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Effects of a constructed wetland and pond system upon shallow groundwater quality

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Abstract Constructed wetland (CW) and constructed pond (CP) are commonly utilized for removal of excess nutrients and certain pollutants from stormwater. This study characterized shallow groundwater quality for pre- and post-CW and CP system conditions using data from monitoring wells. Results showed that the average concentrations of groundwater phosphorus (P) decreased from pre-CW to post-CW but increased from pre-CP to post-CP. The average concentrations of groundwater total Kjeldahl nitrogen and ammonium (NH_4^+) increased from pre-CW (or CP) to post-CW (or CP), whereas the average concentrations of groundwater arsenic (As), chromium, nickel, and zinc (Zn) decreased from pre-CW to post-CW regardless of the well locations. Variations of groundwater cadmium, copper, and Zn concentrations were larger in pre-CP than in post-CP and had a tendency to decrease from pre-CP to post-CP. In general, the average concentrations of groundwater aluminum and manganese decreased and of groundwater calcium, iron, magnesium, and sodium increased from pre-CP to post-CP. The average values of water levels (depth from the ground surface), redox potential, and conductance decreased and of chloride and sulfate (SO_4^{-2}) increased after the wetland and pond were constructed regardless of the well locations. Results further revealed that there were significant differences (α=0.05) between the pre- and post-CW (or CP) for redox potential, water level, and As. This study suggests that the CW–CP system had discernible effects on some of the shallow groundwater quality constituents. This information is very useful for fully estimating overall performance of stormwater treatment with the CW–CP system.

Keywords Constructed wetland and pond · Groundwater quality · Monitoring well

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Introduction

Constructed wetlands (CWs) and constructed ponds (CPs) are engineered systems that utilize natural processes including vegetation, soils, hydrology, and their associated microbial assemblages to assist in treating wastewater. These systems utilize many processes that occur in natural wetlands and ponds but operate in a more controlled environment. Compared with other conventional treatment systems, the CW–CP system is relatively inexpensive and easily operated. CWs have been used to treat wastewater for improvement of water quality and for reuse of reclaimed water for many years (Kadlec and Knight 1996). Gradually gaining acceptance, CWs are now used for many other types of wastewater treatment, including industrial and agricultural wastewater, landfill leachate, and storm water runoff (Vymazal 2005). CWs not only reduce suspended solids, nutrients, organic substances, and pathogens from domestic or municipal sewage, storm water runoff, and agricultural wastewater, but also remove heavy metals from mining effluent and special industrial wastewaters (Tang 1993; Crites et al. 1997; Obarska-Pempkowiak and Klimkowska 1999; Babatunde et al. 2008; Langergraber et al. 2008; Ouyang et al. 2010). Presently, there are three primary types of CWs: (1) surface-flow wetlands, (2) subsurface-flow wetlands (i.e., horizontal flow and vertical-flow wetlands), and (3) hybrid systems that incorporate surface and subsurface-flow wetlands, and, as noted above, there has been considerable research conducted on CW performance and effectiveness (Kadlec and Knight 1996). In contrast, very little research effort has been devoted to investigating the removal of contaminants from wastewater with CPs. Ou et al. (2006) investigated the performance of a CW–CP system for treatment and reuse of wastewater from campus buildings. These authors found that the percent removals of total suspended solids, total nitrogen, and total phosphorus are, respectively, 24, 87, and 62 % with the pond. Torrens et al. (2009) studied the impact of design and operation variables on the performance of vertical-flow CWs and intermittent sand filters treating pond effluent. These authors used the pond for slag and sediment collection without analyzing the removal efficiency of contaminants by the pond. A thorough literature search revealed that no attention has been given to evaluate the effects of CWs and CPs on shallow groundwater quality.

Groundwater pollution is a growing concern everywhere in the world. Characterization of groundwater quality allows evaluation of groundwater pollution and provides information for better management of groundwater resources and for better understanding of the potential adverse environmental effects upon surface water quality. Groundwater quality degradation in an aquifer is a result of natural conditions and human activities. Natural conditions affect water quality in an aquifer by means of recharge to and discharge from the aquifer, dissolution of minerals, and mixing of fresh groundwater with residential water or intruded seawater (Canter 1996; Boniol 1996). Human activities influence groundwater quality through vadose zone leaching and ditch seepage of contaminants due to accidental spill, leakage, and inappropriate application of contaminants and fertilizers on the land surface; the upwelling of water with high dissolved solids from deeper zones due to groundwater withdrawals; and the introduction of irrigation water from deep aquifers to surficial aquifers. With an increased understanding of the importance of groundwater resources for human consumption, agricultural and industrial uses, and ecosystem health, comes a greater need to evaluate groundwater quality.

Although a great deal of attention has been given to understanding the removal efficiency of CWs on excess nutrients and other pollutants from stormwater runoff to surface waters in the Lower St. Johns River Basin, Florida, little to no effort has been devoted to investigating the potential effects CWs and CPs on underlying shallow groundwater quality. Knowledge of this phenomenon is crucial to understanding the functions of CWs and CPs and to estimating potential adverse impacts on shallow groundwater quality. The goal of this study was to ascertain impacts of a CW–CP system on shallow groundwater quality. The specific objective of this study was to investigate the variations of shallow groundwater nutrients, cations, anions, heavy metals, and other physical parameters for pre- and post-CW and CP system.

Methods

Three shallow groundwater quality monitoring wells used in this study were located at the Edgefield property, Palatka, Florida, USA (Fig. 1). These wells surround a CW–CP system that has an area of 32.8 ha, of which, the CW and CP are 22.7 and 10.1 ha, respectively. This property used to be a row crop production field and was purchased by the St. Johns River Water Management District (SJRWMD) in 2001 for the construction of a regional stormwater treatment facility to treat agricultural runoff. In 2003, a project for monitoring shallow groundwater water quality was initiated and three groundwater wells were installed in the area prior to the construction of the CW–CP system. The well depths were about 1.3 m, which are considered shallow groundwater wells in Florida. The construction of the CP–CW system was commenced in 2005 and was fully operational in 2007 for regional stormwater treatment (RST) due to the nutrient-rich runoff associated with agricultural runoff discharged into the Lower St. Johns River (LSJR). The monitoring wells were not removed during the CW and CP establishment, which provided an opportunity for investigating the effects of the CW and CP on shallow groundwater quality. As shown in Fig. 1, the EP-MW-1 and EP-MW-2 wells are located along the boundary of the CW area, while the EP-MW-3 well is located along the boundary of the CP area.

The RST was constructed as a best management practice treatment where agricultural runoff was first pumped into the CP for initial treatment and then conveyed to the CW for final treatment before discharging to a small tributary and final conveyance to the LSJR. During the wetland and pond construction period, soils in the wetland area were amended in 2007 with a combination of a ferric water treatment residual and standard dolomite to bind soil phosphorus resulting from more than 60 years of farming. The RST facility operation commenced in 2007 and was used to capture agricultural stormwater into the CP mainly for total suspended solid settlement. The surface water quality, flow rate, and water level in the CP and CW were monitored periodically and/or in real-time during the RST operation. Detailed construction and operation procedures of the RST can be found in Steinmetz and Livingston-Way (2009).

Seasonal (or quarterly) sampling activities included collection of groundwater samples, measurement of its water levels, and a slug test of hydraulic conductivity from the monitoring wells. All sampling activities were conducted in accordance with the SJRWMD Standard Operating Procedures for the collection of water quality samples and field data (SJRWMD 2010). A total of 4 years of data (2005 to 2006 for pre-CW and pre-CP and 2007 to 2008 for post-CW and post-CP) were used for statistical analysis. Comparisons of the differences of water quality constituents and groundwater levels were performed using *T* test at α=0.05 with Duncan statistics in SAS 8.1.

Results and discussion

Comparison of the average contents of the water quality constituents in shallow groundwater between pre- and post-CW (or CP) is given in Table 1, whereas the summarized descriptive statistics, including the mean, standard error, standard deviation, minimum, maximum, and number of samples, of the selected water quality constituents for the pre-CP and pre-CW as well as for the post-CP and post-CW are given in Tables 2 and 3. Results of two-sample variables *T* test for the water quality constituents between the pre- and post-CP as well as between the pre- and post-CW for each well are presented in Table 4. Additionally, comparisons of the water quality constituents, which were statistically significant between the pre- and post-CP as well as between the pre- and post-CW, were shown

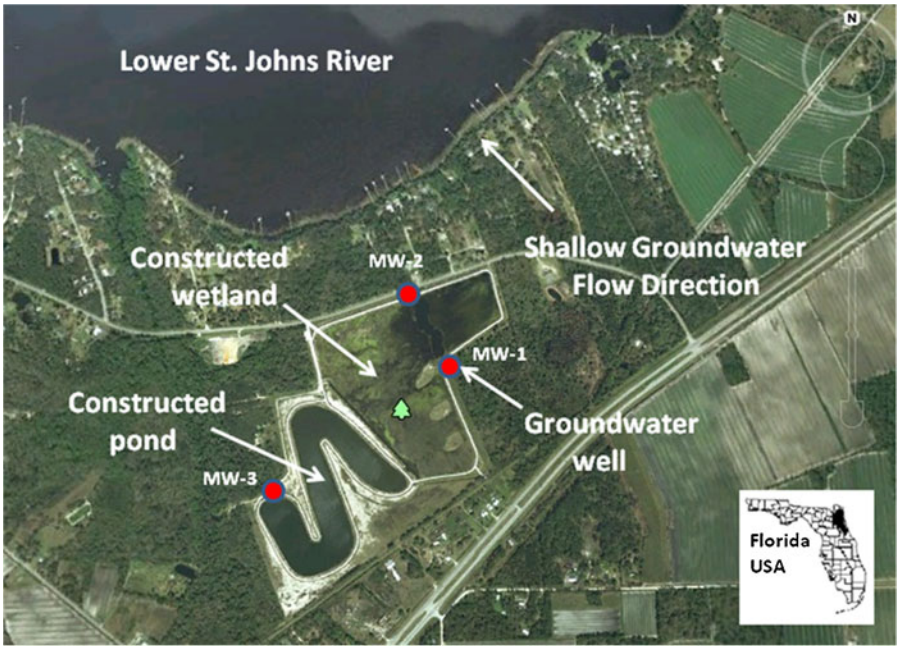


Fig. 1 Location of the constructed wetland and pond with three shallow groundwater wells (points) near its boundary

in Figs. 2, 3, 4, 5, 6, 7, and 8. Detailed discussions of the results are given below.

Nutrients

Shallow groundwater nutrient dynamics for the pre- and post-CW (or CP) conditions were characterized by the following nutrient constituents: ammonium (NH_4^+), nitrate and nitrite (NO_x), total Kjeldahl nitrogen (TKN), total phosphorus (TP), phosphate (PO_4^{2-}), and potassium (K). Comparison of the groundwater nutrients with Environmental Protection Agency's (EPA) water quality criteria shows that all of the groundwater nutrients from both the pre- and post-conditions were below the drinking water standards (http://www.epa.gov/safewater/contaminants/index.html).

Table 1 Averaged contents of water quality constituents for each well before and after the constructed wetland and pond establishment

	EP-MW-1 (well)		EP-MW-2 (well)		EP-MW-3 (well)	
Parameter	Pre-CW	Post-CW	Pre-CW	Post-CW	Pre-CP	Post-CP
Ag-D (μg/L)	0.00	0.00	0.00	0.00	0.00	0.00
Al-D (μg/L)	186.24	128.50	376.54	132.53	553.56	172.05
As-D (μg/L)	9.64	6.89	2.66	1.48	2.27	3.72
Ba-D (μg/L)	223.06	230.10	83.17	80.03	125.48	197.84
Ca-D (mg/L)	92.28	94.66	31.12	63.79	65.47	94.95
Cd-D (μg/L)	0.00	0.00	0.00	0.00	0.20	0.00
Cl (mg/L)	251.51	272.45	81.62	113.10	37.76	236.62
Color (cpu)	315.00	252.00	98.57	87.50	110.00	275.00
Conductance (μmhos/cm)	1,056.60	1,424.00	553.60	981.50	622.20	1,376.75
Cr-D (μg/L)	1.18	0.97	3.15	1.80	2.67	1.18
Cu-D (μg/L)	0.45	0.00	0.00	1.07	7.02	0.00
DOC (mg/L)	17.89	16.60	18.48	19.70	13.56	19.95
Fe-D (μg/L)	67,920.03	71,899.76	12,507.08	5,476.83	6,288.67	64,495.58
K-D (mg/L)	3.39	3.79	2.91	4.97	6.82	4.54
Mg-D (mg/L)	14.89	20.99	10.54	29.10	30.68	24.05
Mn-D (μg/L)	178.95	158.19	41.55	41.84	35.94	147.04
NH4-D (μg/L)	0.60	0.99	0.36	0.39	0.64	1.00
NO_x-D (mg/L)	0.05	0.04	0.03	0.04	0.08	0.08
Na-D (mg/L)	80.24	106.67	50.24	71.37	38.48	98.11
Ni-D (μg/L)	4.53	2.87	1.28	−0.25	1.18	2.85
ORP (mV)	−50.75	−76.36	69.60	42.25	34.00	−42.00
PO_4-D (mg/L)	0.03	0.03	0.02	0.01	0.01	0.03
Pb-D (mg/L)	0.00	0.00	0.00	0.00	0.00	0.40
SO_4 (mg/L)	141.56	245.85	77.59	277.26	292.16	244.61
Se-D (μg/L)	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2-D (mg/L)	15.06	12.34	10.58	8.60	4.86	11.91
TDS (mg/L)	797.50	941.60	385.86	653.25	539.83	957.75
TKN-D (μg/L)	1.26	1.30	0.78	1.17	1.25	1.60
TP-D (μg/L)	0.13	0.08	0.04	0.02	0.03	0.09
Water level_DTW (m)	1.62	0.80	1.72	1.17	4.56	0.75
Water temperature (°C)	21.94	23.65	22.00	24.63	23.38	23.97
Zn-D (μg/L)	5.30	2.17	4.76	11.11	54.44	6.95
pH field	5.87	5.67	5.82	5.55	5.62	5.66

Table 2 Statistical summary of water quality constituents in shallow groundwater in pre- and post-constructed pond and wetland

Parameter	Ag-D µg/L	Al-D µg/L	As-D µg/L	Ba-D µg/L	Ca-D mg/L	Cd-D µg/L	Cl mg/L	Color cpu	Conductance umhos/cm	Cr-D µg/L	Cu-D mg/L
Mean	0.05	506.58	3.03	127.18	65.42	0.21	37.57	116.00	615.50	2.68	7.60
Standard error	0.02	351.90	0.73	27.60	23.73	0.09	14.97	71.11	164.83	0.53	5.27
Standard deviation	0.05	786.87	1.63	61.71	53.07	0.19	33.47	159.00	329.67	1.19	11.78
Minimum	0.00	141.20	0.84	21.22	10.03	0.00	12.02	30.00	132.00	1.65	1.57
Maximum	0.12	1,914.00	4.70	171.10	135.20	0.49	85.03	400.00	852.00	4.43	28.63
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	4.00	5.00	5.00
Parameter	DOC	Fe-D	K-D	Mg-D	Mn-D	NH4-D	NO_x-D	Na-D	Ni-D	ORP	PO_4-D
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	mV	mg/L
Mean	12.93	6,635.40	6.85	30.85	31.75	0.68	0.06	41.00	1.31	45.00	0.01
Standard error	0.83	2,242.78	1.20	11.21	8.49	0.19	0.03	13.95	0.70	18.23	0.00
Sample deviation	1.86	5,015.02	2.69	25.07	18.99	0.43	0.07	31.20	1.58	31.58	0.01
Minimum	10.86	944.20	3.37	3.86	8.20	0.04	0.02	8.33	0.14	9.00	0.00
Maximum	15.66	11,940.00	9.71	64.82	58.30	1.20	0.18	80.51	4.01	68.00	0.02
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.00	5.00
Parameter	Pb-D	SO_4	Se-D	SiO_2-D	TDS	TKN-D	TP-D	Water level	Temperature	Zn-D	pH
	µg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	°C	mg/L	Standard units
Mean	0.29	298.35	0.39	4.54	545.60	1.26	0.03	5.46	24.08	62.43	5.67
Standard error	0.22	97.56	0.39	0.40	137.53	0.19	0.01	0.74	2.48	51.09	0.09
Standard deviation	0.50	218.14	0.88	0.80	307.53	0.42	0.01	1.47	4.97	114.24	0.19
Minimum	0.00	30.67	0.00	3.42	135.00	0.59	0.01	4.21	19.50	4.90	5.54
Maximum	1.15	580.32	1.97	5.30	956.00	1.69	0.04	7.58	30.50	266.60	5.95
Number of sample	5.00	5.00	5.00	4.00	5.00	5.00	5.00	4.00	4.00	5.00	4.00
Pre-constructed wetland											
Parameter	Pb-D	SO_4	Se-D	SiO_2-D	TDS	TKN-D	TP-D	Water level_D	Water temperature	Zn-D	pH field
	µg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	°C	mg/L	Standard units
Mean	0.99	247.93	0.80	10.76	868.40	1.52	0.08	0.80	23.30	8.47	5.61
Standard error	0.71	29.86	0.80	2.68	126.18	0.33	0.04	0.22	0.96	3.00	0.10
Standard deviation	1.60	66.77	1.79	6.00	282.14	0.74	0.08	0.50	2.14	6.70	0.22
Minimum	0.00	168.35	0.00	4.82	511.00	0.70	0.03	0.11	20.60	1.14	5.39
Maximum	3.77	342.37	4.00	17.75	1,169.00	2.62	0.22	1.38	25.80	15.30	5.94
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Parameter	DOC	Fe-D	K-D	Mg-D	Mn-D	NH4-D	NO_x-D	Na-D	Ni-D	ORP	PO_4-D
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	mV	mg/L
Mean	18.29	37,455.33	3.08	11.92	103.95	0.45	0.04	63.25	2.75	−62.43	0.02
Standard error	0.97	12,893.11	0.51	1.03	32.13	0.12	0.01	7.26	0.81	15.58	0.00
Standard deviation	3.22	42,761.60	1.69	3.40	106.58	0.41	0.02	24.08	2.67	41.23	0.01
Minimum	13.29	354.97	1.44	6.83	10.48	0.24	0.01	33.33	−0.07	−128.00	0.01
Maximum	22.55	100,300.00	7.39	18.33	268.00	1.65	0.07	98.60	6.68	−8.00	0.05
Number of sample	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	7.00	11.00	11.00
Parameter	Pb-D	SO_4	Se-D	SiO_2-D	TDS	TKN-D	TP-D	Water level	Temperature	Zn-D	pH
	µg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	°C	mg/L	Standard units
Mean	0.14	98.63	0.33	12.90	561.45	1.01	0.08	1.89	22.23	5.15	5.87
Standard error	0.06	14.00	0.23	2.02	92.15	0.17	0.02	0.49	0.91	0.96	0.06
Standard deviation	0.21	46.42	0.76	4.94	305.61	0.56	0.07	1.37	2.57	3.17	0.16
Minimum	0.00	26.91	0.00	7.65	217.00	0.66	0.01	0.94	19.40	1.88	5.69
Maximum	0.62	161.40	2.22	18.18	933.00	2.41	0.21	4.26	25.30	12.21	6.11
Number of sample	11.00	11.00	11.00	6.00	11.00	11.00	11.00	8.00	8.00	11.00	8.00

Table 3 Statistical summary of water quality constituents in shallow groundwater in pre- and post-constructed pond and wetland

Post-constructed pond

Parameter	Ag-D μg/L	Al-D μg/L	As-D μg/L	Ba-D μg/L	Ca-D mg/L	Cd-D μg/L	Cl mg/L	Color cpu	Conductance umhos/cm	Cr-D μg/L	Cu-D mg/L
Mean	0.03	295.34	3.06	181.67	89.10	0.04	197.03	236.00	1,231.20	1.56	1.31
Standard error	0.03	134.98	1.94	58.61	15.68	0.03	55.05	68.16	219.30	0.62	0.75
Standard deviation	0.07	301.81	4.33	131.05	35.06	0.07	123.09	152.41	490.37	1.39	1.69
Minimum	0.00	43.00	0.00	37.35	51.65	0.00	38.69	80.00	649.00	0.00	0.00
Maximum	0.16	788.50	10.10	341.72	132.04	0.16	377.02	400.00	1,872.00	3.07	4.09
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Parameter	DOC	Fe-D	K-D	Mg-D	Mn-D	NH4-D	NO_x-D	Na-D	Ni-D	ORP	PO_4-D
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	mV	mg/L
Mean	19.31	52,507.46	4.97	25.19	129.01	0.88	0.10	83.67	2.43	−33.40	0.03
Standard error	3.99	24,632.56	1.12	3.75	42.51	0.11	0.02	16.07	1.34	28.01	0.01
Standard deviation	8.93	55,080.08	2.50	8.39	95.05	0.26	0.05	35.94	3.00	62.64	0.02
Minimum	13.84	4,555.00	1.79	16.51	42.51	0.43	0.06	25.92	0.00	−126.00	0.01
Maximum	35.17	122,134.80	7.33	36.55	242.24	1.05	0.19	117.80	5.91	36.00	0.06
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Parameter	Pb-D	SO_4	Se-D	SiO_2-D	TDS	TKN-D	TP-D	Water level_D	Water temperature	Zn-D	pH field
	μg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	°C	mg/L	Standard units
Mean	0.99	247.93	0.80	10.76	868.40	1.52	0.08	0.80	23.30	8.47	5.61
Standard error	0.71	29.86	0.80	2.68	126.18	0.33	0.04	0.22	0.96	3.00	0.10
Standard deviation	1.60	66.77	1.79	6.00	282.14	0.74	0.08	0.50	2.14	6.70	0.22
Minimum	0.00	168.35	0.00	4.82	511.00	0.70	0.03	0.11	20.60	1.14	5.39
Maximum	3.77	342.37	4.00	17.75	1,169.00	2.62	0.22	1.38	25.80	15.30	5.94
Number of sample	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Post-constructed wetland											
Parameter	Ag-D	Al-D	As-D	Ba-D	Ca-D	Cd-D	Cl	Color	Conductance	Cr-D	Cu-D
	μg/L	μg/L	μg/L	μg/L	mg/L	μg/L	mg/L	cpu	umhos/cm	μg/L	mg/L
Mean	0.05	124.96	4.91	164.31	78.76	0.08	195.94	158.18	1,162.18	1.34	0.64
Standard error	0.03	31.83	1.41	37.66	9.85	0.02	40.40	53.98	142.04	0.22	0.27
Standard deviation	0.10	105.55	4.67	124.90	32.67	0.08	133.98	179.04	471.11	0.73	0.88
Minimum	0.00	3.31	0.00	52.00	35.36	0.00	45.33	30.00	538.00	0.24	0.00
Maximum	0.31	386.80	11.06	369.34	137.70	0.19	406.00	600.00	1,916.00	2.12	2.28
Number of sample	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00
Parameter	DOC	Fe-D	K-D	Mg-D	Mn-D	NH4-D	NO_x-D	Na-D	Ni-D	ORP	PO_4-D
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	μg/L	mV	mg/L
Mean	17.94	42,224.30	4.16	23.03	107.22	0.70	0.04	86.93	1.75	−29.71	0.02
Standard error	1.41	15,733.67	0.59	2.82	28.44	0.14	0.01	9.61	0.81	23.29	0.01
Standard deviation	4.69	52,182.70	1.95	9.36	94.31	0.46	0.02	31.86	2.68	77.24	0.03
Minimum	12.12	101.20	1.70	14.33	15.62	0.17	0.01	47.70	−0.87	−141.00	0.00
Maximum	25.90	129,814.20	8.00	40.07	236.24	1.39	0.07	141.67	5.95	83.00	0.10
Number of sample	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00
Parameter	Pb-D	SO_4	Se-D	SiO_2-D	TDS	TKN-D	TP-D	Water level_D	Water temperature	Zn-D	pH field
	μg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	m	°C	mg/L	Standard units
Mean	0.04	240.53	0.13	11.02	784.64	1.19	0.06	0.94	23.52	5.79	5.64
Standard error	0.03	28.04	0.09	1.42	87.09	0.16	0.02	0.16	0.69	1.74	0.07
Standard deviation	0.10	92.99	0.30	4.72	288.85	0.53	0.08	0.53	2.29	5.76	0.22
Minimum	0.00	137.75	0.00	4.31	412.00	0.68	0.01	0.07	20.50	−0.03	5.18
Maximum	0.33	400.79	0.86	16.99	1,210.00	2.21	0.28	2.20	27.10	20.78	5.97
Number of sample	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00

Table 4 Statistical tests of water quality constituents between the pre-CW and the post-CW as well as between the pre-CP and the post-CP

Parameter	Pre- and Post- CW (EP-MW-1)	Pre- and post-CW (EP-MW-2)	Pre- and post-CP (EP-MW-3)
Nutrients			
NH4-D	N	N	N
NO_x-D	N	Y	N
TKN-D	N	N	Y
PO_4-D	Y	N	Y
TP-D	N	N	N
K-D	N	N	N
Cations			
Al-D	N	Y	Y
Ca-D	Y	N	N
Na-D	N	Y	Y
Fe-D	N	N	N
Mg-D	N	N	Y
Mn-D	Y	N	N
Anions			
Cl-D	N	N	N
Color	N	N	N
Conductance	N	Y	Y
Redox potential	Y	Y	Y
SO_4-D	N	N	Y
pH	N	Y	Y
Water level	Y	Y	Y
Heavy metal			
Cd-D	N	Y	Y
Cr-D	N	N	Y
Cu-D	Y	N	Y
Ni-D	Y	N	Y
Pb-D	Y	N	N
Zn-D	N	N	Y
As-D	Y	Y	N

These tests were performed using two-sample variable *T* test. Letter Y denotes significance and N represents not significant at α=0.05. *T* test for two-sample variable, significant at α=0.05

In general, the average concentrations of groundwater TP varied from well to well in pre- and post-CW (or CP) and mixed results were obtained. For example, the average concentrations of TP were 0.13 and 0.04 mg/L in pre-CW, respectively, at the EP-MW-1 and EP-MW-2 wells but were 0.08 and 0.02 mg/L in post-CW, respectively, at the same wells (Table 1). The concentrations from the pre-CW were much higher than the concentrations from the post-CW. In contrast, the average concentration of TP was 0.03 mg/L in pre-CP at the EP-MW-3 well, but was 0.09 in post-CP at the same well. The former was three times lower than the latter. A similar pattern also was observed forPO_4^{2-}. The decrease in P concentrations at the EP-MW-1 and EP-MW-2 wells in post-CW occurred primarily because the area near the wells was treated by ferric sulfate residual to bind the P compounds. No ferric sulfate residual treatment was used near the EP-MW-3 well, which is located at the CP area. In addition, variations of groundwater, pond and wetland hydrology, soil properties, and biological conditions at different well locations could also be the reasons for P variations in pre- and post-CW (or CP).

Unlike the case of P, the average concentrations of TKN and NH_4^+always increased from pre-CW (or pre-CP) to post-CW (or post-CP). For instance, the average concentrations of TKN were 1.26 and 0.78 mg/L in pre-CW, respectively, at the EP-MW-1 and EP-MW-2 wells, but were 1.30 and 1.17 mg/L in post-CW, respectively, at the same wells (Table 1). A similar result also was observed forNH_4^+. Additionally, very little variations in average concentrations were noted for NO_x between the pre- and post-CW (or CP) conditions. Results indicated that increase in N concentrations from the pre-CW or pre-CP to the post-CW or post-CP was primarily due to the increase in organic N andNH_4^+. The increase in organic N concentrations occurred because of the decomposition of organic matter that accumulated in the pond and wetland, which leached into the underlying shallow groundwater. The increase in NH_4^+concentrations occurred because there was more NH_4^+ available in the post-CW and post-CP conditions for leaching into the shallow groundwater. The increased availability of NH_4^+ was mainly due to the accumulation of NH_4^+ and lack of oxygen for nitrification in the post-CW and post-CP conditions.

Figure 2 compares the concentrations of groundwater TKN andPO_4^{2-}, which were significantly different through *T* test at α=0.05, between the pre-CP and the post-CP. Overall, the concentration variations of these two nutrients in post-CP were larger than in pre-CP and had a tendency to increase from pre-CP to the post-CP. The increase in TKN concentrations occurred due to the same reason as stated in the above paragraph NH_4^+,

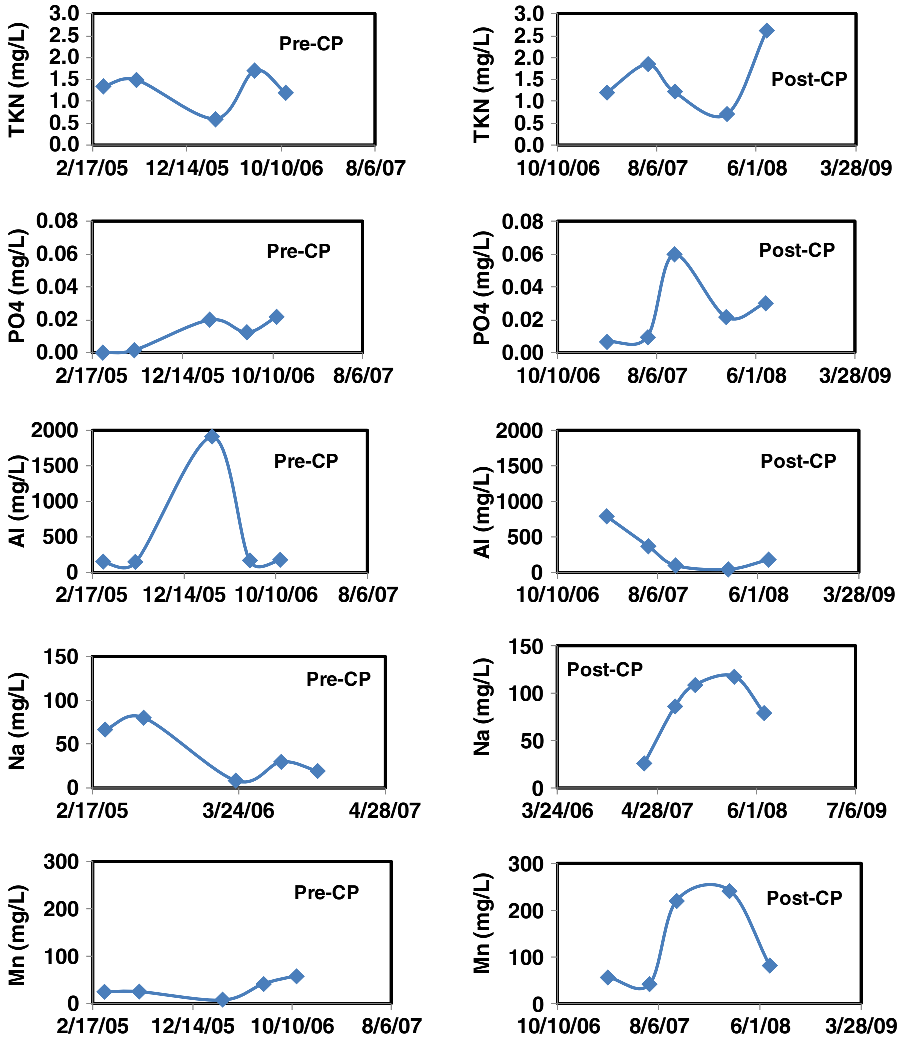


Fig. 2 Comparisons of average concentrations of nutrients and cations between the pre- and post-constructed pond. Only those nutrients and cations that had significant difference in *T* tests between the pre- and post-constructed pond were used for comparisons

whereas the increase in PO_4^{2-} concentrations occurred because no ferric sulfate residual treatment was used for the pond conditions.

Heavy metals

Changes in average heavy metal concentrations, including cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), and arsenic (As), in shallow groundwater between the pre- and post-CW (or CP) are shown in Table 1. Mixed results in concentration were observed among these metals between the pre-CW and post-CW. Average concentrations of As, Cr, Ni, and Zn in shallow groundwater always decreased from pre-CW to post-CW regardless of the well locations. For example, the average concentration of As was 9.64 μg/L in pre-CW at the EP-MW-1 well but was 6.89 μg/L in post-CW at the same well. The former was about 40 % higher than the latter. Similarly, the average concentration of As was 2.66 μg/L in pre-CW at the EP-MW-2 well, but was 1.48 μg/L in post-CW at the same well. The former was about 80 % higher than the latter. Although the exact reasons for the decrease of these heavy metals in the shallow groundwater from pre-CW to post-CW conditions remain unknown, a possible explanation would be the adsorption of these metals by the ferric sulfate residual, which was used during the wetland construction. Additionally, the accumulation of organic matter in CW would also adsorb heavy metals and reduce their leaching into the shallow groundwater.

Unlike the case of the above heavy metals, the average concentration of Cu varied from well to

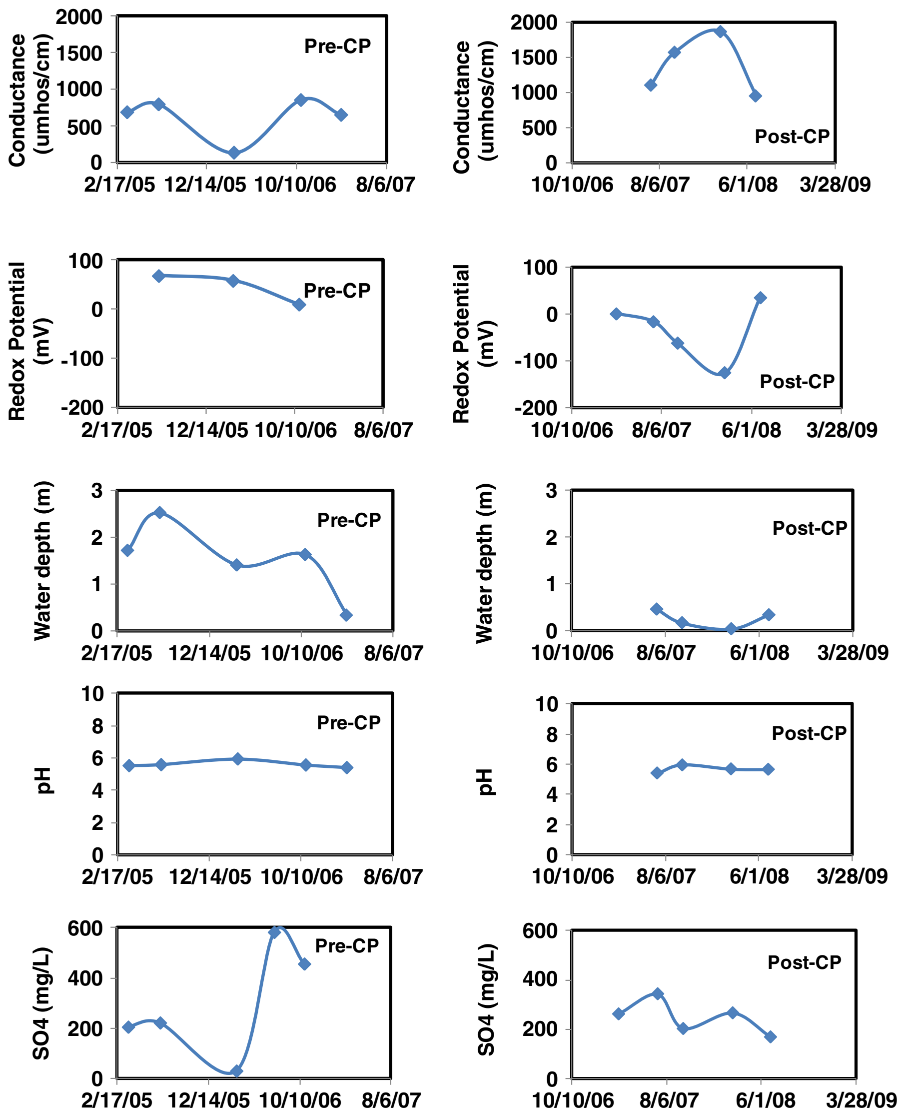


Fig. 3 Comparison of average values of physical parameters and SO_4 between the pre- and post-constructed pond. Only those physical parameters and anions that had significant differences in T tests between the pre- and post-constructed pond were used for comparisons

well regardless of the CW conditions. For example, the average concentration of Cu in the EP-MW-2 well was 0.45 μg/L in pre-CP but was 0.0 μg/L (below detection limit) in post-CP. Furthermore, concentrations of Cr and Pb in shallow groundwater were minimal or below detection limit in either the pre-CW or the post-CW (Table 1).

Analogous to the case of the CW, the average concentrations of the heavy metals varied from pre-CP to post-CP. For instance, the average concentrations of As, Ni, and Pb in the EP-MW-3 well were, respectively, 2.27, 1.18, and 0.0 μg/L (below detection limit) in pre-CP but were, respectively, 3.72, 2.85, and 0.4 μg/L in post-CP, which showed an increase in average concentrations from pre-CP to post-CP. In contrast, the average concentrations of Cd, Cr, Cu, and Zn in the EP-MW-3 well were, respectively, 0.2, 2.67, 7.02, and 54.44 μg/L in pre-CP but were, respectively, 0.0, 1.18, 0.0, 2.85, and 6.95 μg/L in post-CP, which showed a decrease in average concentrations from pre-CP to post-CP. It is apparent that the fate of heavy metals in the CP conditions is very complex.

Figure 4 compares the concentrations of groundwater heavy metals, which were significantly different through T test at $\alpha=0.05$, between the pre-CP and the post-CP. Overall, the concentration

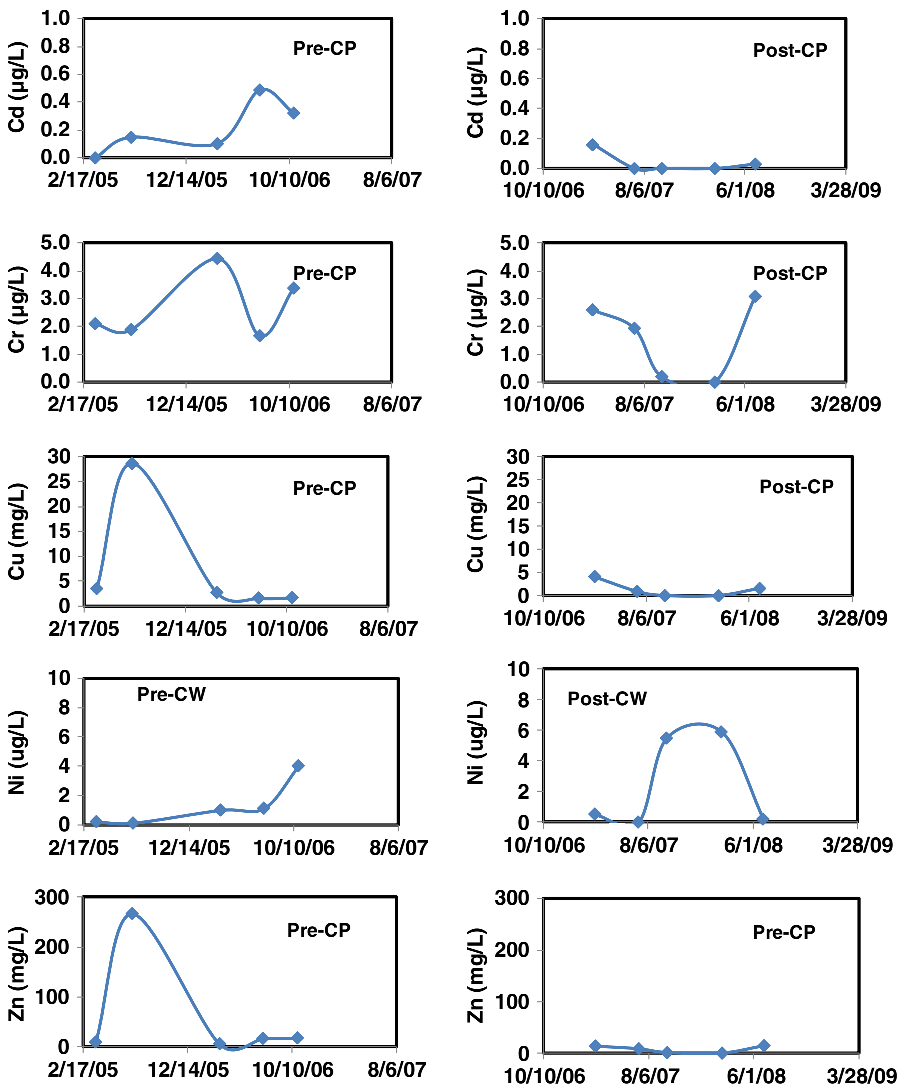


Fig. 4 Comparison of average values of heavy metals between the pre- and post-constructed pond. Only those heavy metals that had significant differences in *T* tests between the pre- and post-constructed pond were used for comparisons

variations of Cd, Cu, and Zn were larger in pre-CP than in post-CP and had a tendency to decrease from pre-CP to the post-CP. The opposite was true for Ni, which had a tendency to increase from pre-CP to the post-CP.

Ions

Impacts of CW and CP on shallow groundwater major cations, including aluminum (Al), calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), and sodium (Na), are shown in Tables 1, 2, and 3. Analogous to the case of nutrients and heavy metals, the average concentrations of most cations in shallow groundwater varied from well to well or from pre- and post-CW conditions. The average concentrations of Al and Fe decreased from pre-CW to post-CW at both the EP-MW-1 and EP-MW-2 wells, whereas the average concentrations of Ca, Mn, and Na increased from pre-CW to post-CW at the same wells (Table 1). However, an exception existed for Mg. Average concentrations of Mg were 14.89 and 10.54 mg/L in pre-CW, respectively, at the EP-MW-1 and EP-MW-2 wells but were 20.99 and 29.10 mg/L in post-CW, respectively, at the same wells. Average concentration of Mg thus increased from pre-CW to post-CW.

Figure 7 compares the concentrations of Al and Na, which were significantly different through *T* test at α=0.05, between the pre-CW and the post-CW at the

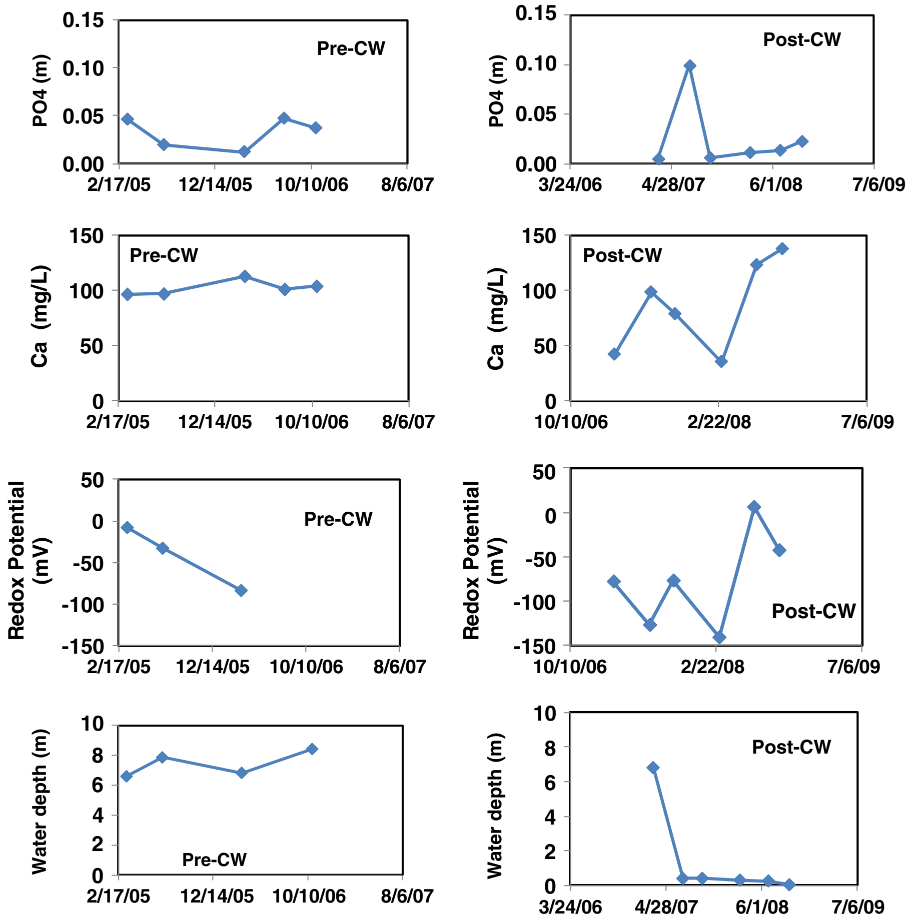


Fig. 5 Comparison of average values of selected water quality constituents and physical parameters between the pre- and post-constructed wetland at EP-MW-1. Only those water quality constituents that had significant differences in *T* tests between the pre- and post-constructed wetland were used for comparisons

EP-MW-1. The variation of Al in pre-CW was larger than in post-CW and had a tendency to decrease from pre-CW to post-CW. The opposite was true for Na, i.e., the variation of Na in pre-CW was smaller than in post-CW.

Similar to the case of the CW, the average concentrations of most cations in shallow groundwater varied from well to well or from pre- and post-CP conditions. In general, the average concentrations of Al and Mn decreased from pre-CP to post-CP, whereas the average concentrations of Ca, Fe, Mg, and Na increased from pre-CP to post-CP (Table 1). Figure 2 compares the concentrations of Al, Na, and Mn, which were significantly different through *T* test, between the pre-CP and the post-CP. The variation of concentrations for Al was larger and for Na was smaller in pre-CP than in post-CP. In contrast, little variation in Mn concentrations occurred between the pre- and post-CP.

Impacts of the CW or CP on shallow groundwater anions such as chloride (Cl^{-1}) and sulfate (SO_4^{2-}) are shown in Table 1. It is interesting to learn that the average concentrations of Cl^{-1} and SO_4^{2-} in groundwater increased after the CW and CP establishment regardless of well locations.

Physical parameters

Impacts of the CW and CP on shallow groundwater physical parameters such as redox potentials, water levels, and conductance are shown in Table 1. By water level, we refer here to the depth of the shallow groundwater table measured from the top of the well casing near the soil surface. As shown in Table 1, the values of water level decreased (or became shallower) for all of the three wells after the wetland and pond construction. For example, the average water level was 1.56 m in pre-CP at the EP-MW-3 well but was 0.75 m in post-CP at the same well. Table 4 reveals that there was a significant difference in water level for each well between the pre- and post-CW or CP. This

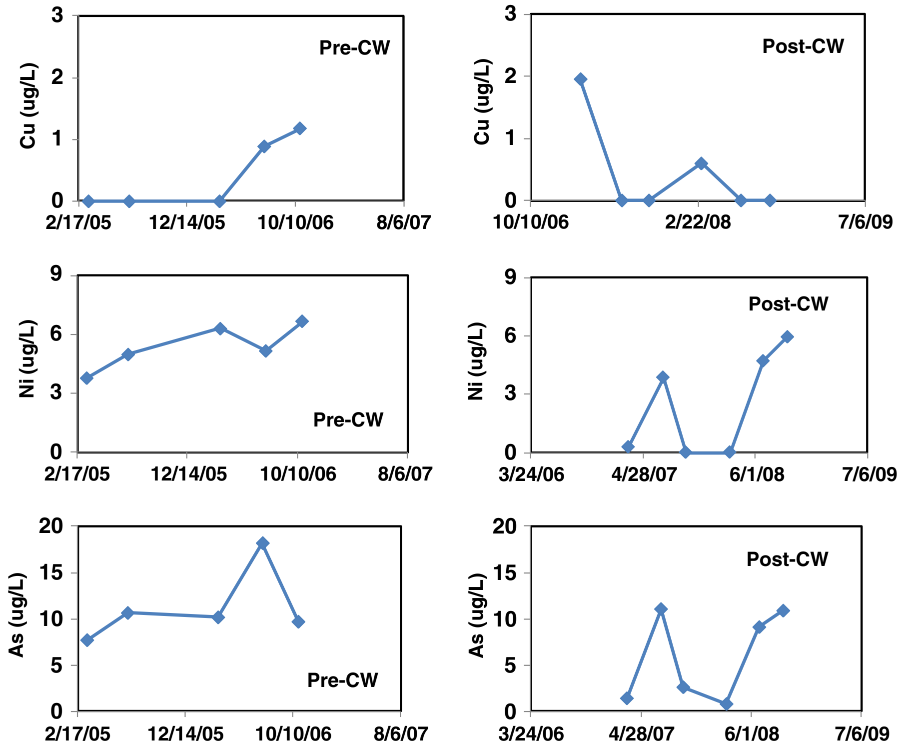


Fig. 6 Comparison of average values of heavy metals between the pre- and post-constructed wetland at EP-MW-1. Only those heavy metals that had significant differences in *T* tests between the pre- and post-constructed wetland were used for comparisons

occurred because the CW and CP retains more surface water for recharge into the groundwater.

Reduction and oxidation (redox) reactions play an important role in groundwater geochemical processes. Redox reactions are defined as reactions in which electrons are transferred. The species receiving electrons is reduced, whereas the one donating electrons is oxidized. Redox reactions determine the mobility of inorganic compounds as well as biologically important materials such as nitrogen and sulfur. They also govern the biological degradation of complex hydrocarbon contaminants. Analogous to the case of water levels, the average redox potential decreased after the wetland and CP construction. For instance, the redox potential was −50.75 mV in pre-CW at the EP-MW-1 well, but was −76.36 mV in post-CW well at the same well. This occurred because a shallower water level in post-CW and post-CP reduced the oxygen concentration (which is the most important electrical acceptor) in the groundwater and thereby reduced the redox potential. A statistical analysis showed a significant difference in redox potential between pre- and post-CW (or CP; Table 3).

Conductance is a measurement of the ability of an aqueous solution to carry an electrical current. It can be used to estimate the amount of total dissolved solids (salts) in water. The more dissolved solids present in the water, the higher the conductance of the water. This is because the solids dissolve into positively and negatively charged ions that can conduct an electrical current proportional to their concentration. Table 1 shows that average conductance increased from pre-CW (or CP) to post-CW (or CP) regardless of the well locations. It is apparent that the CW and CP intercepted more total dissolved solids (salts) or ions that, in turn, leached into the underlying shallow groundwater.

Figure 3 compares the values of conductance, redox potential, and water level, which were significantly different through *T* test, between the pre-CP and the post-CP. The variation of redox potential in pre-CP was smaller than in post-CP, while variation of water level in pre-CP was larger than in post-CP. Figure 8 compares the values of conductance and redox potential, which were significantly different through *T* test, between the pre-CW and the post-CW. More variation was observed in post-CW than in pre-CW.

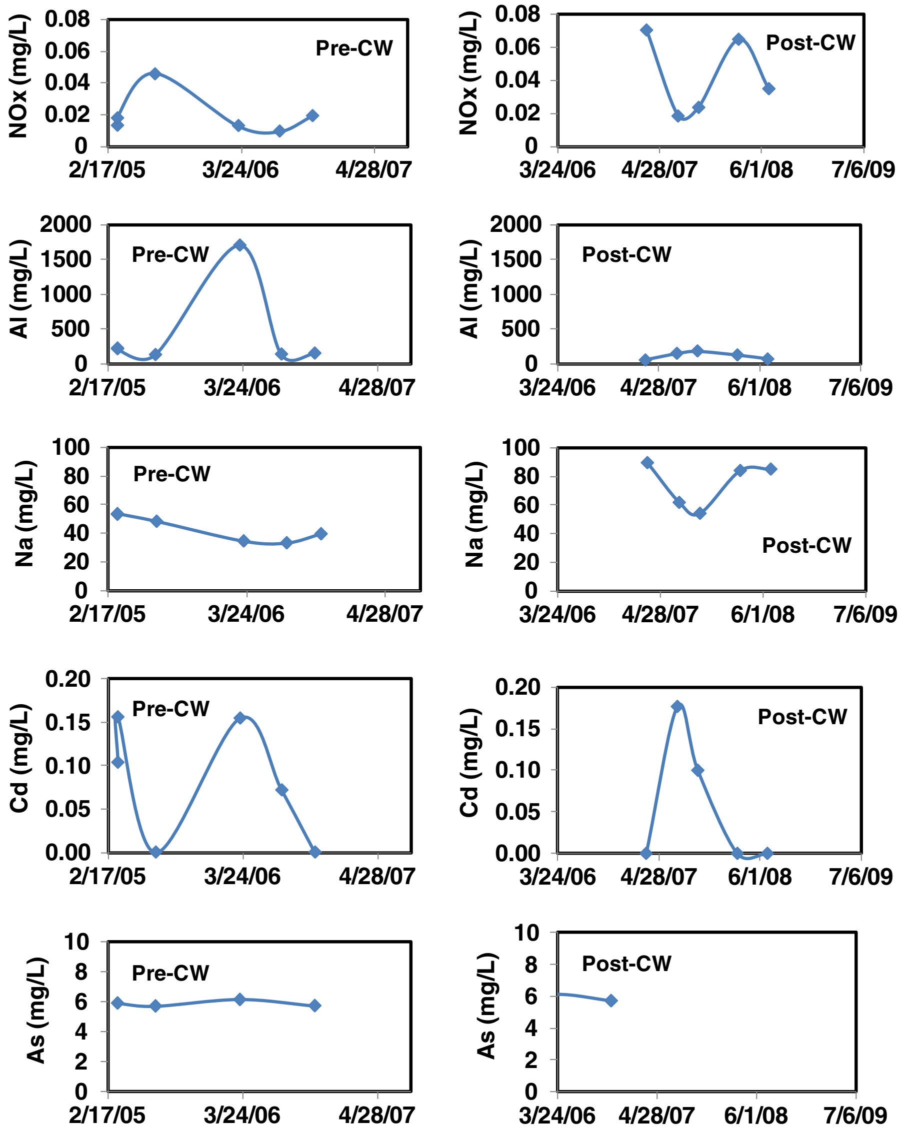


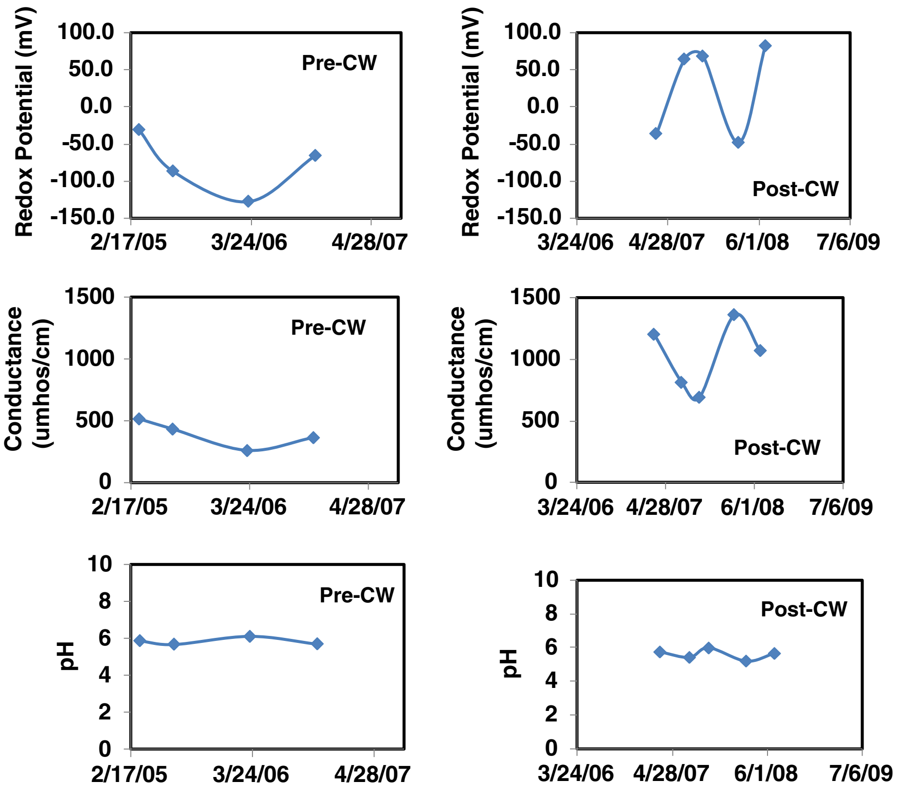
Fig. 7 Comparison of average values of selected water quality constituents between the pre- and post-constructed wetland at EP-MW-2. Only those water quality constituents that had significant differences in *T* tests between the pre- and post-constructed wetland were used for comparisons

Summary and conclusions

Three groundwater monitoring wells were used to investigate impacts of construction and operation of a CW and CP system upon shallow groundwater quality. These wells were installed in a row crop production area in Palatka, Florida in 2003. This area was then converted into a CW–CP system for stormwater treatment in 2006 without altering the monitoring wells, which provided a unique opportunity for estimating impacts of the CW–CP system on shallow groundwater quality. A total of 4 years of data (2 years for pre-CW (or CP) and 2 years for post-CW (or CP)) were used for statistical analysis.

Comparison of groundwater nutrients with US EPA's water quality criteria shows that all of the groundwater nutrients from both the pre- and post-CW (or CP) conditions were below drinking water standards. In general, average concentrations of groundwater TP and PO_4^{-2} decreased from pre-CW to post-CW but increased from pre-CP to post-CP, which occurred primarily because the CW area (but not the CP) was treated with ferric sulfate residual to bind P compounds in the soil.

Fig. 8 Comparison of average values of physical parameters between the pre- and post-constructed wetland at EP-MW-2 well. Only those physical parameters that had significant difference in T tests between the pre- and post-constructed wetland were used for comparisons



Unlike the case of P, the average concentrations of TKN and NH_4^+ always increased from pre-CW (or CP) to post-CW (or CP), whereas very little change in NO_x concentrations was observed between pre- and post-CW (or CP). Results indicated that an increase in N concentrations from pre-CW (or CP) to post-CW (CP) were primarily due to the increase in organic N andNH_4^+. The increase in organic N concentrations occurred because the decomposition of organic matter that accumulated in the pond and wetland, which leached into the shallow groundwater. The increase in NH_4^+concentrations occurred because there was more NH_4^+ available in the post-CW and post-CP conditions for leaching into the shallow groundwater. The more NH_4^+ available might be due to the accumulation of NH_4^+ and lack of oxygen for nitrification in the post-CW and post-CP conditions in the treatment system.

The average concentrations of As, Cr, Ni, and Zn in shallow groundwater always decreased from pre-CW to post-CW regardless of the well locations. Although the exact reasons for such a decrease remain unknown, a possible explanation would be the adsorption of these metals by the ferric sulfate residual, which was used during the wetland construction. Additionally, the accumulation of organic matter in CW would also adsorb heavy metals and reduce their leaching into the shallow groundwater. In contrast, the variations of Cr and Pb concentrations in shallow groundwater were minimal in either the pre-CW or post-CW. Overall, the variations of Cd, Cu, and Zn concentrations were larger in pre-CP than in post-CP and had a tendency to decrease from pre-CP to the post-CP. The opposite was true for Ni, which had a tendency to increase from pre-CP to the post-CP.

Analogous to the case of nutrients and heavy metals, the average concentrations of most cations in shallow groundwater varied from well to well or from pre- and post-CW conditions. In general, the average concentrations of Al and Mn decreased from pre-CP to post-CP, whereas the average concentrations of Ca, Fe, Mg, and Na increased from pre-CP to post-CP.

The values of water level and redox potential decreased for all of the three wells after the wetland and pond construction regardless of the well locations. Variation of redox potential in pre-CP was smaller than in post-CP, whereas variation of water level in pre-CP was larger than in post-CP.

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