments have been quantified in some natural systems (Hayes and Caslick 1984, Manny et al. 1994, Marion et al. 1994, Scherer et al. 1995, Post et al. 1998), but no study has evaluated the process for its potential to compromise constructed wastewater-treatment wetland performance. The present study was undertaken to determine the effect of bird use on the nutrient-removal efficiency of a multipurpose constructed wetland specifically designed to integrate the objectives of municipal wastewater treatment and provision of wildlife habitat. Nitrogen and phosphorus loading by birds using the constructed wetland were estimated and compared with loadings from inflow water, which was secondary-treated effluent from a municipal wastewater-treatment plant. We also estimated wetland nutrient-treatment efficiency in order to test the hypothesis that the bird-mediated nutrient loading had no significant impact on the ability of the wetland to remove nitrogen (N) and phosphorus (P) from the treatment-plant effluent.

STUDY SITE

We worked at the 9.9-ha Eastern Municipal Water District Multipurpose Demonstration Wetland (hereafter, demonstration wetland). The demonstration wetland is located at the Hemet/San Jacinto Regional Water Reclamation Facility (RWRF), 6.4 km north of Hemet, California, USA (33° 48′ N, 117° 1′ W). The site is in the alluvial San Jacinto Valley at an elevation of 457 m. The area has a Mediterranean climate, with hot, dry summers and mild winters; the average length of the frost-free period is 247 days. Annual precipitation at the Riverside Citrus Experiment Station, approximately 50 km northwest of the RWRF, is 25.6 cm (1961–1990 basis), with most rain falling during November to March. Mean pan evaporation is 208 cm yr^{-1}, and summer temperatures frequently exceed 38°C.

The valley contains a number of areas attractive to wintering waterfowl and other birds, including Mystic Lake, a remnant of large, marshy San Jacinto Lake (Willett and Jay 1911), located 11 km northwest of the RWRF. Wetland habitat is also provided within the 1900-ha San Jacinto Wildlife Area, a California Department of Fish and Game facility located 13 km northwest of the RWRF. Large numbers of migratory waterfowl, shorebirds, and songbirds pass through the region, and many overwinter within it (Heitmeyer et al. 1989). The land immediately surrounding the RWRF is predominately devoted to agricultural use, mainly as alfalfa fields and dairy farms. A privately-owned, 30-ha wetland complex adjacent to the boundary of the RWRF and just north of the demonstration wetland is managed as a duck hunting club, one of several in the San Jacinto Valley.

Both the RWRF and the demonstration wetland are owned and operated by the Eastern Municipal Water District (EMWD). The wetland was designed and constructed as a cooperative project between EMWD and the U.S. Bureau of Reclamation to demonstrate the ability of a constructed wetland to serve the combined purposes of improving the quality of RWRF effluent and providing habitat for migratory birds in this section of the Pacific flyway (Stiles 1994).

The RWRF includes a municipal wastewater-treatment plant that uses an activated sludge process and produces an ammonia-dominated, secondary-treated effluent at an average rate of 28,400 m^3 d^{-1} (7.5 MGD). Part of this treated effluent is routed through the demonstration wetland before being blended with the rest of the RWRF effluent in the chlorine-contact chamber. After chlorination, the entire reclaimed water effluent of the RWRF is sold for reuse to agricultural irrigators and duck hunting clubs in the San Jacinto Valley. Inflow to the wetland from the RWRF during the period 1996–1998 averaged 5102 m^3 d^{-1} (1.35 MGD). After reconfiguration of the wetland (described below), the average inflow increased to 8089 m^3 d^{-1} (2.14 MGD).

As originally constructed in 1994, the demonstration wetland was configured as a marsh-pond-marsh system (Figure 1A), with five inlet marshes (normal operating water depth 0.5 m) feeding into a central pond (normal operating water depth 1.8 m), followed by two polishing outlet marshes (normal operating water depth 0.5 m) separated by a longitudinal berm to control short-circuiting of the flow (Stiles 1994). The marsh areas of the wetland were planted with locally-collected California bulrush (*Schoenoplectus californicus* C. A. Meyer) and hardstem bulrush (*Schoenoplectus acutus* G. H. E. Muhlenberg ex. J. Bigelow) in September 1994, just prior to the first flooding of the wetland. The inlet and outlet marshes were planted in strips separated by unplanted open water areas to provide sampling access and to alleviate short-circuiting of flows (Figure 1A). Water quality and particularly nitrogen dynamics in the demonstration wetland were investigated from January 1996, when it became an

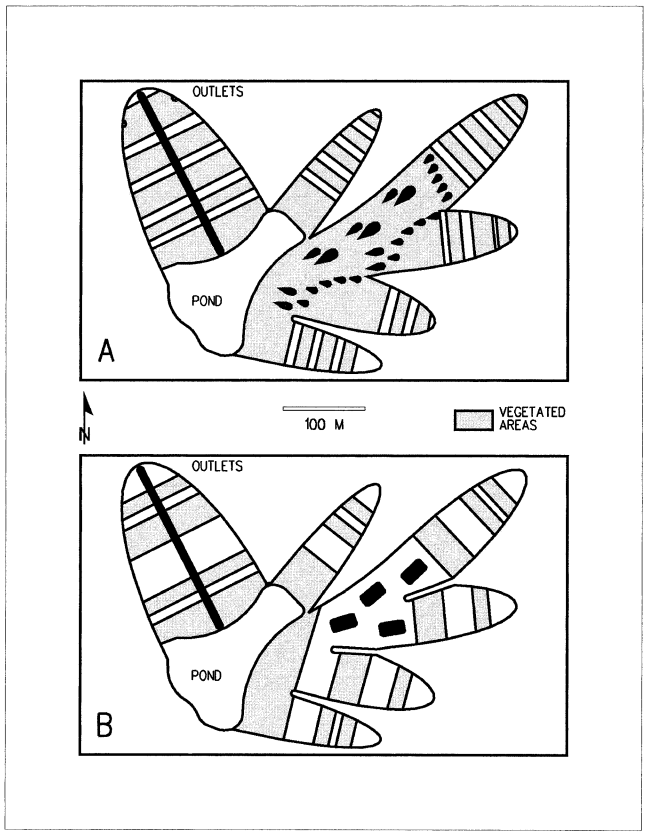

Figure 1. (A) Original configuration of the EMWD Multipurpose Demonstration Wetland, showing the 1.8-m deep pond, teardrop-shaped islands, and berm dividing the outlet arm (black), and areas within the 0.5-m deep zone where bulrush was planted in 1994 (gray). The five wastewater inlet positions are denoted with arrows. (B) Reconfigured wetland, showing four rectangular islands and outlet berm (black) and 0.5-m deep areas where bulrush was allowed to regrow (gray). Other portions of the formerly 0.5-m deep zone were deepened to 1.8 m (unshaded), precluding bulrush encroachment. The five wastewater inlet positions are denoted with arrows.

integral part of the RWRF treatment chain, through March 1998. Nitrogen transformations in the wetland during this period have been described by Sartoris et al. (2000a), and denitrification rates in the wetland during the last two months of the period are presented in Smith et al. (2000). On the basis of the results of these nitrogen dynamics studies, vegetation management experiments conducted elsewhere on the RWRF site (Thullen et al. 2002), and consideration of patterns of bird use up to that time, it was decided that reconfiguring the wetland to include a larger proportion of deep open water would improve its ammonia nitrogen removal function, reduce nuisance mosquito populations (Walton and Workman 1998), and maintain or perhaps improve avian habitat diversity.

Between April 1998 and February 1999, the wetland was drained, the accumulated above-ground emergent vegetation biomass was burned, and the bottom re-excavated to produce a hemi-marsh configuration (Weller and Spatcher 1965, Sartoris and Thullen 1998), with approximately equal areas of deep open water (normal operating water depth 1.8 m) and emergent marsh (normal operating water depth 0.5 m) (Figure 1B). The effects of this reconfiguration of the wetland on denitrification rates and internal nitrogen transformations during the first year of renewed operations are described by Smith et al. (2000) and Sartoris et al. (2000b), respectively. Ecological change within the reconfigured system was also effected by the accidental introduction of mosquito fish (*Gambusia* sp.) in 1999.

METHODS

Estimates of the daily loading rate of nitrogen (organic N, total ammonia-N, NO_2^--N, NO_3^--N, and total N) and phosphorus (total P) to the demonstration wetland from the RWRF, and daily export rate of these same nutrients from the wetland, were calculated for each week during the periods January 4, 1996 to March 31, 1998 (Configuration A) and February 18, 1999 to March 28, 2002 (Configuration B). These rates were estimated by combining concentration data with total daily inflow and outflow volume data obtained as follows. Each week, water samples were collected from the inflow and outflow pipelines and analyzed within 24 hours of collection by EMWD staff for total ammonia-N [(NH_3 + NH_4^+)-N, hereafter referred to as TAN), total Kjeldahl nitrogen (TKN), nitrite-N (NO_2^--N), nitrate-N (NO_3^--N), and total P concentrations, according to EPA protocols (USEPA 1984). Details of the individual laboratory analyses are presented in Smith et al. (2000) and in Thullen et al. (2002). The concentration of organic N was calculated as the difference between TKN and TAN, and total N concentration was calculated as the sum of TKN, NO_2^--N, and NO_3^--N. Inflow to the demonstration wetland was measured by means of an in-pipe magnetic meter equipped with a totalizer, and outflow was measured by a similarly equipped in-pipe propeller meter. Both meters were read and reset daily by the RWRF operations staff, providing a measurement of the total inflow and outflow volumes for the day on which each set of water samples was collected. The N and P load estimates for periods prior to January 2000 are taken from Sartoris et al. (2000a, 2000b).

We measured nutrient-removal performance of the demonstration wetland in the manner suggested for effluent-load removal efficiency (Reed et al. 1988, Kadlec and Knight 1996). Removal efficiency (RE) for a given N species or for total P is defined as the percent

Table 1. Changes in the extent and nature of major habitat components within the EMWD Multipurpose Demonstration Wetland based on aerial photographs and sampling at random locations within bulrush stands. Change within a configuration was due largely to expansion of planted bulrush, whereas change between configurations was due to the reconfiguration process. Tabulated areas are in hectares, with percentage of total wetted area in parentheses. The wetland was reconfigured between April 1998 and February 1999.

	Configuration A			Configuration B	
	May 1995	May 1996	April 1998	Sept 2000	Oct 2001
Component area (ha)					
Total bulrush	0.29 (3%)	6.36 (64%)	7.62 (77%)	3.28 (34%)	3.95 (41%)
Schoenoplectus acutus	0.11	1.17	0.73	0.09	0.15
S. californicus	0.18	5.19	6.89	3.19	3.80
Other vegetation	0	0	0	0.06 (1%)	0.16 (2%)
Open water	8.97 (97%)	3.55 (36%)	2.32 (23%)	6.39 (66%)	5.54 (57%)
Bare soil[a]	0.23	0.03	0.09	0.10	0.12
Total wetted area	9.26	9.91	9.94	9.73	9.65
Bulrush stem density (culms/m^2)[b]					
S. acutus	Not sampled	Not sampled	65	0	0
S. californicus	Not sampled	Not sampled	380	294	201

[a] Bare soil includes islands and berms separating inlet ''fingers'' (see Figure 1) and is not included in calculation of Total Wetted Area.
[b] Based on sampling within quadrats randomly located within the 0.5-m deep portion of the wetland.

by which the load of that particular constituent is reduced by the wetland:

$$RE = [(L_i - L_o)/ L_i] \, 100\%$$

where L_i is the load imported from the RWRF and L_o is the load exported from the wetland, both in units of kg d^{-1}. RE calculated in this manner has a maximum value of 100% but no lower bound. In particular, large negative values are possible when inflow load is unusually small (e.g., when flow from the RWRF to the demonstration wetland is reduced), but outflow value remains at a ''normal'' level due to the lag in system response time. Because this effect led to large variation in RE values at low RWRF-derived nutrient loads (see Results), we only used data for loads above an empirically-derived minimum value in analysis of load-RE relationships.

Counts of the numbers of birds using the wetland, by species, were the basis for the estimates of N and P loading from birds. The wetland was divided into zones, and counts of birds using each zone were made during an early morning census, conducted from a vehicle when vegetation was sparse and by foot once vegetation developed sufficiently to serve as an effective blind. Care was taken to minimize disturbance of birds and to avoid counting individuals more than once. Individuals were minimally identified to species with the aid of binoculars and a spotting scope. Each species was assigned to one or another of seven groups based on taxonomic and ecological affinities: ''blackbird,'' ''rail,'' ''raptor,'' ''songbird,'' ''wader,'' ''waterfowl,'' or ''other.'' Counts were initiated in March 1995 (seven months after planting) and continued at a rate of three or four non-consecutive mornings per 2-wk period through February 1996. Following a 20-month hiatus during which emergent vegetation continued to develop (Table 1), morning censuses were again conducted using a slightly reduced schedule (two or three non-consecutive mornings per 2-wk period) from the end of December 1997 to mid-April 1998. Following the reconfiguration of the wetland in 1998–1999, censuses were again conducted (three non-consecutive mornings per 2-wk period) from mid-September 2000 to mid-September 2001. For each species and throughout all three monitoring periods, the average of the counts made during a 2-wk interval was used as the estimate of the number of individuals of that species using the wetland each day of that interval.

An estimate of daily nitrogen input into the wetland by a species was calculated as the product of the number of birds present, the daily nitrogen output in droppings produced by an individual bird, the proportion of the individual's diet obtained from outside the wetland (P_D), and the probability that its droppings would enter the wetland (P_W). Total N input was then calculated as the sum of the species-specific estimates. Daily nitrogen output by an individual bird was calculated as the product of total daily output of excreta (fecal matter plus urine) and the nitrogen content of excreta. We assessed food sources and sites of excreta deposition from published natural history information and our observations on the species' feeding, nesting, and roosting behaviors in the wetland. Because of uncertainty associated with values of P_D and P_W, we adopted a conservative approach and included in the analysis only species feeding primarily outside the

wetland but returning to it to roost or care for nestlings. For these species, we assumed ($P_D \times P_W$) = 1. We further restrained our analyses to species having ≥50 individuals present at ≥1 census, thereby excluding species whose potential contribution to total avian loading was always very small. The potential export of nutrients from the wetland by birds, which would occur largely through dispersal of young birds reared in the wetland, was not considered.

Excreta production (g dry mass day^{-1}) for waterfowl was assumed equal to 3% of body mass. We consider this value to be reasonable but conservative for our purposes, given the excreta production rate of 2.25% used in other studies (see Scherer et al. 1995). Body mass was taken as the average for sex-specific values presented by Dunning (1993). Nitrogen content of excreta was assumed to be 3.5%, a value intermediate between that obtained for the Mallard (*Anas platyrhynchos* L.; 2.62%, Marion et al. 1994), and wintering Canada geese (*Branta canadensis* L.; 4.8%, Manny et al. 1994). This value should be reasonably representative of the mixed diets likely ingested by waterfowl feeding in adjacent wetlands and fields. For Red-winged Blackbirds (*Agelaius phoeniceus* L.), N input was estimated as the number of birds roosting overnight multiplied by the N content (9.6%) of an individual bird's nightly production of fecal material (0.727 g dry mass, Hayes and Caslick 1984). For other species in the blackbird group [Brewer's Blackbird (*Euphagus cyanocephalus* Wagler), Great-tailed Grackle (*Quiscalus mexicanus* Gmelin), Tricolored Blackbird (*Agelaius tricolor* Audubon), and Yellow-headed Blackbird (*Xanthocephalus xanthocepahlus* Bonaparte)], excreta production rate was calculated as the product of the excreta production rate for the Red-winged Blackbird multiplied by the species' body mass relative to that of the Red-winged Blackbird. For waders feeding off the wetland, we assumed daily excreta production to equal 2% of body mass (because of the bird's relatively large size) and used N and P values for Red-winged Blackbird excreta, based on our assumption that diets (mixed grains and insects) were similar. Measured values of N (4.2%) and P (11.5%) in piscivorous heron excreta (Marion et al. 1994), suggest the blackbird values are again conservative for our purposes and probably more biologically realistic than assignment of a largely fish diet.

An analogous method was used to estimate phosphorus input, with the P content of waterfowl excreta assumed to be 1.4%, again intermediate between the value for the Mallard (1.32%, Marion et al. 1994) and the Canada Goose (1.5%, Manny et al. 1994). For blackbirds and waders, we used the P content of 1.3% (Hayes and Caslick 1984).

We used regression analysis to relate the estimates of nutrient-removal efficiency (arcsin-square root transformed data) to contemporaneous estimates of daily nutrient loads due to bird use. We used multiple regression analysis to assess the relative importance of bird loading, inflow nutrient loading, and wetland water temperature to nutrient-removal efficiency. Because water-temperature measurements were available for only ten widely-spaced, short (mean = 3.4 days, range 1–7 days) periods during 2000–2001, we first developed a regression equation relating those measurements to local air temperature, for which a continuous record of daily maximum and minimum values was available (Riverside Co., Station HEMET.T accessed through http://www.ipm.ucdavis.edu/WEATHER/wxretrieve.html). The raw water-temperature data, obtained at hourly intervals during each period with Hydrolab® recording sondes, were averaged over multiple locations and depths (range 0 to 1.8 m) within the wetland and over time, in order to minimize the effect of short-term weather events. We calculated a contemporaneous air temperature by averaging the midpoint between the daily maximum and minimum values over the same dates during which the water temperatures were obtained. We used the resulting regression equation to estimate wetland water temperature on days for which RE was estimated, using as input the average mid-range air temperature over the 4-day period ending on the date when RE was estimated. All analyses were performed using SYSTAT® 10 statistical software, with the exception of non-linear regressions, which were performed using SigmaPlot® 2000.

RESULTS

Nutrient Concentrations in RWRF Effluent Entering the Demonstration Wetland

During the period from January 4, 1996 through March 31, 1998 (Configuration A), the mean (± SD) inflow concentrations for total N, TAN, and total P were 19.9 (± 6.3) mg/L, 14.5 (± 6.1), and 2.5 (± 1.6) mg/L, respectively. The mean concentrations in the wetland outflow during this same period were 13.4 (± 6.3) mg/L, 11.1 (± 6.8) mg/L, and 2.7 (± 0.7) mg/L, respectively.

During the period from February 18, 1999 through March 28, 2002, after reconfiguration of the wetland to Configuration B, the mean inflow concentrations for total N, TAN, and total P were 17.8 (± 5.1) mg/L, 14.1 (± 5.3) mg/L, and 2.3 (± 1.0) mg/L, respectively. Mean wetland outflow concentrations during this period were 13.0 (± 5.7) mg/L, 9.3 (± 5.9) mg/L, and 2.2 (± 0.6) mg/L, respectively.

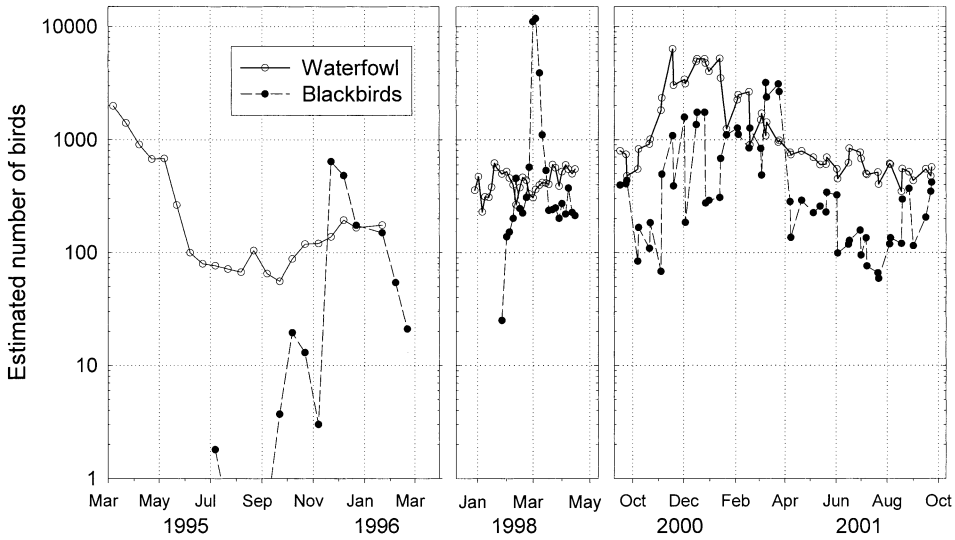

Figure 2. Seasonal variation in abundance of birds categorized as either waterfowl or blackbirds in the EMWD Multipurpose Demonstration Wetland during the three monitoring periods. The wetland was in Configuration A (see Figure 1) during first two monitoring periods, and in Configuration B for the third period. Note that abundance is plotted on a logarithmic scale.

Patterns of Bird Use

The demonstration wetland consistently attracted a large number of bird species and individuals. Ignoring species observed only flying over the wetland, a total of 63, 48, and 68 species were noted during the 1995–96, 1998, and 2000–2001 monitoring periods, respectively (a species list is available on request). Even though total species richness was comparable between the 1995–96 and 2000–01 monitoring periods, almost half the species were different. A total of 96 species were observed using the wetland during the study. Waterfowl were usually most numerous (Figure 2), with ducks typically contributing the most individuals. Geese were never observed, whereas American Coots (*Fulica americana* Gmelin), several duck species, and grebes (all lumped into the waterfowl group) were present year-around. The migratory waterfowl were already leaving the wetland when monitoring was initiated in March 1995, resulting in decreasing waterfowl abundance until migrants began to return in late summer (Figure 2). Most of the March 1995 waterfowl (85%) were American Wigeon (*Anas americana* Gmelin). The largest estimate for waterfowl use was made in mid-November 2000, when an estimated 6360 were present. Most of the waterfowl were again American Wigeon (41%), but Northern Shovelers (*A. clypeata* L.; 19%), Cinnamon Teal (*A. cyanoptera* Vieillot; 17%), and Green-winged Teal (*A. crecca* L.; 13%) were also abundant. Most migratory waterfowl had left the wetland by April, but several hundred birds, primarily Ruddy Ducks (*Oxyura jamaicensis* Gmelin), Cinnamon Teal, Northern Shovelers, Mallards, American Coots, Eared Grebes (*Podiceps nigricollis* Brehm) and Pied-billed Grebes (*Podilymbus podiceps* L.) were present throughout the summer of 2001.

Blackbirds constituted the second largest group of birds at the wetland. Few blackbirds were present until autumn 1995, and their appearance coincided with development of the first tall and relatively dense stands of bulrush in the wetland (Table 1). Numbers then increased rapidly as wintering species (primarily the gregarious Red-winged Blackbird) began using the stands as a roosting site. The extensive and dense stands of bulrush present in Spring 1998 (Table 1) undoubtedly had a role in attracting the very large number of blackbirds (approximately 11,800) that moved into the wetland in early March 1998. Although virtually all birds in this group were identified as Red-winged Blackbirds, some may have been Tricolored Blackbirds (listed by both federal and state authorities as a Species of Special Concern; Beedy and Hamilton 1999). Total blackbird numbers again peaked in March of 2001, when an estimated 3200 were using the reconfigured wetland (Figure 2). At that time, 52% were Tricolored Blackbirds and 43% were Red-winged Blackbirds.

Some larger species within the ''waders'' group were also potentially important in wetland functioning because of their abundance. As early as autumn 1996, there was a noticeable accumulation of excreta on some areas of bulrush attributable to roosting White-faced Ibises (*Plegadis chihi* Vieillot), Cattle Egrets (*Bubulcus ibis* L.), and herons. Aggregations of egrets containing up to 340 individuals were noted in the wetland in summer 2001.

Table 2. Estimated total daily input of nitrogen and phosphorus (g ha^{-1} day^{-1}) to the EMWD Multipurpose Demonstration Wetland from birds feeding off the wetland site but depositing excreta within it. Tabulated values are the mean daily input and the maximum daily input estimated for each of the three monitored periods, and the mean values for the December 1995 to February 1996 portion of the first monitoring period, when RWRF loading rate and wetland removal efficiency data were also available. Also tabulated for comparison are estimates of mean daily input of nitrogen and phosphorus in the RWRF inflow water, expressed in the same units (bottom two rows).

		March 1995 to February 1996		December 1995 to February 1996	January 1998 to April 1998		September 2000 to September 2001	
Species or Group		Mean[a]	Maximum	Mean	Mean	Maximum	Mean	Maximum
American Wigeon	N	12.1	139.3	0.9	1.2	3.9	49.8	251.8
	P	4.8	55.7	0.4	0.5	1.6	19.9	100.7
Mallard	N	0.6	3.3	0.3	2.0	8.7	5.8	15.3
	P	0.3	1.4	0.1	0.8	3.5	2.2	6.1
Blackbirds[b]	N	0.5	4.7	0.7	7.5	83.0	4.7	24.4
	P	0.1	0.6	0.1	1.0	11.2	0.6	3.3
Cattle Egret	N	0.1	0.6	<0.05	—	0	1.4	13.1
	P	<0.05	0.1	<0.05	—	0	0.2	1.8
White-faced Ibis	N	0.2	3.6	0	—	0	5.9	32.2
	P	<0.05	0.8	0	—	0	0.8	4.4
Total for all species	N	13.5	139.3	1.9	10.8	86.4	67.6	312.1
	P	5.2	55.7	0.6	2.3	12.6	23.9	124.3
RWRF loading	N	—[c]		4.84×10^3	17.26×10^3		11.80×10^3	
	P	—		1.04×10^3	2.26×10^3		1.78×10^3	

[a] Wetland area from Table 1: 9.3, 9.9, and 9.6 ha for monitoring periods 1, 2, and 3, respectively.
[b] Additive rate for Red-winged Blackbird, Tricolored Blackbird, Yellow-headed Blackbird, Brewer's Blackbird, and Great-tailed Grackle.
[c] RWRF inflow data are not available for the entire March 1995 to February 1996 monitoring period.

Avian Inputs of Nitrogen and Phosphorus

Only two waterfowl species met our criteria as significant contributors of nitrogen and phosphorus to the demonstration wetland, the American Wigeon and Mallard ducks. Other waterfowl were considered largely to recycle nutrients within the wetland (i.e., they fed as well as deposited excreta within it). All species of blackbirds and two waders, the White-faced Ibis and the Cattle Egret, were also considered contributors to nutrient loading. Birds added a maximum of 139 g N ha^{-1} day^{-1} to the wetland during the first year of monitoring (Table 2), all attributable to the large numbers of American Wigeon present during March 1995. Waterfowl numbers were decreasing at this time, suggesting that nutrient inputs would have been greater earlier in the year. Wintering wigeon (and waterfowl in general, see Figure 2) were less abundant in 1998, when peak nutrient loading rate was due almost entirely to the colony of 11,000 blackbirds that nested in the wetland in early March (Table 2). Even so, N loading peaked at only 86 g N ha^{-1} day^{-1}. Waterfowl again contributed the greatest nutrient load during the 2000–2001 year of monitoring (Table 2). The additive N input rate (calculated by adding contributions from each species on a given date) peaked at 312 g N ha^{-1} day^{-1} in mid-January. Because species' abundances (and thus their loading rates) peaked at different times, the maximum additive input rate was always less than the sum of the maximum loadings for all contributing species (Table 2). Values for phosphorus input parallel those for nitrogen in all monitoring periods, with a maximum loading of 124 g P ha^{-1} day^{-1} in 2001 (Table 2).

RWRF Loading of Nitrogen and Phosphorus

Mean daily areal loading rates of the various nitrogen species and total P to the wetland from the RWRF are summarized for the period of record of each configuration in Table 3. Loading rates of both total N and total P increased after reconfiguration of the wetland. Inflow also increased from an average of 5102 m^3 day^{-1} to 8089 m^3 day^{-1}, and an upgrade of treatment processes at the RWRF during the reconfiguration resulted in a slight increase in the proportion of NO_3^--N and decreases in the proportions of organic N and NO_2^--N in the effluent entering Configuration B. TAN, however, was always the predominant N species entering the wetland from the RWRF, comprising an average of 72% and 80% of the total N during the periods of record for configurations A and B, respectively (Table 3). The TAN removal efficiency varied greatly when loading rate was small (< 5 kg ha^{-1} d^{-1}; Figure 3), a condition produced whenever inflow from the RWRF to the demonstration wetland was reduced as part of treatment plant operations. Using only data

Table 3. Summary of loadings of nitrogen (N) and phosphorus (P) from the RWRF treatment plant to the EMWD Multipurpose Demonstration Wetland (g ha^{-1} day^{-1}) and the wetland's nutrient removal efficiencies for configurations A and B (see also Table 1 and Figure 1). Data in parentheses indicate the percentage of total N contributed by the N species.

	Organic N	TAN	NO_2^--N	NO_3^--N	Total N	Total P
Configuration A: 4 Jan 96–31 Mar 98						
Mean loading rate	1.82×10^3 (18%)	7.47×10^3 (72%)	7.9×10^2 (8%)	3.3×10^2 (3%)	10.4×10^3	1.25×10^3
Mean removal efficiency (%)	63.6	23.7	96.3	29.1	36.3	4.6
Configuration B: 18 Feb 99–28 Mar 02						
Mean loading rate	1.91×10^3 (13%)	11.68×10^3 (80%)	4.9×10^2 (3%)	6.5×10^2 (4%)	14.7×10^3	1.85×10^3
Mean removal efficiency (%)	−2.8	34.8	51.3	−16.6	28.4	8.7

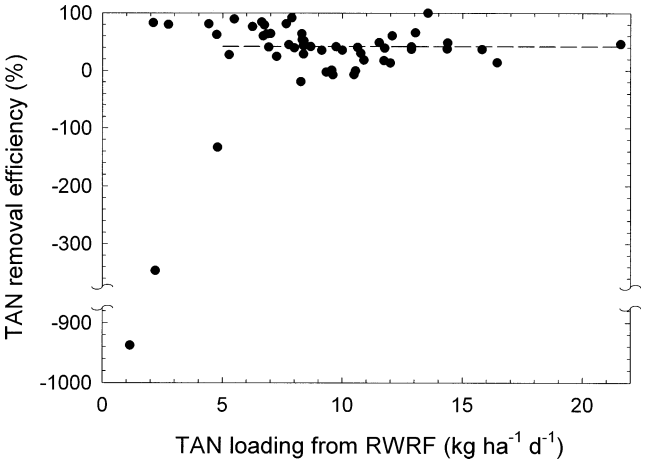

Figure 3. Removal efficiency (%) for total ammonia nitrogen [TAN = (NH_3 + NH_4^+)-N] in the EMWD Multipurpose Demonstration Wetland as a function of loading rate from the RWRF during 2000–2001. An analysis of data for loading rates > 5 kg N ha^{-1} d^{-1} (see text for rationale) detected no relationship between the variables (linear regression, P = 0.44); the horizontal dashed line depicts the mean removal efficiency value of 41.8%.

collected when loading rate from RWRF was above 5 kg ha^{-1} d^{-1}, a linear regression analysis failed to detect any effect from RWRF loading rate on removal efficiency (n = 47, P = 0.44). The mean removal efficiency (± SE) at the higher loading rates was 41.8 ± 4.0 %.

Effect of Avian Loading on Wetland Nutrient Removal Performance

A comparison of the values for avian inputs of N and P and RWRF loadings (Table 2) shows that the mean daily avian input of N during the three bird monitoring periods was only 0.04%, 0.06%, and 0.6% of the RWRF mean daily loading rate, respectively. The mean daily avian input rate of P during the same three periods was 0.06%, 0.1%, and 1.3% of the RWRF mean daily loading rate, respectively. The maximum contribution by birds to both N and P loading occurred on January 13, 2001, during the third period, when the estimated input of N was 312 g ha^{-1} day^{-1} and P was 124 g ha^{-1} day^{-1} (Table 2). These estimated avian N and P loading rates were equal to 2.1% and 10.6%, respectively, of the RWRF total N and P loading rates observed during the same period in January 2001.

Because the magnitude of avian nutrient loading rates relative to RWRF loading rates was greatest during the third bird-monitoring period (September 2000 to September 2001), we focused analyses to detect effects from avian nutrient loading rates on wetland nutrient removal efficiency on this period. Figure 4 pre-

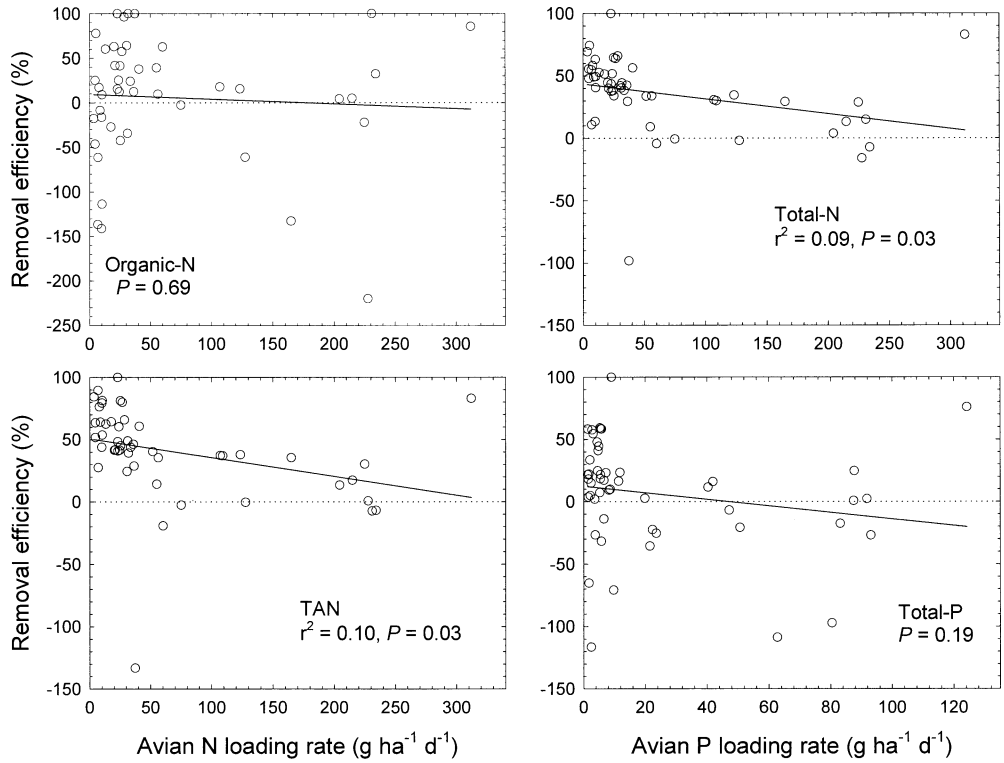

Figure 4. Relationship between nutrient loading from birds and nutrient-removal efficiency of the EMWD Multipurpose Demonstration Wetland for organic-N, total ammonia-N [TAN = (NH_3 + NH_4^+)-N], total N, and total P. Data are from the period when the wetland was in Configuration B. The avian loading rate for the Total-N figure is expressed as for the other nitrogen species (g N ha^{-1} d^{-1}).

sents the results of linear regression analyses, using the individual (weekly) data from the third period, of the relationship between estimated avian total N loading rate and the wetland removal efficiencies for total N, organic N, and TAN. Figure 4 also presents the relationship between estimated avian daily total P loading rate and the wetland removal efficiency for total P. Organic N and TAN removal efficiencies were chosen for analysis in addition to the total N removal efficiency because we reasoned that the deposition and decomposition of bird excreta in the wetland would most immediately add to the pools of those particular nitrogen species. The wetland's removal efficiency for both TAN and total N was significantly and negatively related to the estimated avian total N loading rate, although avian loading rate accounted for only 10% and 9% of the variance in TAN and total N removal efficiency, respectively (Figure 4). Total N loading from birds was not significantly related to wetland organic N removal efficiency, however, nor was avian total P loading significantly related to wetland total P removal efficiency. Over the period of record, the wetland's removal efficiency for TAN tended to show a cyclical pattern, with high values predominantly in summer and fall and low values predominantly in winter and spring (Figure 5).

Effect of Water Temperature on Wetland Nutrient-Removal Performance

The relationship between mean wetland water temperature derived from our measurements and mean local air temperature was well-described by a linear model (Figure 6). Water temperatures in the demonstration wetland estimated using the regression equation ranged from 12.6 to 27.5 °C.

Stepwise forward multiple regression analysis indicated that variation in the demonstration wetland's TAN removal efficiency during September 2000 to September 2001 was best explained by water temperature (R^2 = 0.21). The addition of bird loading and RWRF nutrient loading data added very little to the model (R^2 = 0.22). The relationship between water temperature and RE appeared to be linear (Figure 6). As expected, the relatively large abundance of birds that contributed to nutrient loading during winter and early spring, when water temperatures were lowest, led to a significant negative correlation between wetland water temperature and bird N loading ($r = -0.61$, $P < 0.001$).

DISCUSSION

Given the well-documented use of the San Jacinto Valley by waterfowl, the inclusion of waterfowl hab-

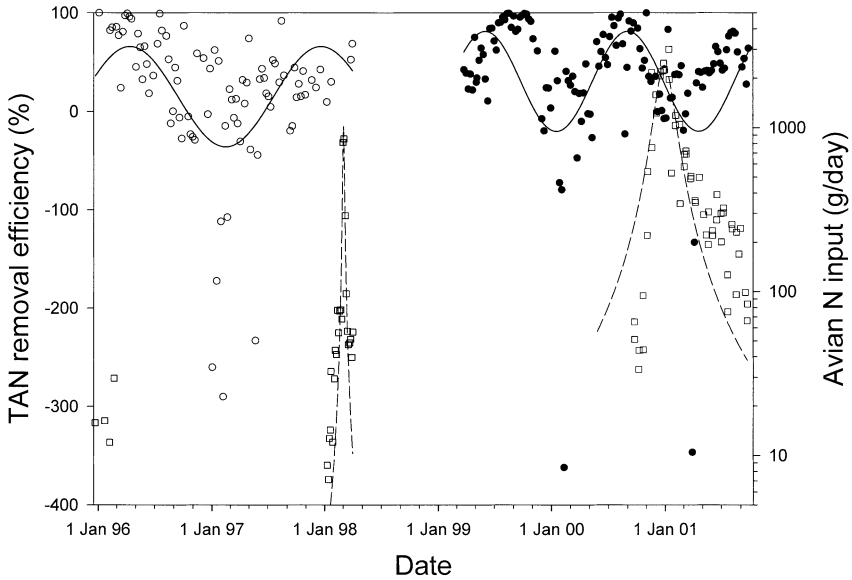

Figure 5. Temporal fluctuation patterns in total ammonia nitrogen [TAN = (NH_3 + NH_4^+)-N] removal efficiency (RE) within configurations A (open circles) and B (solid circles) of the EMWD Multipurpose Demonstration Wetland and in nitrogen loading from birds (open squares; note the log scale). The solid curves represent 4-parameter sine functions fit to the RE data (Configuration A: $r^2 = 0.26$, $P < 0.001$; Configuration B: $r^2 = 0.11$, $P = 0.002$), and the dashed curves represent 3-parameter Lorentzian functions fit to the bird loading data for 1998 ($r^2 = 0.96$, $P < 0.001$) and 2000–2001 ($r^2 = 0.81$, $P < 0.001$). Although neither sine curve has a precise 1-yr-long periodicity, note their common trend to have lowest amplitude (RE value) in winter or spring and the lack of phase synchrony between RE and bird N loading curves.

itat features in the demonstration wetland design ensured that members of this group would find and use the wetland. Nevertheless, the appearance of specific kinds or particular numbers of waterfowl could not be reliably predicted, nor could we precisely predict which other kinds of birds would use the wetland. We attribute the 25% drop in the number of bird species observed between the first and second monitoring periods to the fact that the first period covered a full year, whereas the second period was restricted to winter and early spring. Differences observed between the third and earlier periods were likely due to a combination of factors: the reduction in the area of emergent vegetation that accompanied reconfiguration (Table 1), the development of woody and herbaceous vegetation in wetland margin areas, the presence of fish in the wetland, and/or the modest changes in the surrounding landscape.

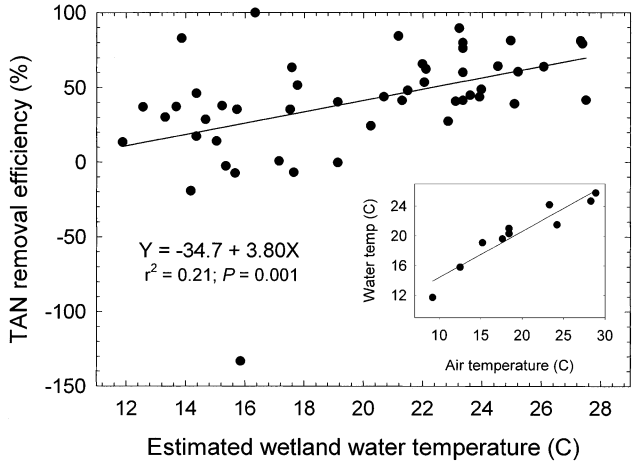

Figure 6. Relationship between estimated wetland water temperature and total ammonia nitrogen ([TAN = (NH_3 + NH_4^+)-N]) removal efficiency of the EMWD Multipurpose Demonstration Wetland. Data are from the period when the wetland was in Configuration B. The inset figure shows the linear relationship ($P < 0.001$, $n = 10$, $r^2 = 0.90$) between mean values for measured wetland water temperatures and means for local air temperature used to estimate wetland water temperatures (see text for details).

Nitrogen and phosphorus loading due to birds was consistently small relative to the load entering the system in RWRF wastewater. The estimated maximum daily bird input of nitrogen to the wetland was equal to only 0.5% of the mean daily nitrogen loading from inflow wastewater during the period immediately before reconfiguration (January to April 1998) and 2.6% of the mean daily wastewater nitrogen loading during the period after reconfiguration (September 2000 to September 2001). In the case of phosphorus, the estimated maximum daily bird inputs during these same periods were equal to 0.6% and 7.0% of the mean daily wastewater phosphorus loading, respectively (Table 2).

Despite the relatively small contributions to nutrient loading from birds, we found a negative relationship between N loading from birds and wetland treatment efficiency for both TAN and total N (Figure 4). Efficiency fell to nearly zero (no reduction in mass between inflow and outflow) when loading from birds was maximal. Given the statistically significant relationship between bird loading and TAN reduction, a similar relationship with total-N is not surprising because TAN constituted most of total N (Table 3).

There are several possible explanations for the apparent linkage between relatively small additions to loading by birds and a reduction in the wetland's TAN treatment efficiency. First, nutrient-removal efficiency could be sensitive to relatively small increases in loading, at least at greater total loading levels. This seems unlikely, however, because no similar pattern was seen in the analysis of removal efficiency and nutrient load entering the wetland with RWRF wastewater (Figure 3). An alternative explanation is that nutrients contributed by birds made up a disproportionately large fraction of outflow concentrations and thus distorted our estimates of system removal efficiency. If loading from birds occurred primarily near the wetland outlet, the added N (in fecal matter plus uric acid) may exit the system largely as NH_3 and NH_4^+, the first decomposition products. We noted that, as waterfowl abundance increased, individuals tended to disperse within the wetland and thus increased their density near the outlets. Further, some taxa, in particular egrets and ibises, appeared to roost preferentially on bulrush within the outlet arm of the wetland (D. C. Andersen, unpublished data).

A third explanation is that the decrease in removal efficiency is independent of avian loading and simply happens to coincide with the winter and early spring increase in avian inputs. This alternative is supported by the fact that a basic treatment process, N assimilation by bulrush and aquatic algae, decreases as wetland water cools during autumn and winter (Vymazal 1995). Microbial processes such as nitrification and denitrification would also be reduced as water temperature falls (Reed et al. 1988, USEPA 1993, Kadlec and Knight 1996). Thus, even in the absence of birds, TAN and total N removal efficiency would be expected to decrease during winter. This seasonal effect is evident in the positive relationship we found between TAN removal efficiency and the estimate of contemporaneous wetland water temperature (Figure 6). The multivariate analysis also supported the concept that the observed decrease in removal efficiency is largely (if not entirely) due to this plant- and microbe-mediated seasonal decrease and that the significantly negative slopes noted in Figure 4 are either much steeper than the true relationship between avian loading and efficiency would reflect, or simply spurious. In fact, TAN removal efficiency showed a winter decrease of similar magnitude in every year for which we have data, regardless of the avian loading levels (Figure 5).

Our calculations of avian loading rate are based on the assumption that droppings enter the wetland as they are produced. In fact, bird abundance and their contribution to N loading may be temporally decoupled to some extent because much of their excreta does not directly enter the wetland. This particularly affects contributions from blackbirds and roosting waders, whose droppings deposited on islands and vegetation could produce short-term, high magnitude N inputs during rainfall events. Blackbirds can reach very large densities while nesting, based on observations at the demonstration wetland and in very similar vegetation at nearby sites. Using an estimate of 0.25 adult birds/m^2, which may be conservative, the 4 ha of bulrush in Configuration B would harbor 10,000 birds. Together, these birds would produce 0.7 kg N $night^{-1}$, ignoring any contribution due to excreta from nestlings. However, much of the excreta is deposited on vegetation, where it may accumulate for weeks or months before a significant rain washes it into the water. Given this scenario, it is possible that large pulses of nitrogen enter the system sporadically. Tempering this input, however, is dilution from the rain itself: 1 cm of rainfall over the 21-ha catchment area represents 2100 m^3 of water or about 55% of the nominal daily input at the wetland. An attempt to document the presence of a pulse of N loading due to rain washing in excreta was made in early November 1996, five days after 2.5 cm of rain fell on the RWRF, ending a period of approximately 180 days without measurable precipitation (data from Hemet, CA, National Climatic Data Center Cooperative Station No. 43896). Nitrogen levels in the wetland were not unusually large (authors, unpublished data), suggesting that either the pulse had already moved through the system or that the N in the summer's accumulation of excreta was readily reduced by the wetland.

The avian N and P loadings we calculated for the demonstration wetland are similar to loading estimates generated for birds using ''natural'' wetlands, suggesting that bird use was not abnormally high. Our 2000–2001 data (Table 2) represent input values of 2.5 g m^{-2} yr^{-1} and 0.9 g m^{-2} yr^{-1} for N and P, respectively. Manny et al. (1994) reported loadings from geese and ducks of 1.9 g N m^{-2} yr^{-1} and 0.6 g P m^{-2} yr^{-1} into a 15-ha lake in Michigan. Scherer et al. (1995) reported 0.15–0.16 g P m^{-2} yr^{-1} into 105-ha Green Lake in Seattle. Hayes and Caslick (1984) reported that total loadings from roosting blackbirds and European Starlings (*Sturnus vulgaris* L.) reached 2.8 g N m^{-2} yr^{-1} and 0.4 g P m^{-2} yr^{-1} in New York cattail (*Typha*)

marshes. In contrast, data in Marion et al. (1994) indicate a mean loading rate of 0.14 g N m^{-2} yr^{-1} and 0.05 g P m^{-2} yr^{-1} by birds into France's largest natural lake (mean area ~5150 ha). Nutrient inputs into some managed wetlands are much greater than these values. Post et al. (1998) reported that wintering geese added 17.5 g N m^{-2} yr^{-1} and 2.2 g P m^{-2} yr^{-1} to wetlands in a New Mexico wildlife refuge. Isotope data showed that the nitrogen was incorporated into local food webs, and mass balance calculations indicated little or no net export of N and P from the refuge (Kitchell et al. 1999). Because similar, and in some cases the same, sets of physiological parameters underlie all of the above loading estimates, differences are attributable largely to the kinds and numbers of birds present. This, in turn, will depend, at least in part, on the mix and extent of particular habitat resources present, including open water and emergent vegetation. Because we have no data on nest densities or fledging success, it is unclear whether the concentrations of breeding birds observed at the demonstration wetland were unusual. Piest and Sowls (1985) and Hanson (2002) attributed large densities of breeding waterfowl at wetlands receiving sewage effluent to the combination of abundant food resources and nesting cover.

The N loading to the wetland due to inflow from the RWRF, calculated on an areal basis, is somewhat greater than loadings at the few other constructed wetlands for which data are available (see Figure 20-7 in Mitsch and Gosselink 2000). The inflow N concentrations are also somewhat greater than the mean value reported for secondary effluent from activated sludge municipal wastewater-treatment plants in the United States (15.8 ± 1.2 mg/L, n = 244; Gakstatter et al. 1978), although not exceptionally so. The concentrations of P in inflow to the wetland from the RWRF, however, were well below the national survey mean (6.8 ± 0.4; Gakstatter et al. 1978). In the activated sludge treatment process, nitrogen removal is achieved through sequential nitrification and denitrification, which requires energy-intensive mixing and aeration. Given the fact that the entire effluent of the RWRF is reused, rather than being discharged to receiving waters, the treatment process has been operated to reduce energy costs rather than achieve nitrogen removal—hence the relatively high total N concentrations in the inflow to the wetland. The low total P concentrations in the RWRF treated effluent relative to the national survey values are probably the result of the reduction of phosphates in detergents in the United States since the survey was performed in 1978.

A literature analysis conducted by the U.S. Army Corps of Engineers Waterways Experiment Station (Phillips et al. 1993) found that concentration-based removal efficiencies for constructed wetlands treating municipal wastewater ranged from 25 to 93% for total N. The mean concentration-based removal efficiencies for total N observed during this study were 31% during the period before reconfiguration of the wetland and 27% afterward. These removal efficiencies fall within the lower part of the range reported by Phillips et al. (1993).

The surveys of Gakstatter et al. (1978) and Phillips et al. (1993) suggest an inverse relationship between inflow total N concentration and constructed wetland total N removal efficiency. Our study, however, suggests that the response in removal efficiency to a change in loading could be small (Figure 3). Regardless of the shape of the relationship, our data suggest that, within the range of typical total N concentrations found in treatment plant effluent, avian loading is unlikely to effect removal efficiency strongly. For example, if inflow concentration of total N from the RWRF was set to the national survey mean value of 15.8 mg/L, the loading rate to the wetland (assuming Configuration B) would have been 12,927 g N ha^{-1} day^{-1}, and the maximum avian loading rate we observed (312 g N ha^{-1} day^{-1}) would remain a comparatively small additional load. Although a decrease in RE with increased loading is theoretically sound, the actual form of the relationship will be virtually system-specific because of the variety of factors involved (e.g., quantity and quality of inflow wastewater, type and density of vegetation, amount and spatial arrangement of open water, climatic conditions). Finally, the monetary cost of reducing N in inflow wastewater has to be weighed against wetland performance goals.

As a case study, we believe that the Eastern Municipal Water District's Multipurpose Demonstration Wetland supports the concept that bird use of a constructed wetland does not lead to a significant reduction in treatment performance. However, a clear demonstration of the independence of the winter decrease in treatment performance and the concurrent rise in bird use is not possible without excluding birds, an unlikely proposition at this site. It also remains to be seen whether a simpler wetland design, such as one with a smaller perimeter-to-area ratio or fewer patches of emergent vegetation, retains a similar ability to accommodate waterfowl and other bird use.

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