INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
10–153/SAA/2010/12–6–821–827
http://www.fspublishers.org

Full Length Article

Performance of a Surface Flow Constructed Wetland System Used to Treat Secondary Effluent and Filter Backwash Water

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ABSTRACT

The performance of a surface flow wetland used to treat activated sludge effluent and filter backwash water from a tertiary treatment facility was evaluated. Samples were collected before and after vegetation removal from the wetland system, which consisted of two densely vegetated settling basins (0.35 ha), an artificial stream and a 3-ha surface flow wetland. Bulrush (*Scripus* spp.) and cattail (*Typha domingensis*) were the dominant plant species. The average inflow of chlorinated secondary effluent during the first two months of the actual study was 1.84 m^3 min^{-1}, while the inflow for backwash water treatment ranged from 0.21 to 0.42 m^3 min^{-1}. The system was able to reduce TSS and BOD_5 to tertiary effluent standards; however, monitoring of chloride concentrations revealed that wetland evapotranspiration is probably enriching pollutant concentrations in the wetland outflow. Coliphage removal from the filter backwash was 97 and 35% during 1999 and 2000, respectively. However, when secondary effluent entered the system, coliphage removal averaged 65%. After vegetation removal, pH and coliphage density increased significantly ($p<0.05$) at the outlet of the wetland. This study showed that surface flow wetlands are an alternative technology for TSS, BOD_5 and turbidity removal from both secondary or backwash water. However, growth of bacterial populations or recovery of injured bacteria may occur.

Key Words: Wetlands; Backwash water; Secondary effluent; BOD_5; TSS; Turbidity

INTRODUCTION

In conventional wastewater or drinking water treatment plants, backwash water results from periodic backwashing of single or mixed media filters used for removing organic matter, enteric pathogens, and other particulate matter from raw drinking water or activated sludge secondary effluent (Persson *et al*., 2005; Khan & Subramania, 2007; Horan & Lowe, 2007). Consequently, backwash water without efficient treatment or recycling in treatment facilities may represent a public health risk (Koivunen *et al*., 2003). In order to protect public health, environmental protection agencies have regulated its recycling in conventional drinking water treatment plants to control disinfection resistant microbial pathogens and consequently waterborne diseases (USEPA, 2002). In the wastewater treatment industry, constructed wetlands are considered an attractive technology to treat low strength domestic sewage and secondary wastewater effluents.

Wetland technology has also offered an innovative approach for reduction, with different degrees of success, of a wide range of chemical pollutants (Kara & Kara, 2005; Grove & Stein, 2005; Abou EL-Kheir *et al.,* 2007; Matamoros *et al*., 2007; Troesch *et al*., 2009) and microbial indicators (Mendez *et al*., 2009; Von Sperling *et al*., 2010). However, until recently, few or not data existed on the efficacy of constructed wetland systems to treat backwash water; even though, one of the most common methods to treat backwash water has been settling in lagoon facilities (Montgomery, 1985). In 1997, two wetland systems were constructed at the Sweetwater Recharge Facility to treat backwash water from a tertiary wastewater treatment plant in Tucson AZ, USA. After soil aquifer treatment, wastewater is recovered from the aquifer at 1.6 x 10^7 m^3 $year^{-1}$ extraction rates to be deliver in golf course facilities, parks, schools and residential sites.

The objective of the actual study was to assess wastewater quality performance in the wetland system before aquifer recharge. Hence, physical, chemical and microbial indicators for wastewater quality were evaluated

To cite this paper: Vidales-Contreras, J.A., C.P. Gerba, M.M. Karpiscak, H.R. Fuentes, J.J.H. Escareño and C. Chaidez-Quiroz, 2010. Performance of a surface flow constructed wetland system used to treat secondary effluent and filter backwash water. *Int. J. Agric. Biol.*, 12: 821–827

in the wetland during secondary effluent and backwash water treatment from February to September 1999 and 2000. The actual paper presents the results of this monitoring study.

MATERIALS AND METHODS

Research site and sampling: The research was conducted at the Sweetwater Wetland and Recharge Facility (SWRF) in Tucson, AZ. In this site (Fig. 1), two polishing wetland systems referred to as East and West were designed in about 12.46 ha to reclaim backwash water from the City of Tucson Reclamation Plant. At this site, residual chlorine in secondary effluent at the pressure mixed media filters was on average 1 mg L^{-1}. After backwashing mixed media filters, the backwash effluent was kept free of chlorine additions. At the wetland facility, both the East or West polishing systems consist of a 3-ha wetland cell and a pair of settling basins vegetated with bulrush species (*Scirpus* spp.) and cattail (*Typha domingenses*). However, in the East Polishing System (EPS), wastewater flows briefly through an artificial stream before entering the 3-ha wetland cell for additional wastewater treatment. A sequence of islands of different sizes, shallow vegetated zones and 1.2-m deep open water areas is the geometric configuration of the wetland to provide tertiary treated wastewater. After wetland treatment, polishing wastewater goes by gravity to four recharge basins, located at the vicinity area of The Santa Cruz River, for soil aquifer treatment. Eventually, drilling wells pump reclaimed water from the aquifer to the Pima County Roger Road Wastewater Treatment Facility (RRWTF) for chlorine disinfection and deliver in parks, schools and golf course fields. In spite of both polishing systems were designed to treat backwash water, chlorinated secondary effluent from RRWTF was introduced for starting wetland operation in October 1997; on April 1998, the polishing wetland systems began to treat backwash water. In the winter 1999, wetland vegetation was harvested from the EPS; however, by the end of Spring a new complete plant canopy had taken its place. From February to September of 1999 and 2000, water samples were collected monthly from the EPS at the backwash splitter box (1), outlet of the south settling basin (2), both ends of the stream (3 & 4) and outlet of the wetland cell (5). Concurrently, measurements of water temperature (T), biochemical oxygen demand (BOD_5), total suspended solids (TSS), SO_4^{-2}, Cl^-, total and free chlorine (Cl_2), turbidity, pH, native coliphages (NC) and total (TC) and fecal coliforms (FC) were conducted.

Physical and chemical analysis: The 5-days incubation method (APHA/AWWA/WEF, 1998) was used for BOD_5 analysis. Determination of TSS was conducted by filtering a known volume of sample through a pre-cleaned and pre-weighed glass fiber filter. TSS concentration was estimated reweighing the filter after a 24-h drying period at 100°C. Sulfate was assessed by adding $BaCl_2$ to a known volume of sample measuring the absorbance at 420 nm in a HACH DR/2000 spectrophotometer (Loveland, CO). Chloride was quantified by a chloride-specific electrode and turbidity with a portable turbidimeter (HACH, model 2100P, Loveland, CO) reading as Nephelometric Units (NTU). A pH meter (model 8005, West Chester, PA) quantified water pH whereas the DPD (N, N-diethyl-p-phenylenediamine) indicator method (HACH Spectrophotometer, model DR/2000, Loveland, CO) was chosen for total and free chlorine (Cl_2) determination.

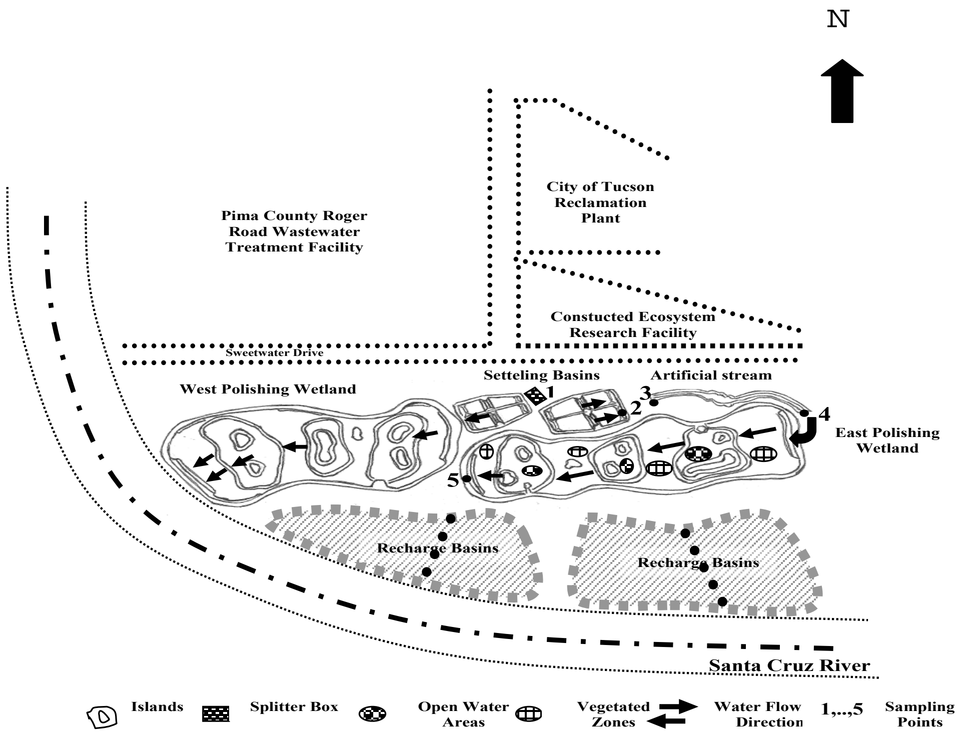
Coliforms and coliphages: Total and fecal coliforms were analyzed within 4 h of sampling by membrane filtration using mEndo Agar Les and mFC culture media (DIFCO, Detroit, MI), respectively. The membrane filters were 47 mm diameter with a 0.45-µm pore size (Millipore, Molsheim, France). Sample volumes of 0.1, 1 and 10 mL were assayed and incubated at 37°C for total coliforms and 44.5°C for fecal coliforms, results are reported as colony forming units (CFU). Native coliphages were quantified by the double layer agar method described by Adams (1959). A 1-mL aliquot from *Escherichia coli* ATCC 15597 (ATCC) culture, previously incubated at 37°C for 24 h in trypticase soy broth (DIFCO, MI), was combined with one mL of sample in a test tube containing molten overlay agar. This suspension was poured onto a layer of tripticase soy agar (DIFCO, MI) and incubated at 37°C for 18 h in order to enumerate the coliphage as plaque forming units (PFU). This method detects both somatic and male specific coliphages.

Statistical analysis: The statistical analysis was conducted using the Statistical Package for Social Science 12 (SPSS Inc., Chicago ILL). Tests to determine significant differences between sampling periods and monitoring sites were conducted by two way ANOVA analysis. Because of extreme concentration values and high variability into microbial data sets, ANOVA analysis was conducted transforming microbial concentrations to base 10 logarithmic units (log_{10}) for backwash water operation. The geometric mean was used as a centrality measure for observed microbial indicator distributions. Extent of data dispersion was represented by geometric coefficient of variation, $(10^\wedge (\sigma) - 1) \times 100$, where σ is the standard deviation of log_{10} microbial concentration values. The physical/chemical data sets were analyzed without transformation.

RESULTS

Hydrologic conditions: An actual hydraulic residence time of 7.2 days was estimated by a tracer study in the East wetland cell. During this study, February 12 to March 18, 1999, the wetland was receiving chlorinated secondary effluent at an average rate of 1.84 m^3 min^{-1}. From March 19 to 22, a mixture of chlorinated secondary effluent and backwash water was introduced into the East and West system changing to 100% backwash water at 0.42-m^3 min^{-1}

Fig 1: Schematic representation of the Seetwater Wetland and Research Facility in Tucson AZ where the sampling study was conducted from 1999-2000



flow rate, on March 23. This hydraulic condition was changed to 0.25 m^3 min^{-1} on June 30 and was held until September 21, when the EPS started to be drained for vegetation harvesting in the winter of 1999. The EPS returned to normal operation in February 2000 at an average inflow rate of about 0.32 m^3 min^{-1} of backwash water (Tucson Water, 1999 & 2000).

Sampling of chlorinated secondary effluent: Two water samples were collected per sampling site during February and March, 1999. Influent BOD_5 and TSS concentrations were 29 and 21.5 mg L^{-1}, respectively decreasing about 69% at sampling location 2 (Table I). Turbidity reduction was very similar to BOD_5 and TSS performance with a 56% decrement from location 1 to 2. At sampling site 2, a significant increase of indicator bacteria was observed; in fact, TC inflow concentration increased by a forty five-fold factor, approximately, at this sampling site. In contrast, the East wetland cell noticeably removed TC, FC, and NC reaching reductions about 91, 81 and 72%, respectively from end to end of the 3-ha wetland. Chloride was practically constant in the wetland system showing the lowest concentration at site 5. Sulfate revealed a greater variability than Cl^- ranging its concentration between 122.5 and 144.5 mg L^{-1}. For pH, the lowest value was observed in the settling basin and the highest at splitter box. An average temperature of 22.7°C was recorded at site 1 decreasing to 10.5°C at wetland outlet, 3.66°C below the average temperature for February and March 1999 recorded at the Tucson Meteorological Station (The Arizona Meteorological Network, AZMET, 2008). On February 19, total and free Cl_2 concentrations were 1.19 and 0.14 mg L^{-1}, respectively in the splitter box water. Both concentrations were below the method detection limit thereafter. On March 20, Cl_2 was undetected at any sampling point in the EPS.

Sampling of Backwash Effluent

Indicator microorganisms: Geometric mean concentrations for total coliforms, fecal coliforms and coliphage observed at monitoring sites during backwash water study are presented in Fig. 2. It can be clearly seen that TC and FC average concentrations increased in the settling basin. The remaining wetland treatment units resulted in further bacterial removal. At the system outflow, inflow NC concentrations decreased by about 97 and 35% in 1999 and 2000, respectively. Table II illustrates the high variability observed in microbial concentrations particularly in the first sampling period when geometric coefficient of variation (CV) ranged between 90 and 633% for TC and from 120 to 526% for FC. The ANOVA analysis revealed a significant difference for microbial indicator concentrations between sampling sites ($p<0.05$) but not for sampling periods ($p>0.05$).

BOD_5, TSS, temperature and turbidity: Table III shows BOD_5, TSS and turbidity descriptive statistics for 1999 and 2000 backwash water treatment. The CV values for those water quality parameters varied from 14.33 to 127.66%; however, CV estimates during 2000 ranged between 19 to 76.10% for all the sampling sites. In contrast to the artificial stream and wetland cell, the settling basins were efficient for

Table I: Two-sample average concentrations for parameters analyzed in the Sweetwater wetlands during secondary effluent operation study, February-March 1999

Site	Total coliforms	Fecal coliforms	Coliphage	BOD_5	TSS	Cl^-	SO_4^{-2}	Turbidity	pH	Temperature
	CFU/100 ml × 10^3		PFU/100 ml × 10^3							
				mg /L				NTU	$-Log_{10}$ [H]	ºC
1	0.36	0.064	4.89	29	21.5	126.0	128.5	17.9	8.17	22.7
2	16.21	8.51	7.24	9	6.5	125.0	133.0	7.8	7.22	20.2
3	11.74	4.26	7.94	7	8.0	122.5	127.0	7.6	8.15	19.0
4	6.48	1.17	6.02	7	5.0	127.0	144.5	6.3	7.95	18.0
5	0.58	0.22	1.69	8	5.0	116.5	122.5	2.8	7.49	10.5

Table II: Geometric coefficients of variation (CV) for coliform, fecal coliform and native coliphage concentrations observed at sampling sites in the East Polishing System during backwash water inflow

Indicator	Coefficient of variation (%)									
	1999					2000				
	Sampling site					Sampling site				
	1	2	3	4	5	1	2	3	4	5
TC	90	103	100	110	633	302	126	81.7	125	346
FC	120	410	182	188	526	145	119	122	107	468
NC	240	206	216	293	221	91	83	119	125	186

Table III: Descriptive statistics of TSS (mg L^{-1}), BOD_5 (mg L^{-1}) and TUR (NTU) in samples collected from monitoring sites in the EPS during backwash water operation

Variable	Number of samples		Min		Max		Mean		Standard Error		CV (%)	
	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
TSS (site 1)	6	7	98	7	380	278	190.66^{a}	115.57^{a}	40.76	37.24	127.66	69.17
TSS (site 2)	5	8	5	5	60	13	17.4^{b}	7.87^{b}	10.68	0.98	51.1	35.55
TSS (site 3)	6	8	5	5	30	16	10.33^{b}	7.50^{b}	5.38	1.30	37.2	49.37
TSS (site 4)	6	8	5	5	12	22	6.66^{b}	10.37^{b}	1.17	1.88	28.42	51.50
TSS (site 5)	6	8	5	5	10	30	7.0^{b}	11.62^{b}	1.00	3.12	14.33	76.10
Total Removal (%)							96.32	89.94				
BOD_5 (site 1)	6	7	71	78	252	207	127.66^{a}	144.71^{a}	27.12	19.31	52.03	35.31
BOD_5 (site 2)	4	8	10	25	136	46	51.5^{b}	37.37^{b}	28.58	2.52	111	19.07
BOD_5 (site 3)	5	8	12	22	63	45	37.2^{b}	36.87^{b}	8.71	2.79	52.38	21.42
BOD_5 (site 4)	6	8	10	19	42	42	28.42^{b}	31.25^{b}	7.39	2.85	58.29	25.81
BOD_5 (site 5)	6	8	9	19	21	36	14.33^{b}	23.62^{b}	1.81	1.99	31.03	23.83
Total Removal (%)							88.77	83.67				
TUR* (site 1)	6	7	30.36	16.3	344	308	150.85^{a}	142.62^{a}	39.35	33.00	63.90	64.96
TUR (site 2)	6	8	13	17	70	105	32.81^{b}	49.87^{b}	8.10	11.20	60.49	63.53
TUR (site 3)	6	8	20	27.9	113	123	44.26^{b}	57.9^{b}	13.98	11.62	77.36	56.76
TUR (site 4)	6	8	14	31.2	68	129	37.93^{b}	57.05^{b}	10.45	11.11	67.48	55.08
TUR (site 5)	6	8	5.28	21.4	64	44.5	31.8^{b}	32.9^{b}	10.59	3.06	81.84	26.32
Total Removal (%)							78.91	76.93				

^{a,b} Means within the same column and different letter for the same variable are significantly different ($p<0.05$)
*turbidity

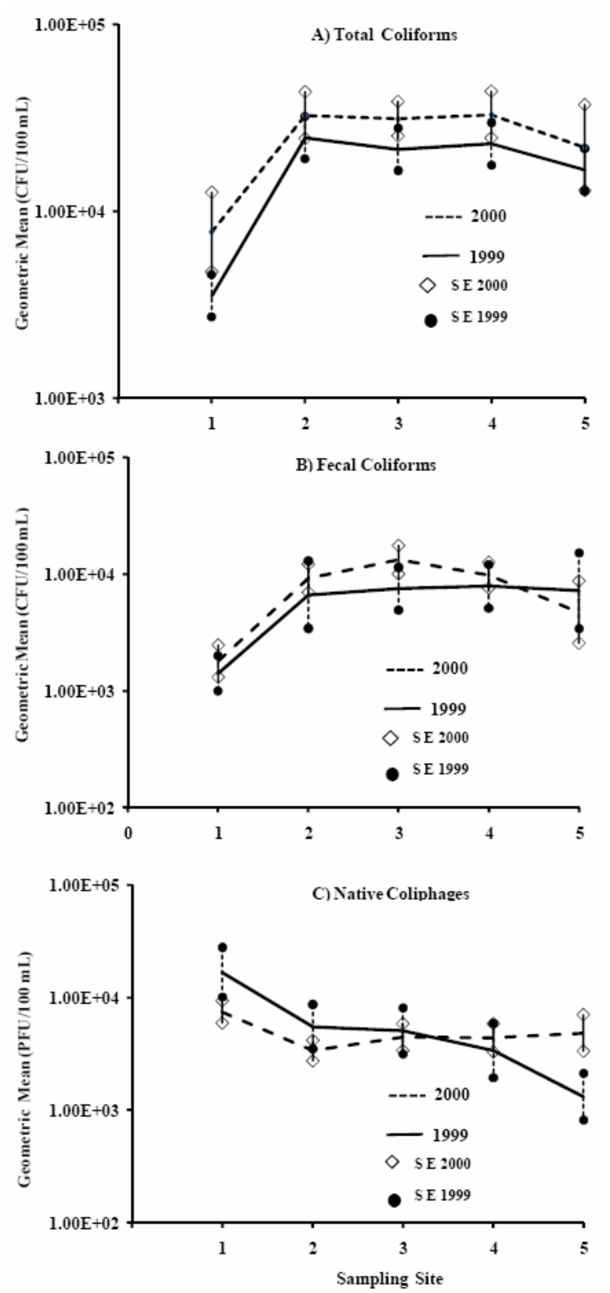
Table IV: Coefficients of variation, CV (%) for Cl^- and SO_4^{2-} observed at sampling sites in the East Polishing System during backwash influent operation

Indicator	1999 sampling site					2000 sampling site				
	1	2	3	4	5	1	2	3	4	5
Cl^-	17.31	15.72	9.80	9.50	12.83	14.18	9.33	11.24	9.29	19.14
SO_4^{2-}	13.41	6.03	7.46	10.45	14.52	24.42	13.80	13.89	14.46	19.13

backwash water treatment. At this site, the average TSS, BOD_5 and turbidity were significantly ($p<0.05$) reduced to 91-93%, 60-74% and 65-78%, respectively. These results are fairly lower than the estimates for the entire polishing system during both sampling periods, 90-96% for TSS; 84-89% for BOD_5 and 77-79% for turbidity, suggesting that TSS are more efficiently removed than BOD_5 and turbidity.

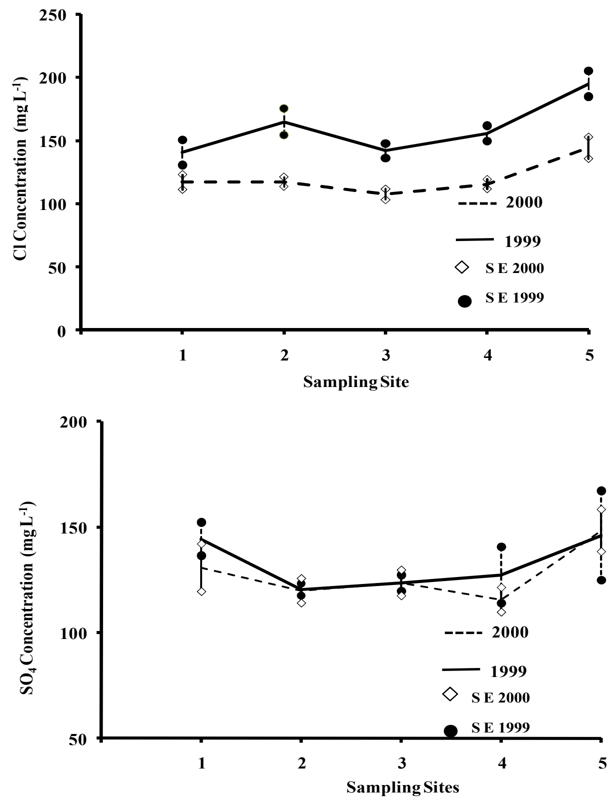
Cl^-, SO_4^{-2} and pH: From April to September 1999, ANOVA analysis indicated that Cl^- average influent concentration was 141 mg L^{-1} increasing significantly

Fig. 2. Observed geometric concentrations and standard error (SE) bars for A) total coliforms; B) fecal coliforms; and C) native coliphages durng 1999 and 2000 backwash water treatment in the East Polishing system



($p<0.05$) to 164 mg L^{-1} at site 2 (Fig. 3). Thereafter, its concentration was 142 and 155 mg L^{-1} at site 3 and 4, respectively. At 5, a significant increase ($p<0.05$) of 40 mg L^{-1} above site 4 concentration was recorded. During the 2000 backwash sampling period, lower Cl^- concentrations than in 1999 were observed at monitoring sites. ANOVA analysis revealed a statistical difference ($p<0.05$) between both backwash water periods for Cl^-, in fact, a 16%

Fig. 3: Observed concentrations and Standard Error (SE) bars for Cl^- and SO_4^{2-} during 1999 and 2000 backwash water operation in the East Polishing Basin



difference between sampling periods for influent Cl^- concentrations at site 1 was estimated. For SO_4^{-2}, this estimate was 11%, Table IV gives coefficients of variation for Cl^- and SO_4^{2}; it seems clear that observed concentrations for both parameters showed a lower variation than the other water quality indicators (TC, FC, NC, TSS, BOD_5 & turbidity). For example, in 2000, the calculated CV at the system outflow was about 19% for both Cl^- and SO_4^{-2}, which is similar to the lowest CV estimated for TSS, BOD_5 and turbidity in the polishing system during backwash water treatment. In the same effluent in 1999, water pH ranged from 7.4 to 7.5 at sampling sites 1 to 3; whereas at the wetland outflow pH decreased not significant ($p>0.05$), to 7.35. In contrast, after vegetation removal, water pH increased significantly ($p<0.05$) at the end of the 3-ha wetland cell. Regarding residual Cl_2, its concentration was below the method detection limit at the sampling sites during the backwash water treatment study.

DISCUSSION

Physical/chemical water quality indicators: For secondary effluent treatment, outflow water in the wetland met on average the 10 mg L^{-1} tertiary standard required by the Arizona Department of Environmental Quality (ADEQ) for BOD_5 and TSS. A significant increase of turbidity,

BOD_5, and TSS occurred when secondary effluent was switched to backwash water at site 1. At the wetland outlet, removal of BOD_5 was comparable to the 89% reduction reported by Vrhovsek *et al.* (1996) in a subsurface flow wetland operated at 962 mg L^{-1} BOD_5 loading rate. Overall BOD_5, and TSS removal in the East Polishing System was according to reported values for constructed wetlands operating across USA and other countries (Kadlec & Knight, 1996; Masi *et al.,* 2010). In fact, the average TSS and BOD_5 at the outlet end of the system were lower than the 30 mg L^{-1} secondary standard limit established by the ADEQ for wastewater treatment.

Chloride is considered highly stable in most terrestrial environments. In wetlands, its total mass is approximately constant (Kadlec & Knight, 1996), because its incorporation in plant tissues is negligible (Hayashi *et al.*, 1998). Consequently, Cl^- has been used as a conservative tracer to estimate evapotranspiration in wetland ecosystems (Hayashi *et al.*, 1998). In the 3-ha polishing wetland, evapotranspiration may be a suitable mechanism for Cl^- augmentation during both backwash sampling periods when water flow rate was below 0.42-m^3 min^{-1}. Concentrations of Cl^- in the polishing wetland increased, from end to end, 25 and 19% during backwash operation, before and after vegetation removal, respectively. The ANOVA analysis indicated that only in 1999 was there a significant difference ($p< 0.05$) between inflow and outflow concentration from the 3-ha wetland cell. Sulfate is an essential nutrient for plants; thus, it can be retained by plant uptake in terrestrial environments; however, it is rarely a limiting factor for plant growth in wetlands (Kadlec & Knight, 1996). Its presence in high organic content environments induces production of hydrogen sulfide, because SO_4^{-2} is an electron acceptor for sulfur-reducing bacteria (Maier, 2000). This microbiological mechanism probably was responsible for reduction of SO_4^{-2} in the settling basin, mainly observed during 1999 backwash water treatment. Similar to Cl^-, an increase of SO_4^{-2} concentration occurred at the outflow of the wetland. After vegetation removal, water pH statistically increased at the outflow of the wetland cell. Probably, vegetation removal allowed sun light penetration in the shallow areas promoting a water pH increase in the outflow of the wetland basin because alga proliferation (Kadlec & Knight, 1996).

Indicator microorganisms: Removal efficacies greater than 90% for FC in surface flow wetlands receiving 10^4-10^6 UFC/100 inlet concentration loads have been reported (Kadlec, 2005; Ghermandi *et al.,* 2007). It appears that the amount of organic matter introduced into the settling basins is playing an important role for regrowth or recovery of injured coliform bacteria (Gerba, 2000; Bucklin *et al*., 2003; Bolster *et al.*, 2005). Coliform bacteria such as *Klebsiella*, *Enterobacter* and *Citrobacter* have shown ability to proliferate during wastewater treatment. For example, *Klebsiella* was found at high densities in the outflowing water from a treatment facility receiving municipal wastewater (Elmund *et al.*, 1999) apparently, because of an increase of carbohydrates in the wastewater influent. F-specific RNA bacteriophages have been used as potential indicator for human enteroviruses instead of fecal coliforms and fecal streptococci (Stetler, 1984; Havelaar *et al.*, 1993). A 90% removal of coliphage has been previously observed in constructed wetlands (Gersberg *et al.*, 1987; Chendorain *et al.*, 1998); however, removals lower than 90% were reported by Karpiscak *et al.* (1995) in a duckweed (*Lemna* spp.) pond and by Gersberg *et al.* (1989) in non-vegetated wetland. The extent of somatic and F-specific RNA coliphage replication in water has been discussed by several researchers (Muniesa & Jofre, 2004; Jofre, 2009). Their findings suggest that coliphage replication is possible at host bacteria and virus concentrations uncommonly found in water environments.

However, threshold concentrations may emerge, because of bacterial growth. In the present study, coliphage removal in the settling basin, site 2, showed a decrease from 98 to 65% after vegetation harvesting in 1999. Probably, some mechanism associated to vegetation density or phage replication was responsible for undetectable coliphage removal from site 3 to 5 during the second backwash sampling period.

CONCLUSION

Settling basins are an acceptable facility for BOD5, TSS and turbidity removal from both secondary effluent and backwash water; however, growth of bacteria population or recovering of injured bacteria also may occur. The actual study has shown the complexity of a wetland environment, where biological, physical, and hydrological conditions may explain pollutant performance during wastewater treatment.

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(Received 13 April 2010; Accepted 11 June 2010)