

Removal of nutrients and metals by constructed and naturally created wetlands in the Las Vegas Valley, Nevada

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Abstract Increased water use associated with rapid growth in the Las Vegas Valley has inadvertently led to the creation of unique wetland systems in Southern Nevada with an abundance of biological diversity. Constructed and naturally created wetlands in the Las Vegas Valley watershed were studied to characterize and understand their potential role for improving ecosystem services (i.e., water purification). Nutrient and metal removal was assessed at four sites including a natural urban runoff wetland, a constructed urban runoff wetland, a constructed wastewater wetland, and a natural urban runoff/wastewater wetland. Plant nutrient uptake was dependent on ambient nutrient concentrations in water and sediments of

specific wetlands, irrespective of the type of plants present. Phosphorus was mostly concentrated in below-ground plant parts whereas nitrogen was concentrated in above-ground parts. As for metalloids, bulrushes were more efficient than cattails at taking up arsenic and selenium. Averaging all the wetland sites and plant species, total nitrogen, phosphorus, arsenic and selenium removal was 924.2, 61.5, 0.30, and 0.38 kg/ha/year, respectively. Our findings suggest that natural and created wetland systems can improve water quality in the Las Vegas Valley watershed for some common pollutants, however, other measures are still needed to improve water quality below regulatory thresholds.

Keywords Bulrush · Cattail · Constructed wetlands · Nutrients · Pollutant removal · Nevada

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Introduction

Wetlands with a variety of hydrologic, vegetation, and soil conditions can occur naturally or be constructed in many landscape positions (Kadlec and Wallace 2009). Wetlands are often highly productive systems where numerous biological transformations are taking place, driven by the natural energies of the sun, soil, wind, and by microorganisms, plants, and animals (Thullen et al. 2005).

Performance efficiencies of constructed or natural wetlands depend on several variables, such as the quality and quantity of effluent to be treated, and biological, physical, and chemical activities in that particular wetland system (Greenway and Woolley 2001; Greenway 2003). Until recently, nitrogen and phosphorus were primary constituents of concern in wetland systems, with their concentrations varying depending on the source of wastewater and the extent of nonpoint source pollution (Vymazal 2006; Toet et al. 2005). However, recently, other pollutants such as heavy metals, radioactive chemicals, and pharmaceutical and industrial organic chemicals have also emerged as pollutants of concern.

Wetland plants mediate important processes in constructed wastewater treatment wetlands. For example, plant metabolic activity releases oxygen into the rhizosphere, which aids in nitrification through the direct uptake of nutrients (Brix 1997; Greenway and Woolley 2001). The access and availability of nutrients affects plant growth response and resource allocation, which influences removal efficiency in wetlands (Tanner 2001). Emergent aquatic plant species such as cattails (*Typha* spp.), bulrushes (*Schoenoplectus* spp.), and reed (*Phragmites australis*) have been widely used in the U.S. and elsewhere around the world for nutrient removal in constructed wetlands (Kadlec and Wallace 2009). Nutrient removal can be optimized by selecting suitable species with higher capacities for absorption of inorganic nitrogen and phosphorus and conversion into plant biomass (Greenway 2003; Vymazal 2007; Mitsch and Gosselink 2000). A basic understanding of the growth requirements and characteristics of wetland plants is essential for successful design and operation of wastewater treatment. Several authors have studied the importance of vegetation in removing metals from natural and constructed wetlands for wastewater treatment (Lesage et al. 2007; Vymazal and Krása 2005; Vymazal 2007). Bioaccumulation processes are found to be effective in reducing some metals such as arsenic (As) and selenium (Se) into insoluble forms in some constructed wetlands (Zhang and Moore 1997; Zhang et al. 2007; Lin and Terry 2003).

The Las Vegas Valley watershed located in Southern Nevada, an arid region of the U.S., supports many ecologically significant wetlands and is often regarded as an oasis in the desert (LVWCC 2009). Excessive erosion has resulted in the loss of wetlands and wildlife habitat, loss of property, damage to infrastructure, excessive sediment transport, and water quality concerns in Lake Mead (LVWCC 2009). Wetlands have decreased significantly, from about 2000 acres in 1975 to about 300 acres in 1999 (Eckberg and Shanahan 2009). The multi-stakeholder Las Vegas Wash Coordination Committee developed a management and enhancement plan to restore the ecological services of the Las Vegas Valley's primary drainage channel, the Las Vegas Wash. As a restoration initiative, many erosion control structures are being built to stabilize the channel and lands that are adjacent to these structures are being revegetated with plants native to Mojave Desert riparian ecosystems. Like wetlands in many other rapidly growing urban centers, the wetlands in Las Vegas receive relatively high amounts of nutrients from wastewater discharge and potential pollutants from nonpoint sources. For example, selenium concentrations in urban runoff channels in the Las Vegas Valley are above regulatory thresholds. Consequently, wetlands have been pursued as a low-cost solution for improving water quality in various locations in the valley. Until now, performance of these wetlands has not been cumulatively assessed.

The goal of this study was to compare and contrast the key characteristics of various types of wetlands in the Las Vegas Valley watershed to determine how well they function to improve water quality. We investigated nutrient (nitrogen and phosphorus) and trace metal (selenium and arsenic) uptake by wetlands plants (one species of cattail and three species of bulrush) in four different wetlands. Above- and below-ground plant parts were compared between each site to understand nutrient and metalloid uptake and storage with respect to the ambient concentration in the water column and sediment. By determining the limits of wetland function, watershed management actions can be tailored to improve ecological services in the Las Vegas Valley.

Methods

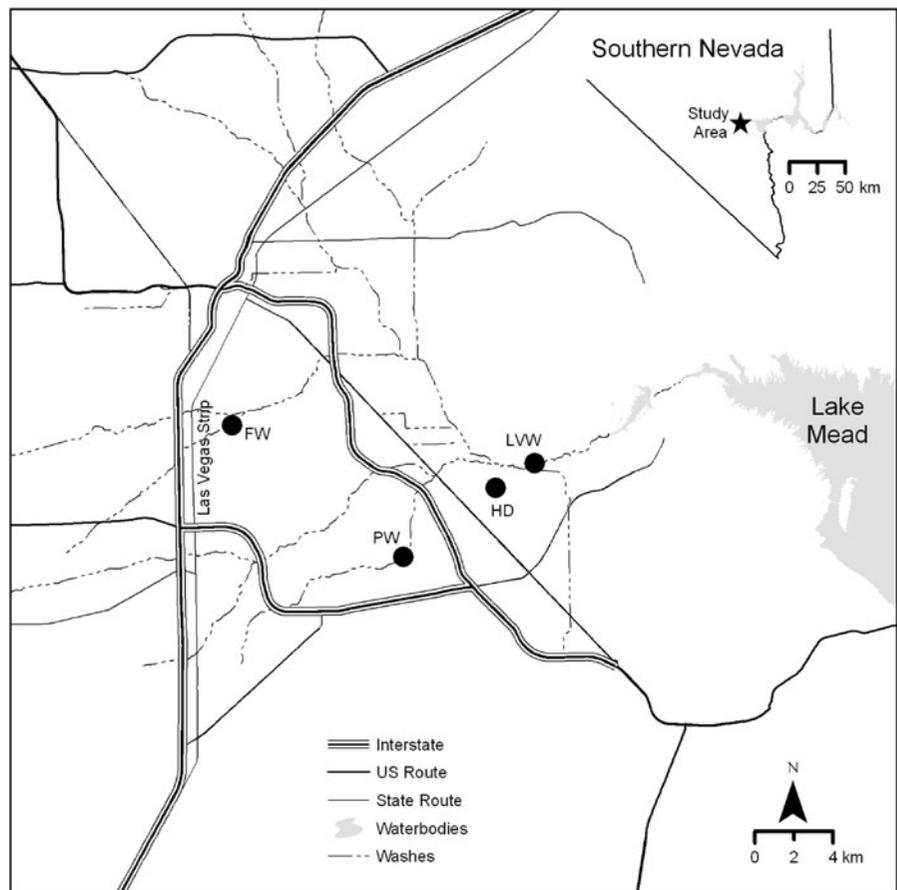
Site description

The study was carried out in four lowland wetlands types (elevation less than 2,100 feet) in the Las Vegas Valley (Fig. 1), including (a) a constructed wastewater effluent treatment wetland (Demonstration Wetlands at the City of Henderson Water Reclamation Facility, ‘HD’ hereafter), (b) a constructed urban runoff treatment wetland (Pitman Wash Pilot Wetland, ‘PW’ hereafter), (c) a naturally occurring in-situ urban runoff treatment wetland (Flamingo Wash, ‘FW’ hereafter), and (d) a natural wetland created behind an erosion control structure in the main Las Vegas Wash (Las Vegas Wash, ‘LVW’ hereafter). The Las Vegas Valley is a low-lying alluvium-filled valley surrounded by steep mountain ranges. Soil cover

in the study area generally consists of depositional silts and clays from the Cenozoic era. Intermittent streams continue to cut into the floodplain and deposit alluvium into the surrounding wetlands.

Las Vegas wash wetlands The Las Vegas Wash (36°06’49.23” N and 115°08’53.17” W) is the major drainage for the Las Vegas Valley, which drains into Las Vegas Bay in Lake Mead. The Las Vegas Wash currently discharges ~290 cubic feet per second (cfs) providing nearly 2% of the inflow to the Lake Mead (Leising 2003; SNWA 2010; USGS 2010). The Las Vegas Wash wetlands site, which consists mostly of treated wastewater effluent from three municipal facilities, is located in the main channel of the Las Vegas Wash and was created from the backwater pool behind the Pabco Road erosion control structure (i.e., weir). The LVW meets stringent water quality standards set

Fig. 1 Map showing different wetlands sites located within the Las Vegas Valley Watershed (FW: Flamingo Wash, PW: Pitman Wash Pilot Wetlands, HD: Demonstration Wetlands at the City of Henderson Water Reclamation Facility, and LVW: Las Vegas Wash)



by Nevada Division of Environmental Protection at all times for the safe return of water to Lake Mead and Colorado River. Land use type around the LVW wetlands are dominated by undeveloped desert areas and mixed riparian vegetation. The wetlands area extends nearly 220 acres and the wetland vegetation in this area is dominated by cattail (*Typha domingensis*) and common reed (*P. australis*). The Las Vegas Wash also conveys untreated urban runoff, groundwater, and stormwater (Zhou et al. 2004).

Flamingo wash wetlands These wetlands are located in the Flamingo Wash (36°05'17.02" N, and 114°59'10.80" W), a tributary to the Las Vegas Wash, and consist of urban runoff with an average discharge of ~5 cfs. The adjacent lands are dominated by dense residential, commercial, and park/golf course uses. The Flamingo Wash stretches for several miles but the wetlands are somewhat patchy and sparsely located (~5 acres). Dense vegetation of annual weeds mixed with cattails exists throughout the channel and provides habitat to many aquatic and avian species.

Pittman wash pilot wetlands The Pittman Wash (36°04'31.79" N and 115°00'07.07" W) is a demonstration-type pilot wetland created to study water quality improvements in urban runoff before it enters the Las Vegas Wash. The PW wetlands are experimental (20 m by 20 m) and have both surface and sub-surface flow components and a discharge of ~5 cfs and total area of 0.009 acres. The surrounding land use type is similar to that of the FW. The main vegetation in the PW wetlands is three species of bulrushes (*Schoenoplectus acutus*, *Schoenoplectus americanus*, and *Schoenoplectus californicus*).

Demonstration wetlands at the City of Henderson water reclamation facility This is another demonstration-type wetlands located at the City of Henderson Water Reclamation Facility (36°02'48.29" N and 115°03'13.06" W). This site was constructed to show how wetlands can improve partially treated wastewater effluent. The land use type consists of residential and undeveloped land. The 5.75-acre wetland is a triangular-shaped pond with 14 loafing and emergent

vegetation islands constructed with varying depths of water coverage. Three species of bulrush (*S. acutus*, *S. americanus*, and *S. californicus*) were planted on eleven specially designed hummocks (Zhou and Van Dooremolen 2004).

Sampling and analyses

Water

Water samples were collected monthly from all four sites from inlets and outlets beginning in July 2008 and ending in June 2009. Various parameters, including total nitrogen (TN, measured as $\text{NO}_3 + \text{NO}_2 + \text{NH}_4$), total phosphorus (TP, measured as orthophosphate), dissolved oxygen (DO), pH, electrical conductance, and temperature, were measured from the four sites. Nalgene bottles (1 l) used during sampling were acid rinsed prior to the sampling. Water samples were then immediately stored on ice. TP concentration was determined using the colorimetric analysis after persulfate digestion (APHA 2005). TN was analyzed using an automated colorimetric method using a Lachat QC8000. Metal analysis of water samples were determined by ICP-MS using a method based on USEPA Method 200.8 (USEPA 2001).

Sediment

Sediment samples were collected from the same inlet and outlet locations as the water samples at all four wetlands seasonally. Vertically mixed sediment samples were collected using a plastic scoop up to ~10 cm depth and transferred into 100-ml glass bottles with polyvinyl caps. Samples were then dried in a convection oven at 70°C until they were completely dry. Subsamples of dry sediment (~1 g) were processed for metal digestion following USEPA Method 3050B at the Desert Research Institute Ecological Engineering Laboratory. Sediment samples were digested with repeated addition of 70% HNO_3 and 30% H_2O_2 . A low-temperature thermostat (Lauda Ecoline, U.S. version) was used to provide uniform heating of 95°C. The resultant digest was diluted to 100 ml, centrifuged, and stored at 4°C until analysis. Samples were analyzed for trace metals using

inductively coupled plasma optical emission spectrometry (ICP-OES) at the Goldwater Environmental Laboratory at Arizona State University. Sediment TP content was analyzed for 1 g dry subsamples using the colorimetric method (APHA 2005). Sediment TN content was analyzed on a dry subsample (~1 g) using a PerkinElmer 2400 CHN analyzer.

Plant

Plant samples were collected seasonally between the inlet and outlet locations of all four wetlands using 0.5 m by 0.5 m quadrants. A total of 14 quadrants were selected, 5 in LVW wetlands and 3 each in HD, PW, and FW wetlands for vegetation study and sampling purposes. The LVW wetlands was sampled at five quadrants due to its larger size compared to the rest. All plant material (above- and below-ground) in each quadrant was harvested and measured for biomass, nutrients (TN and TP), and a suite of metals. Plant biomass was calculated using methods described in APHA (2005) for dry plant weight by storing for 72 h at 70°C or until a consistent dry weight was obtained. Dry plant samples were separated into roots, stems, and leaves prior to sub-sampling for nutrients and metals analyses. A Cyclone Sample Mill (UDY Corporation, Fort Collins, Colorado) was used to grind dry plant tissue to a homogenate sample of approximately 1 mm in size for nutrient and metal analyses. Plant TP and TN contents were determined using the methods used for sediment analyses. For metals, 1-g plant samples were digested following USEPA Method 3050B. Digested samples were processed for metal concentration using ICP-OES. Twenty-nine trace metals were analyzed in plant, sediment, and water samples. Among the detected metals, selenium and arsenic were critically evaluated because of their higher concentrations, known presence in the valley, and potential adverse impact on water quality and aquatic wildlife. QA/QC protocols were based on standard methods and included reagent blanks, check standards, fortified samples, laboratory and field duplicates and certified reference materials for water, sediment and plant samples (APHA 2005). All samples were analyzed at an EPA certified laboratory.

Statistical analysis

Statistical analyses were carried out using JMP software (SAS Institute, Cary, North Carolina). One-way analysis of variance (ANOVA) was used to study the effect of wetlands type and plant species on the nutrient and metal concentrations in plants. Two-way ANOVA was used to study the interactions of wetlands type and species distribution with TP, TN, and metal concentrations. Differences detected in ANOVAs from the wetlands sites were compared using the Tukey pairwise comparison test. For all of the tests, *p* values < 0.05 (95% confidence interval) were considered significant. Plant, water, and sediment nutrients and metals were regressed among sites to see correlations among them.

Results

Water quality parameters other than nutrients and metals such as TSS, BOD, pH, temp, etc were generally consistent in all the wetlands. The treatment facilities are fitted with tertiary treatment systems and do a good job of keeping the TSS and BOD low in the LVW wetland similar to urban and residential runoff fed wetlands (FW, HD, and PW wetlands). On average, pH and temperature range from 7.2–8.1 and 22 to 25°C at all four wetland sites. Similarly, average DO and TSS range between 6–10 mg/L and 4 to 47 mg/L in all the wetlands.

Plant biomass

Most of the plants in the LVW and FW wetlands were cattails, whereas the HD and PW wetlands were dominated by three species of bulrush. The total mass of cattails and bulrushes varied significantly among the four wetlands sites (Table 1). Of the two cattail dominated sites, LVW had greater average biomass production than FW (Table 1). For the bulrush sites, all three bulrush species had higher biomass in HD than in PW. Overall, total biomass harvested per quadrant was highest in the HD wetlands compared to the other three wetlands (Table 1).

Table 1 Average biomass and nutrient concentrations of above-ground plant parts of *Typha domingensis* and *Schoenoplectus* spp. at the Las Vegas Wash (LVW),

Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW)

Site	Species	Total	Total culm	Total biomass	Total biomass	TN storage	TP storage
		quadrant	per quadrant	per culm	(kg/m ²)	(g/m ²)	(g/m ²)
		<i>N</i>	(number)	(kg)	(kg/m ²)	(g/m ²)	(g/m ²)
LVW	<i>T. domingensis</i>	5	14 ± 5	0.27 ± 0.05	9.69 ± 0.21	135.7 ± 12	6.6 ± 0.6
HD	<i>S. americanus</i>	3	17 ± 6	0.26 ± 0.04	11.37 ± 0.17	152.4 ± 9.3	16.0 ± 1.0
	<i>S. californicus</i>		13 ± 5	0.35 ± 0.07	11.20 ± 0.29	170.2 ± 17.8	13.4 ± 1.4
	<i>S. acutus</i>		15 ± 6	0.11 ± 0.04	4.09 ± 0.15	48.3 ± 6.9	4.7 ± 0.7
PW	<i>S. americanus</i>	3	11 ± 4	0.16 ± 0.05	4.61 ± 0.19	44.7 ± 7.2	2.2 ± 0.4
	<i>S. californicus</i>		14 ± 9	0.16 ± 0.03	3.79 ± 0.13	37.5 ± 5.4	1.5 ± 0.2
	<i>S. acutus</i>		14 ± 9	0.11 ± 0.03	2.26 ± 0.11	15.8 ± 3.0	0.5 ± 0.1
FW	<i>T. domingensis</i>	3	11 ± 3	0.08 ± 0.03	2.62 ± 0.12	28.6 ± 5.2	1.5 ± 0.3

Digits after the ± sign indicate standard errors

Nutrients analysis

Plant, sediment, and water column nutrient data measured at the various wetlands differed in mean concentrations ($p < 0.05$). Annual average plant tissue analyses indicate that TP concentration varied significantly among the four wetlands ($p < 0.05$), showing that TP was significantly different among the HD, PW, and FW wetlands for both cattail and bulrush plants ($p < 0.05$). TP concentration in the LVW wetlands, however, was similar to that in FW ($p = 0.55$, Fig. 2a). Based on the results for mean %TP in plant tissue and mean plant biomass, HD wetlands appear to accumulate the highest amount of TP among the four wetlands. Plant tissue %TP generally followed the trend of the ambient sediment and water column concentrations for the wetlands sites rather than for the individual species. The HD wetlands had the highest average sediment TP concentration (0.08%), followed by the LVW (~0.045%), PW (~0.043%), and FW (~0.03%) wetlands. The pairwise comparison showed that sediment TP concentration in the HD wetlands was significantly different than in the LVW and FW wetlands (Tukey LSD, Fig. 2b). Unlike in plants and sediments, phosphorus concentrations in the water were not significantly different among the PW, FW, and LVW wetlands. However, the HD wetlands had a significantly higher TP concentration, ~1.5 mg/L, in the water column (Tukey LSD, Fig. 2c). The other three wetlands did not

show any uncharacteristically high TP water concentrations. Overall, the annual mean TP water concentrations were ~0.145 mg/L at the LVW, ~0.01 mg/L at FW, and ~0.010 mg/L at the PW wetlands. All four wetlands had significant drops in sediment TP concentrations at the outlets ($p < 0.01$). A relatively lower reduction of 16% was measured at LVW, whereas the reduction was nearly 60% at the FW, 30% at the PW, and 26% at the HD wetlands. Unlike sediment concentrations, there was no significant drop off in water concentrations towards the outlets. From regression analysis, plant tissue TP concentrations were found to be highly correlated with sediment concentrations ($R^2 = 0.82$, Fig. 3a) and moderately significant at 90% confidence level ($p < 0.1$). The annual average phosphorus concentrations in the water column were also positively correlated with plant tissue concentrations among the four wetland sites at 90% confidence level ($R^2 = 0.84$, $p < 0.1$, Fig. 3b).

Unlike TP, plant TN did not follow the trend of the ambient water column and sediment concentrations. TN concentrations measured in cattail and bulrush plants were significantly different among the four wetlands ($p < 0.05$). Cattail plants in the LVW wetlands and bulrush in the HD wetlands appeared more efficient in N storage compared to the other two wetlands (Table 1, Fig. 2d). As for the sediment nitrogen, LVW and FW had the highest TN concentration (0.09%), followed by PW (0.06%), and HD (0.05%). Pairwise

Fig. 2 Average annual total phosphorus (TP) and total nitrogen (TN) concentrations in **a, d** plants (*T. domingensis* and *Schoenoplectus* spp.); **b, e** sediments; and **c, f** water at the Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). Letters above bars denote significant differences based on pairwise (Tukey HSD) comparisons. Error bars represent standard errors

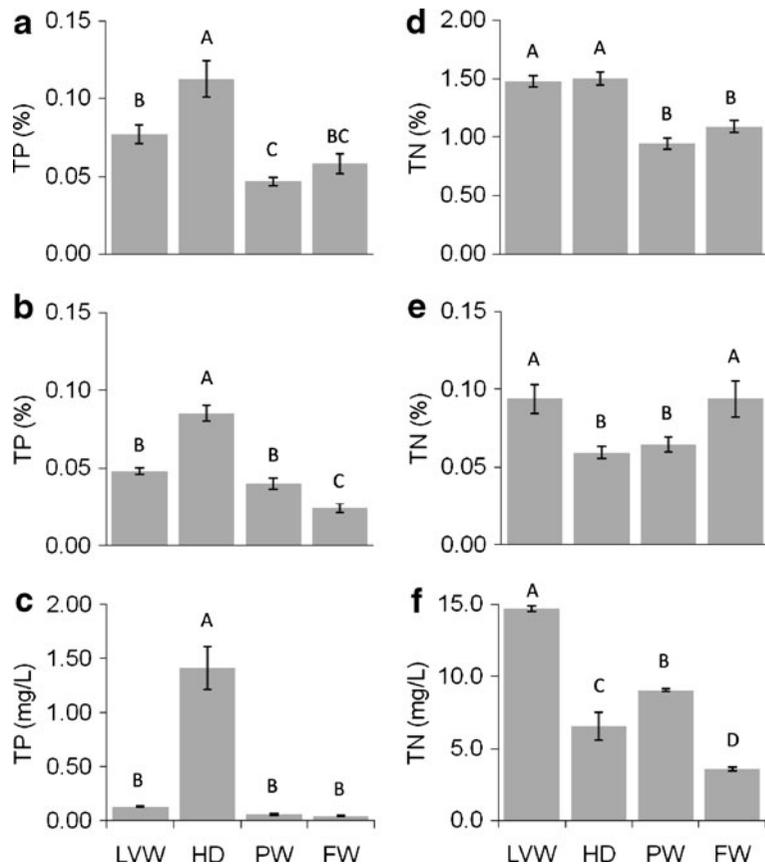
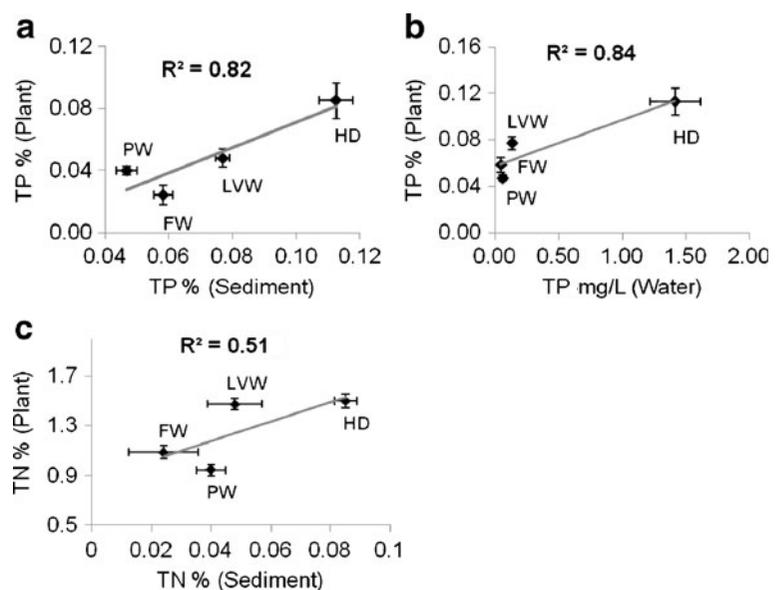


Fig. 3 Overall correlations between annual average plant tissue and **a** sediment total phosphorus concentrations (TP%), **b** water column total phosphorus (mg/L), and **c** sediment total nitrogen (TN%) in the Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). The line shown is a least-square linear regression



comparisons showed that sediment TN in the HD and PW wetlands was significantly different from sediment in the LVW and FW wetlands (Tukey LSD, Fig. 2e). Nitrogen concentrations in the water columns were also significantly different among the four wetlands ($p < 0.01$, Fig. 2f). Overall, the mean TN concentration in water at the LVW wetlands (14 mg/L) was higher than in the PW wetlands (~9 mg/L) and FW wetlands (~4 mg/L). Despite consisting of only treated wastewater effluent, the inlet of the HD wetlands had a lower mean TN (~5 mg/L) than the inlets of the LVW and PW wetlands. There was a significant drop in sediment %TN at the outlets ($p < 0.01$). This reduction of TN in FW was 61%, followed by 23% for HD. The other two wetlands (PW and LVW) had less than 5% reductions. Average TN concentrations in water measured at the inlet and outlet of the LVW wetlands did not show any major differences. The regression analysis did not reveal any correlation between the plant tissue TN concentration and the water column TN concentration. However, the plant tissue TN concentration was moderately correlated to the sediment TN concentration among the four wetland sites ($R^2 = 0.51$, $p < 0.1$) at 90% significant level (Fig. 3c). Above-ground plant parts for both species were more efficient at taking up TN at all four wetlands when compared to below-ground parts ($p < 0.01$), whereas below-ground plant were more efficient for TP uptake (Tukey LSD, Fig. 4a, b).

Metals analysis

Among a suite of trace elements analyzed, As and Se were detected at relatively higher concentrations at all wetlands sites and were studied in more detail due to their history in the Las Vegas Valley watershed. Several other trace metals, e.g., Hg, Pb, Zn, Cd, Fe, and Mo in plants and Cd, Co, Cr, Cu, Hg, Fe, Li, Ni, Pb, and Zn in sediments were detected, but all were under the MCL (maximum contaminant level) (USEPA 2004). The concentrations of these metals showed no significant differences among four wetland sites.

Among the four wetlands, the PW wetlands had the highest average annual As concentration in plants, sediments, and water. PW plants (bulrushes) had ~6.0 $\mu\text{g/g}$ As, which was significantly higher than the As levels in the other wetland sites ($p < 0.01$, Fig. 5a). LVW plants (cattails) had the second highest As concentration (~3.5 $\mu\text{g/g}$). However, the tissue concentrations of As were relatively lower in FW and HD wetland plants. Similarly, annual mean sediment As concentrations were significantly different among the four wetlands sites ($p < 0.01$, Fig. 5b). Also, sediment in the PW wetlands had the highest concentration (~6.06 $\mu\text{g/g}$) followed by LVW (~4.71 $\mu\text{g/g}$), FW (~3.65 $\mu\text{g/g}$), and HD (~3.36 $\mu\text{g/g}$). Similar to the plants and sediments, the water column As concentrations differed among the four wetland sites ($p < 0.01$, Fig. 5c). There was no significant decrease in As concentrations in sediment from

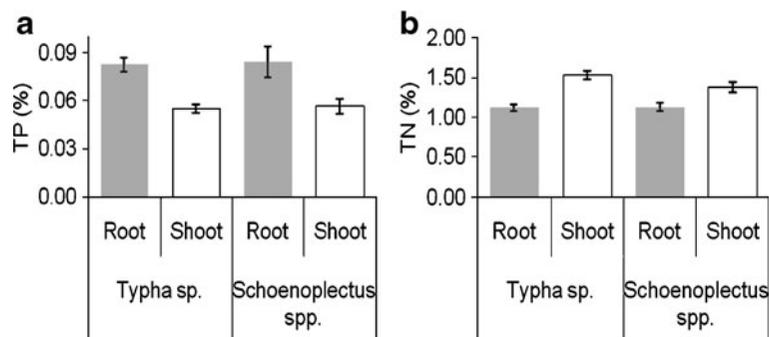


Fig. 4 Average annual **a** total phosphorus (TP), and **b** total nitrogen (TN) in the shoot and root parts of plant tissues (*T. domingensis* and *Schoenoplectus* spp.) at the Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wet-

lands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). Error bars represent standard errors

Fig. 5 Average annual arsenic (As) and selenium (Se) concentrations in, **a** and **d** plants (*T. domingensis* and *Schoenoplectus* spp.); **b** and **e** sediments; and **c** and **f** water at Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). Letters above bars denote significant differences based on pairwise (Tukey HSD) comparisons. Error bars represent standard errors

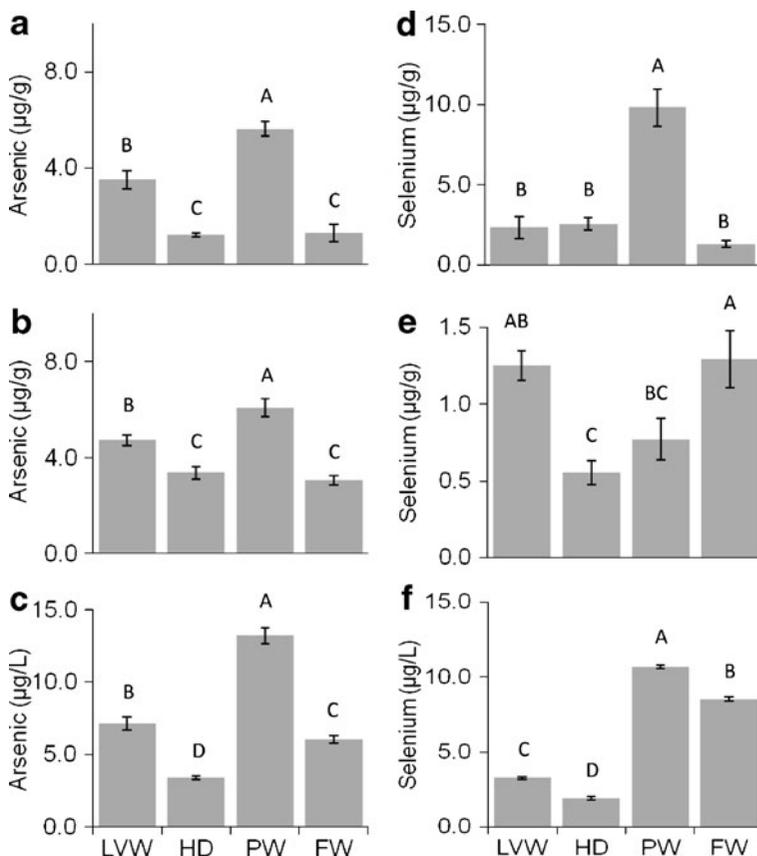
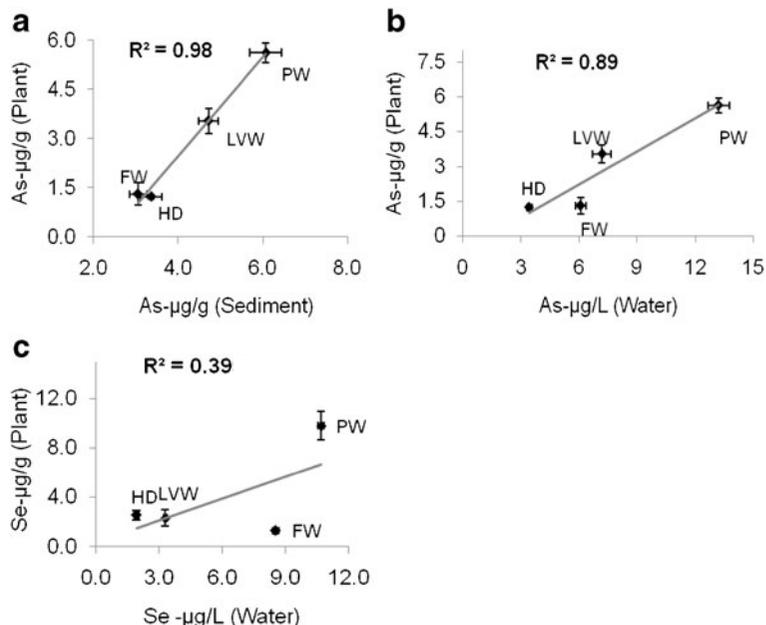


Fig. 6 Overall correlations between annual average plant tissue (µg/g) and **a** sediment arsenic (µg/g), **b** water arsenic (As) concentrations (µg/L), and **c** water selenium (Se) concentrations (µg/L) in the Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). The line shown is a least square linear regression



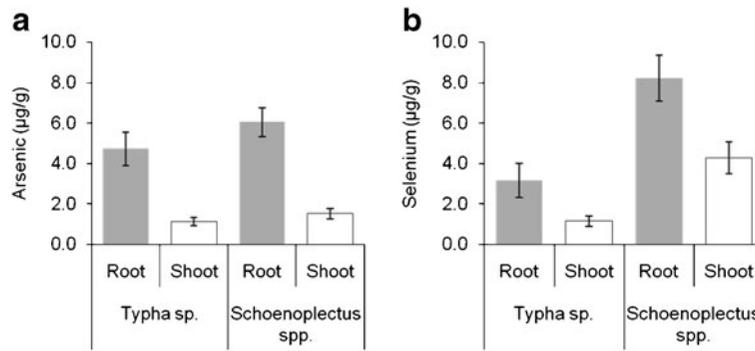


Fig. 7 Average annual **a** arsenic (As) and **b** selenium (Se) concentrations in the shoot and root parts of plant tissue (*T. domingensis* and *Schoenoplectus* spp.) at the Las Vegas Wash (LVW), Flamingo Wash (FW), Demonstration Wet-

lands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW). Error bars represent standard errors

inlet to outlet in any of the wetland sites. The PW wetlands had the highest concentration of As (13.1 µg/L) in the water column, followed by LVW (~7.1 µg/L), FW (~4.47 µg/L), and HD (~3.42 µg/L). Generally, As concentrations in the water column at the outflow sites were similar to those at the inflow sites and did not show any significant reduction. Regression analysis showed that the annual average As concentrations in plant tissues were highly correlated with the sediment concentrations at 90% confidence level ($R^2 = 0.98$, $p < 0.1$, Fig. 6a) and water column concentrations ($R^2 = 0.8$, $p < 0.1$, Fig. 6b) among the four wetland sites.

There was a remarkably high Se concentration (~9.80 µg/L) detected in the bulrush plant tissues in the PW wetlands. The rest of the wetlands each had about one-fourth of the concentration of Se as in the PW wetlands. Cattails appeared to have lower Se concentrations at both the LVW (~2.32 µg/L) and FW wetlands (~1.29 µg/L) as compared to the bulrushes of the HD (2.5 µg/L) and PW (9.8 µg/L) wetlands (Fig. 5d). The LVW and FW wetlands sediments measured higher concentrations than the HD and PW wetlands ($p < 0.01$, Fig. 5e). The annual mean sediment Se concentrations were higher in FW (1.3 µg/g) and LVW (1.2 µg/g) but relatively lower in PW (~0.77 µg/g) and HD (~0.55 µg/g). Annual average Se concentrations in the water column were significantly different among the four wetland sites ($p < 0.01$, Fig. 5f). The PW wetlands had the highest concentration of Se in the water column

(~10.68 µg/L), followed by FW (~8.2 µg/L), LVW (~3.2 µg/L), and HD (~1.91 µg/L). Se concentrations in sediment did not show any significant differences between the inlets and the outlets among the four wetland sites. Similarly, As concentrations in the water column at the outflow sites did not show any significant reductions. Regression analysis was not significant between plant tissue and sediment Se concentrations. However, the plant tissue Se concentration was weakly correlated with the water column concentration among the four wetland sites ($R^2 = 0.39$, $p < 0.1$, Fig. 6c). At all sites, comparing above- and below-ground data revealed that Se and As concentrations were significantly higher in the below-ground parts of either species than in the above-ground parts ($p < 0.05$, Fig. 7a, b).

Discussion

Plant biomass

Cattail and bulrush biomass ranged from 2.2–11.3 kg/m²/year, which is comparable with constructed wetlands in highly productive ecosystems. Total plant productivity at the end of the vegetation cycle was estimated to be 13–20 kg/m²/year for cattails and bulrush species in constructed ecosystems but was only 3–5 kg/m²/year in natural and less-polluted areas (Vymazal et al. 1998; Mitsch and Gosselink 2000; Reddy and DeBusk 1987). In our study, we measured the peak stand-

ing crop, which is also known as the single largest value of plant material present during a year's growth (Richardson and Vymazal 2000). Plant productivity and nutrient accumulation in plant biomass varied widely for cattail and bulrush species among the four different wetland sites (Table 1). This variation could be due to differences in environmental parameters such as incoming nutrients and hydrology in the wetland systems. For example, bulrushes, especially *S. americanus*, showed a high density of stem growth in the HD wetlands but relatively less density and biomass in the PW wetlands.

Similarly, cattails in the LVW wetlands yielded higher plant density and biomass per quadrant compared to the FW wetlands. The LVW and HD wetlands receive high nutrient loads from wastewater treatment plants, whereas the PW and FW wetlands receive relatively lower nutrient loads as they are fed by urban runoff systems. In both of these cases, incoming nutrients might have played a role in the plant densities. Aquatic plants take up large quantities of nutrients and assimilate them efficiently (Cronk and Fennessy 2001). The present results show that the plants may be capable of growing better by taking up more nutrients (if available in the wetland system) and producing more biomass. The biomass values measured in our study represent maximum seasonal biomass values and are higher than productivity estimates that include a carryover of biomass from the previous season. For HD, the restrictive nature of hummocks and multi seasonal growth might be the major reasons behind high plant biomass. Because we did not know the exact age of the plants, some plants might represent two or more growing seasons in our random sampling. However, plants representing two growing seasons do not necessarily carry maximum nutrient concentrations (Reddy and DeBusk 1987).

Nutrients analysis

Our data suggest that nutrient concentrations tended to be highest for *S. californicus* compared to the other two bulrush species. Cattails were also found to have relatively higher nutrient concentrations. Cattail plants in our wetland sites

had high nutrient uptake compared with similarly constructed wetlands in other parts of the U.S (Kadlec and Wallace 2009). In a study similar to ours, in two free-water surface treatment cells at the Iron Bridge Wetland in Florida, *S. californicus* and *Typha latifolia* removed TN and TP to a similar extent (USEPA 2000). Nitrogen uptake by cattails and bulrushes was in the range of 100–300 g N/m² at different constructed treatment wetlands in the U.S. (Kadlec and Wallace 2009); this is comparable to our results. However, the nutrient storage per m² in our study differs significantly because of the plant biomass values varying among the four wetlands (Table 1). High densities of bulrush species carried large amount of nutrients in the system, up to 170.2 g TN/m² and 16.0 g TP/m². Our results are on the high end compared to the findings of Vymazal (2006), who reported that the nitrogen standing stock for emergent species was in the range of 14 to 156 g N/m². Similarly, Tanner (2001) showed that bulrush plant tissues accumulated 8.8–13.4 g TP/m² and 48–69 g TN/m² in total biomass (root and shoot). These data are within a close range of our wetlands systems.

TN and TP contents of living biomass in different wetlands vary considerably among species, plant parts, and wetland sites (Table 1). Despite their differences in total biomass, nutrient concentrations in plant tissues were similar between cattail and bulrush species. Nutrient content per unit of biomass was generally more site-specific than species-specific. This is not unique only to our system; for example, another study found that nutrient removal efficiency of a system depends on the plant type, growth rate, nutrient composition of the water, and physicochemical environment in the water-sediment system (Reddy and DeBusk 1987). Also, in our study, below-ground parts appear to be more efficient in phosphorus uptake compared to the above-ground plant parts (of both cattails and bulrushes). However, in contrast, above-ground plant parts had higher nitrogen concentrations compared to the below-ground parts for both species. Our results are in agreement with Greenway (2005), who compared nitrogen and phosphorus in root/rhizomes and leaf/stem tissues for a variety of native wetlands species in constructed wetlands in Queensland, Australia, and found that the nitrogen content was highest in

the above-ground parts and the phosphorus was highest in the below-ground parts.

Species differences had little to no effect on TP uptake, rather the ambient concentration of nutrients in the sediments appeared to drive differences among the specific wetland sites. Sites with higher ambient nutrients also had generally higher nutrients in the plants. This is not completely unexpected because plants have higher plasticity for nutrients. This has also been found in many algal nutrient studies; for example, a previous study found that algae grown in higher nutrient concentrations have higher algal N and P concentrations due to weaker homeostasis in plants compared to other organisms (Acharya et al. 2004; Sterner and Elser 2002). There was a noticeable reduction between the inlet and outlet sediment TP concentration for all the wetlands. However, reductions were less significant and highly variable for TP in water. Phosphorus removal in the water column is highly variable and depends on many factors such as settling of fine particles, among others. This is also suggested in a study by Kadlec and Wallace (2009) of 250 different free-water surface wetlands that showed that the reduction of phosphorus from inflow to outflow is unpredictable and variable.

Also, our data suggested that TP concentrations in plant tissue had relatively higher correlation with concentrations in the sediments and water columns (Fig. 3a, b). Relative concentrations were particularly strong in the HD wetlands (Fig. 2a, b, c). This is perhaps expected considering that the HD wetland receives treated effluent from a wastewater treatment plant and the wetland has a long retention time. Similarly, other previous studies suggest for TP removal contact time may play a major role in the distribution within constructed wetlands (Drizo et al. 2000), and it has been suggested that the removal efficiency of TP is positively correlated with retention time (Klomjcek and Nitorisavut 2005).

Total nitrogen measured in water and sediments were higher in the LVW wetlands than in other wetlands (Fig. 2e, f). The source of the higher nitrogen input (~ 14 mg/L) is the effluent coming from the wastewater discharge (~ 290 cfs) in the LVW wetlands. Whereas the FW wetland, which is a tributary of the LVW wetland, receives

much less discharge (~ 5 cfs) and has much less nitrogen in the system show higher difference in removal (between inlet and outlet concentrations). Both of these wetlands have similar hydrology and plant types. Comparing the difference between inlet and outlet measurements, the FW wetlands were found to be more efficient in sediment nutrient removal. Higher discharge might be too much to overcome for the wetlands in LVW to substantially increase removal of nitrogen from the system. Despite a loss in TN at the outlet of the FW wetlands, cattails in the FW wetlands generally had lower TN concentrations than in the LVW wetlands. This may be due to a less favorable habitat for plants to flourish in channel wetlands combined with other means or nitrogen removal such as denitrification. Furthermore, nutrient inputs can directly modify or change biological communities. Fluctuations in hydrological conditions induce changes in nutrient inputs. Therefore, high dependence on hydrology is particularly important in semi-arid and arid areas, where surface water levels fluctuate seasonally (Mitsch and Gosselink 2000).

In our study, nitrogen uptake by plants was not significantly correlated with either ambient water and sediment concentrations, as suggested by the weak regression coefficients for both the water column and sediment (Fig. 3c). Different hydrological regimes observed in our wetlands might have contributed to different TN and TP concentrations in the plants, sediments, and water columns. Despite less nitrogen input and lower water and sediment concentrations, TN recovery through plant assimilation was remarkably high in the HD wetlands as compared to PW wetlands. It may be due to the denitrifying of pond water by the City of Henderson Water Reclamation Facility in March 2008 just prior to our sampling date. Also, the plants have been growing in the HD wetlands for several years and thus were growing when TN concentrations in the water and sediment were much higher than during our study period (Zhou and Van Dooremolen 2004). Better performance of the HD wetlands might also be due to the better vegetation management practice of using hummocks. A study in the southwestern U.S. found the properly configured hummocks in constructed wastewater treatment wetlands can

be used to maintain the proper balance of vegetation necessary to optimize treatment function (Thullen et al. 2005).

Metals analysis

Similar to nutrients, both cattail and bulrush species were effective bioaccumulators of these metalloid pollutants (As and Se) from the wetland systems. Our study suggested that As and Se uptake capacity was significantly higher in bulrushes than in cattails. Among the three species of bulrush, *S. americanus* was the most effective at As and Se uptake, followed by *S. acutus* and *S. californicus*. However, both of these latter species are also known to acquire heavy metals in their root, rhizome, and leaf tissues, as found in studies of constructed wetlands for treatment of pond effluents in Alabama, U.S. (Schwartz and Boyd 1995) and for metal contaminated urban streams in southeast Queensland, Australia (Cardwell et al. 2002). Similarly, below-ground plant tissues (root) had higher concentrations of both As and Se than the above-ground (shoot) parts (Fig. 7a, b). Our results are comparable with the study by Vymazal et al. (2009) who found that concentrations decreased in the order of roots > rhizomes > leaf > stems for 19 different trace elements, including As and Se, for *P. australis* plants growing in constructed wetlands with subsurface flow for treatment of municipal sewage in the Czech Republic.

A number of trace metals are essential micronutrients at low concentrations, but some trace metals may occur in wastewater at concentrations that are toxic to aquatic wildlife (Hamilton 2004; Fox and Doner 2003). Concentrations of As in the plants of the four wetlands were consistent with the trends in the ambient concentrations of the sediments and water columns (Fig. 5a, b, c). The regression analysis showed that the As in plants is significantly correlated with sediment and water column (Fig. 6a, b) concentrations. Overall, the highest measured As uptake in plants was in the PW wetlands followed by the LVW wetlands. The HD and FW wetlands had the lowest plant As concentrations. Among the four wetland sites, the PW wetlands also had the highest sediment and water column As concentrations,

followed by LVW wetlands. The As concentration (13.12 $\mu\text{g/L}$) measured in the water column of the PW wetland appears to exceed the drinking water standard (10 $\mu\text{g/L}$). It is thought that the As in PW is naturally occurring through the groundwater system rather than from anthropogenic sources (Cizdziel and Zhou 2005). Sediment from the outlets of the PW and HD wetlands showed a small but significant drop in concentrations, but this was not the case in the FW and LVW wetlands. In contrast to As, among the four wetlands, Se concentrations in plants were relatively more consistent with water column than with sediment concentrations. Se concentrations in the sediments of the four wetlands (<2.0 $\mu\text{g/g}$) were moderate and perhaps without any consequential impact on aquatic life. A Se concentration of less than 2 $\mu\text{g/g}$ is considered below the toxicity threshold (USEPA 2004). Unlike concentrations in the sediments, Se concentrations in the water column were relatively higher (10–15 $\mu\text{g/L}$) in both the FW and PW wetlands. Regression analysis between plant tissue Se concentrations and Se in the water columns among four wetland sites (Fig. 6c) was relatively weak (than As).

Waterborne Se in FW and PW wetlands exceeded the EPA standard for chronic exposure (5 $\mu\text{g/L}$) and even came close to acute exposure (20 $\mu\text{g/L}$; USEPA 2004). Although fish and wildlife may be exposed to an elevated risk of Se toxicity (Hamilton 2004), site-specific evidence shows that the risk is low to moderate based on our unpublished data. Se concentrations analyzed in plants from the LVW, FW, and HD wetlands (>3.0 $\mu\text{g/g}$) are similar to those found in the study by Seiler et al. (2003) in the western U.S. Our results for plant Se concentrations in the LVW, FW, and HD wetlands are similar to those of Pollard et al. (2007) for bulrushes and cattails in the Nature Preserve wetlands and Hansen et al. (1998) for shoot and root tissues of wetland plants in the constructed wetlands of the San Francisco Bay. Seiler et al. (2003) provided a typical background level for plant tissue Se (1.5 $\mu\text{g/g}$) and dietary effect levels in these tissues (\sim 3 $\mu\text{g/g}$). Se concentration in plants from LVW, HD, and FW were below these levels and only plant tissues in PW exceeded (\sim 10 $\mu\text{g/g}$) this level. The PW wetlands' relatively high Se concentrations could

pose an elevated risk of bioaccumulation for birds and wildlife and transfer to higher trophic levels in the food chain. Se concentration in the PW wetlands in bulrush plant tissue, sediments, and water column is similar to Se concentrations in constructed wetlands from other parts of the world (Kadlec and Wallace 2009). Kadlec and Wallace's study compiled Se concentrations in vegetation in treatment wetlands exposed to Se, and found that they were typically in the range of 1–20 $\mu\text{g/g}$ for plants and 1–10 $\mu\text{g/g}$ for sediments.

Seasonal variation

Seasonal variation of nutrients (TN and TP) and metals (As and Se) were also analyzed to see whether there were any noticeable differences. There were only a few signals of variations but these trends were not validated by statistical testing. For example, seasonal average TP concentrations in the cattails were higher in LVW during the summer season but there was no apparent difference between spring and winter. Similar trends were seen at HD and PW wetlands for TP% in bulrush plants with typically higher concentrations in summer followed by lower concentrations in spring and winter. Similarly, seasonal mean TN% in cattail and bulrush plant tissues was similar to that of TP in all the wetlands. Also, seasonal As concentrations ($\mu\text{g/g}$) in cattail at the LVW wetlands appeared slightly higher in

summer followed by spring and winter seasons but were not statistically significant. Three of our wetland sites (LVW, HD, and PW) were somewhat similar in that winter samples (not particularly fall) generally had higher Se concentrations in shoots for both plant types. This may be because of higher volatilization of Se in summer and spring season. These differences did not result in direct correlations with sediment and water data.

Ecosystem function of wetlands

Comparison of annual average nutrient storage in standing plants biomass showed that nutrient removal from the LVW wetlands was significantly higher than from the FW wetlands. This can perhaps be attributed to higher productivity (and thus more efficient nutrient removal) by cattails in the LVW wetlands. The LVW and FW wetland plants stored $\sim 1,357$ kg/ha/year and 257 kg/ha/year of nitrogen, respectively. Also, the LVW wetland plants sequestered ~ 66 kg/ha/year phosphorus compared to 15 kg/ha/year at the FW plants (Table 2). However, based on our annual average nutrient storage in plants (kg/ha/year) in the HD and PW wetlands, we calculated that the HD and PW wetlands plants stored $\sim 1,612$ and ~ 441 kg/ha/year of nitrogen, respectively. Similarly, the HD wetland plants sequestered ~ 147 kg/ha/year phosphorus compared to ~ 18 kg/ha/year at the PW wetlands. Better

Table 2 Inflow source, annual average nutrient and metal concentrations in water versus annual average nutrient and metal removal by plant (kg/ha/year) at the Las Vegas

Wash (LVW), Flamingo Wash (FW), Demonstration Wetlands at the City of Henderson Water Reclamation Facility (HD), and Pittman Wash Pilot Wetlands (PW)

Site	Inflow source	Nutrient concentration of water (mg/l)		Metal concentration of water ($\mu\text{g/l}$)		Nutrient removal by plant (kg/ha/year)		Metal removal by plant (kg/ha/year)	
		TN	TP	As	Se	TN	TP	As	Se
LVW	Urban runoff, wastewater discharge	14.7 ± 0.2 ($n = 48$)	0.13 ± 0.05 ($n = 30$)	7.1 ± 0.4 ($n = 27$)	3.2 ± 0.1 ($n = 36$)	1357	66	0.53	0.35
HD	Wastewater discharge	6.5 ± 0.9 ($n = 37$)	1.41 ± 0.1 ($n = 24$)	3.4 ± 0.1 ($n = 16$)	1.9 ± 0.1 ($n = 14$)	1613	147	0.21	0.44
PW	Urban runoff	9.02 ± 0.1 ($n = 41$)	0.05 ± 0.01 ($n = 15$)	13.2 ± 0.5 ($n = 40$)	10.6 ± 0.1 ($n = 38$)	441	18	0.41	0.71
FW	Urban runoff	3.58 ± 0.1 ($n = 65$)	0.04 ± 0.006 ($n = 22$)	6.1 ± 0.3 ($n = 28$)	8.5 ± 0.1 ($n = 12$)	286	15	0.05	0.04

Digits after the \pm sign indicate standard errors

ecosystem function of the HD and LVW wetlands is not only due to higher plant biomass and nutrient concentrations but also due to the larger surface area of the wetlands.

Metal removal efficiency among the four wetland plants suggests that the annual average As uptake was higher at the LVW wetland plants (0.53 kg/ha/year) compared to FW (0.05 kg/ha/year). Similarly, LVW wetland plants stored (0.35 kg/ha/year) Se which was also higher than at FW plants (0.04 kg/ha/year). It appears that the larger the surface area of wetland vegetation, the higher the metal accumulation and therefore the higher the flux, suggesting that wetland acreage is important as well. However, this was contradicted to some extent by the PW wetlands data which showed higher metal storage per unit area than any other wetlands in our study (Table 2).

Despite clear evidence that nutrients and metals are taken up by the plants in our study, it is puzzling that any significant water quality improvements are not seen between inlets and outlets. This could be because of the short residence time of water or short distance between inflow/outflow sampling locations which needs further investigation in future studies. However, it does appear that annual harvesting of the plants from these wetlands would provide significant removal of nutrients and metals.

Conclusions

Constructed and naturally created wetlands in the Las Vegas Valley watershed were studied to understand their potential for pollutant removal. Significant removal of nutrients was found in the wetlands receiving high nutrient loads and both plant species in the four wetlands sites were quite efficient in taking up large amounts of nutrients and metals. The nutrient removal capacity of a wetland system was more dependent on individual plant biomass irrespective of plant type, i.e., on the size of individual plants or plant density. The nitrogen concentration was higher in above-ground plant parts but the phosphorus was higher in the belowground parts, which suggests that harvest of the root system would be necessary

for maximum phosphorus removal, but an above-ground harvest would be sufficient for nitrogen removal from our wetlands systems. Plant nutrients in the four wetland sites correlated well with ambient nutrient concentrations in the sediments and water columns, irrespective of the type of plants present. Overall, this study suggests that different plant species have different capacities to take up nutrients, with these capacities mostly determined by the ambient nutrient and hydrologic conditions. Bulrush species seem particularly efficient for taking up metals such as As and Se, as compared to cattails. Also, the below-ground plants for both species seemed to store metals more efficiently than above-ground parts. Higher metal accumulation in the PW wetlands plants suggested that there is a potential for wildlife exposure. Better information on the bioaccumulative properties of the bulrush species found in the wetlands in this study might provide clues for Se removal using existing wetland plants in these wetlands. These findings have important implications for improving our ability to engineer ecological solutions to problems associated with nutrient-rich wastewater and to implement sustainable wetlands management plans.

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