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Original Contribution

Human Health-Related Ecosystem Services of Avian-Dense Coastal Wetlands Adjacent to a Western Lake Erie Swimming Beach

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Abstract: Wetlands provide many valuable ecosystem services, including water quality improvement to protect downstream aquatic ecosystems such as lakes, rivers, and estuaries. However, their ability to improve water quality to safe levels for direct human exposure while largely surrounded by agricultural lands and hosting large wildlife populations remains unknown. Our aim was to examine the ecosystem service capabilities of an avian-dense coastal wetland surrounded by agricultural lands along the southwestern shore of Lake Erie in Ohio by assessing the quality of water as it flows through the wetland (Ottawa National Wildlife Refuge (ONWR)) and into Lake Erie beach waters. Our study used total phosphorus and fecal indicator (*Escherichia coli*) concentrations as water quality metrics across the wetland and at an adjacent Lake Erie swimming beach during the 2012 summer swim season. *E. coli* and total P levels were consistently highest at the site, where water enters the ONWR (mean *E. coli* = 507 CFU/100 mL; mean total P = 535 μg/L), and steadily decreased as water flowed through the wetland and into the adjacent beach (mean *E. coli* = 10 CFU/100 mL; mean total P = 41 μg/L). *E. coli* and total P showed statistically significant ($\alpha = 0.01$) correlations with phycocyanin, chlorophyll-*a*, turbidity, specific conductivity, dissolved oxygen, and pH; total P was also significantly correlated with total N. The results suggest that this wetland may be contributing to improving water quality, which is beneficial for human health as well as to downstream ecosystem health (e.g., limiting eutrophication promoting conditions, etc.).

Keywords: Wetland, Beach water, Lake Erie, Avian

Introduction

Managed and naturally occurring ecologically healthy wetland ecosystems support biologically diverse plant and animal communities, improve water quality, mitigate downstream flooding, and protect shorelines from storm damage (Mitsch et al. 2009; United States Environmental Protection Agency (USEPA) 2013). In 1997, the global economic value of wetlands was estimated to be $14.9 trillion dollars (Constanza et al. 1997). Furthermore, because wetlands intercept heavy runoff and slow water flow to inland rivers and provide protection from storms

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for coastal areas, they may become even more important as heavy precipitation events and coastal storms are expected to become more frequent as a consequence of climate change and variability (Füssel 2009). Yet, in 1989, when the North American Wetlands Conservation Act (NAWCA) was enacted, over 50% of U.S. wetlands had disappeared, largely as a consequence of human agricultural, industrial, and residential development (Mitsch and Gosselink 2007).

Another consistent hallmark of wetlands is their ability to host abundant plant and animal populations, including large and diverse groups of birds. However, many of these wildlife species are also carriers of multiple types of infectious agents (e.g., bacteria, protozoa, viruses), and their behaviors and migratory patterns can lead to the spread of numerous pathogens of human health concern to surface waters (Reed et al. 2003; Jones 2005; USEPA 2011). For example, birds frequently congregate in areas where they can readily disperse zoonotic pathogens to surface waters via direct (e.g., fecal deposition to water) and indirect (e.g., runoff) pathways (USEPA 2009a, 2011). As a result, nearby recreational and drinking water sources can become contaminated. Waterfowl and shorebirds are found in near shore wetlands and are of particular concern to surface waters because they can carry human disease causing pathogens (e.g., *Campylobacter* spp., *Cryptosporidium* spp., avian influenza, etc.). Birds and wildlife are not the only surface water concern related to human health—agricultural sources also frequently pollute recreational waters (USEPA 2009b). Excessive nutrients entering waterways as fertilizer runoff are of particular concern because they can cause eutrophication and lead to deteriorated water quality. Algal blooms spawned by excessive nutrient concentrations, especially elevated phosphorus, commonly lead to the production of harmful toxins, including: hepatotoxins, neurotoxins, cytotoxins, and gastrointestinal toxins (Carmichael 1997; Codd et al. 2005). Based on evidence of algal toxicity and increases in bloom frequency, public health concerns are increasing (Harvell et al. 2000; Peperzak 2003; Edwards et al. 2006; O'Neil et al. 2011; Cheung et al. 2013).

The Great Lakes are a major area of concern for this confluence of contaminants. This is because of their importance as the largest single source of available fresh water in the world. Indeed, the Great Lakes provide ecosystem services to a population of 43 million people within the region (GLRC 2005). Among the Great Lakes, Lake Erie, especially the western basin, is the most vulnerable due to a cumulative result of its geophysical characteristics (southernmost, shallowest, warmest) and the multiple contaminants it receives from erosion, urban sewage discharges, agricultural runoff, and industrial discharges (Matisoff & Ciborowski 2005, OEPA 2010). The Great Lakes are being further threatened by population growth, climate change and variability, aging urban infrastructure, and land use practices; these combined impacts are acting together to degrade water quality (Joseph et al. 2009).

Since the 1950s, the link between adverse health outcomes and contact with contaminated recreational water has been well documented (Stevenson 1953). Dufour (1984) established *Escherichia coli* and enterococci densities as criteria indicators for fecal contamination in freshwater (USEPA 1986). Additional associations between fecal indicator presence and illness in beach swimmers have continued to be established over the last three decades (Prüss 1998; Wade et al. 2003, 2006; Colford et al. 2007). Multiple studies have demonstrated connections between heavy precipitation events, runoff, contaminated surface waters, and elevated risk of gastrointestinal illnesses (Curriero et al. 2001; Drayna et al. 2010; Veldhuis et al. 2010). Furthermore, *E. coli* levels at Great Lakes coastal beaches often exceed the USEPA recommended single sample primary contact limit of 235 CFU/100 mL (Bower et al. 2005, Lee et al. 2012) and previous studies have suggested an elevated risk of gastrointestinal illness for recreational water users (Wade et al. 2008; Marion et al. 2010; Schets et al. 2011).

The severity of human health risks around the Great Lakes could be mitigated by the ecosystem services provided by wetlands if they can reduce levels of nutrients and pathogens sufficiently. However, whether wetlands can lower concentrations of nutrients and fecal indicator bacterial counts in adjacent beaches to levels considered safer for direct human exposure is unknown.

The hypothesis of this study was that fecal indicator bacteria and nutrient levels within a near shore wetland and swimming beach would be reduced along the hydrological gradient. It was expected that spatial differences would be indicative of reduced loading of the contaminants to nearby recreational waters and would allow us to investigate the extent of the human health-related wetland ecoservices performed by the wetland area at the Ottawa National Wildlife Refuge (ONWR) near Lake Erie. Specifically, we examined the role of an avian-dense, agriculturally surrounded wetland in altering water quality as it flows into Lake Erie and reaches nearby beach water. To test our hypothesis, the study was designed to characterize nutrient (total phosphorus and total nitrogen) and fecal indicator bacteria (*E. coli*) concentrations across a near shore wetland and at an adjacent Lake Erie swimming beach from May through September 2012.

METHODS

Study Sites

Study sites were located approximately 30 km southeast of Toledo, OH, USA along the southwestern shore of Lake Erie. Samples were collected within ONWR and at the adjacent Magee Marsh Wildlife Area beach (Fig. 1). ONWR has an area of 2700 ha and provides some of the most important avian habitat in the Great Lakes region, especially for birds (e.g., Canada Goose, Dunlin, Snow Goose, Mallard, Ring-billed Gull, Great Blue Heron, Snowy Egret, etc.) who depend on the wetlands for feeding, nesting, and resting when

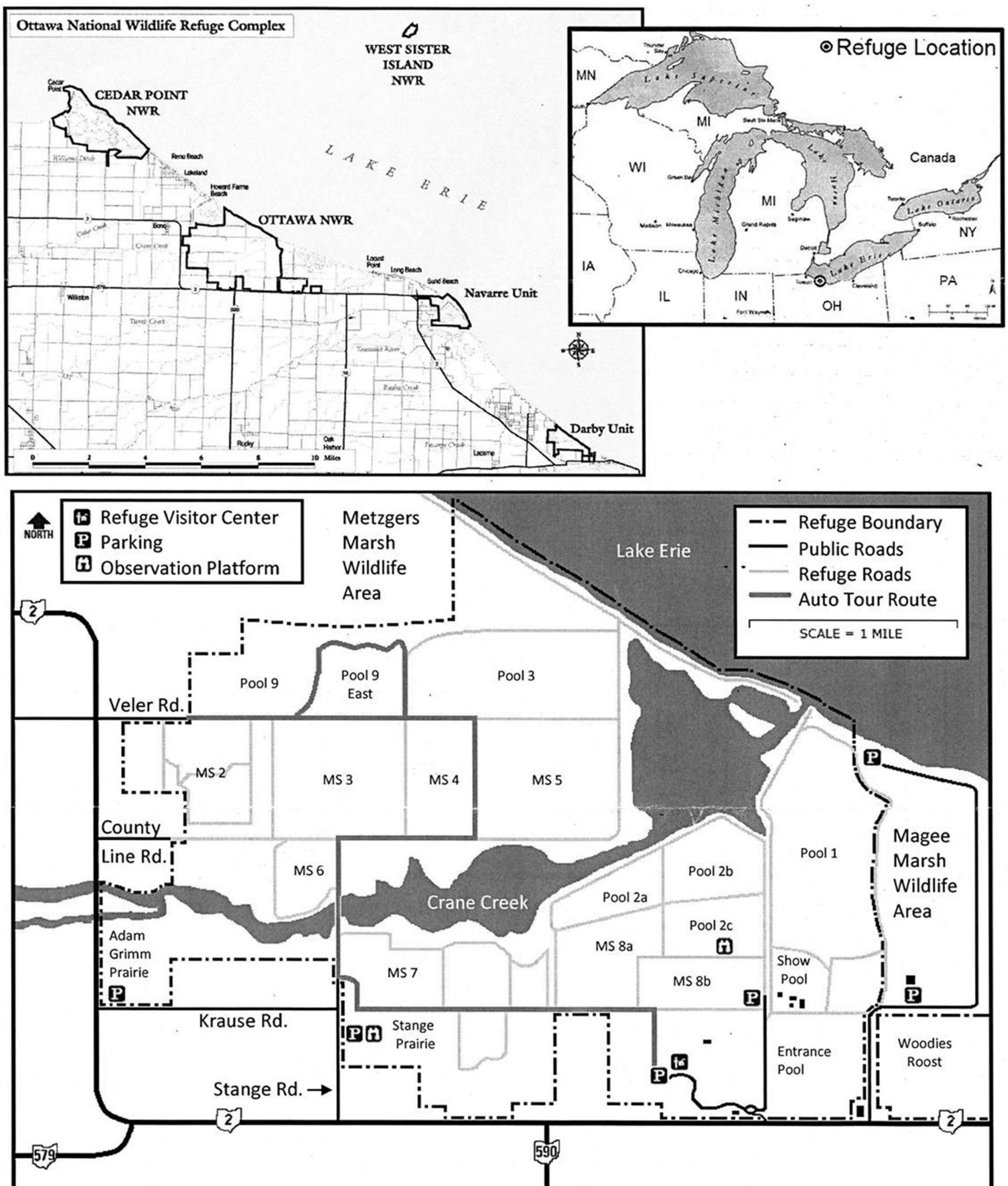

Figure 1. The study sites were located within the Ottawa National Wildlife Refuge, located on the southwestern shore of Lake Erie, in northwestern Ohio, USA. Water samples were collected at three upstream to downstream locations along the Crane Creek (*sites 1, 2,* and *3*) and at an adjacent recreational beach (*site 4*).

traversing the Mississippi and Atlantic flyways during their migrations. Four sites were selected to assess water quality across the wetland and at the adjacent beach. Samples were collected from Crane Creek (sites 1–3) and Lake Erie (site 4)—Crane Creek approximately bisects ONWR. Site 1 is located at a point in Crane Creek where water typically flows into the refuge from surrounding agricultural lands; site 2 is approximately midway through Crane Creek's passage across the refuge; site 3 is within the channel where Crane Creek and Lake Erie meet; and site 4 is at the adjacent swimming beach approximately 250 m east of the channel (Fig. 1). The entire refuge lies within the larger Western Lake Erie Basin watershed and is part of the Lake Erie Direct Drainage subwatershed. The western basin of Lake Erie is the shallowest of the Great Lakes and, consequently, is readily affected by contaminants. The subwatershed is dominated by agricultural lands that runoff into creeks and rivers before emptying directly into Lake Erie's western basin.

Sample Collection

Water samples ($\sim$3.2 L) were collected once per week during the 17 weeks of sampling according to the USEPA's Direct Method of surface water sampling using four sterile 1L Whirl–Pak bags (Nasco, Fort Atkinson, WI, USA) at each site. Sixty-eight water samples (17 per site) were collected sequentially from site 1, 2, 3, and 4 from May 2012 through September 2012 to coincide with the summer recreation (i.e., swimming; boating) season. Samples were collected sequentially from site 1 to site 4 between 10:00 a.m. and 5:00 p.m. on each sampling day following the sampling guidelines of Ohio Department Health (ODH)'s beach waters (ODH 2005). Very slow water flow velocity was observed at the sampling sites (as is typical for the ONWR wetland) and daily air and water temperature variability across sites was minimal, thus samples were collected sequentially in an effort to control intra-site variability by gathering the water at roughly the same time of day during each sampling event. The sterile sampling bags were filled at sites 1 and 3 by wading into the water approximately 2–3 m from the shore (water depth $\sim$1 m) and then opening the bag approximately 10–30 cm under the water's surface. Site 2 was shallow and site 4 was gently sloping, thus they both required wading farther from the shore to collect samples at a similar depth. Samples were placed on ice and transported to the Ohio State University laboratories where they were stored at 4 °C for analysis.

Environmental Parameters

Water temperature, dissolved oxygen, pH, and specific conductivity were measured in situ using a YSI 650-MDS Multiparameter Water Quality Sonde (YSI Incorporated, Yellow Springs, OH, USA). Wave height was estimated in the field using a semi-submerged measuring tape. Air temperature, dew point, wind speed, and relative humidity data were also collected in situ using an Ambient Weather WM-4 handheld weather meter (Ambient Weather, Chandler, AZ, USA). The UV index was determined by calculating the mean of the National Weather Service's UV indices for Detroit, Michigan, USA and Cleveland, OH, USA—Ottawa National Wildlife Refuge is located nearly equidistant from Detroit and Cleveland. Precipitation data was based on Quality Controlled Local Climatological Data (QCLCD) collected and available from the National Oceanic and Atmospheric Administration (NOAA) and National Climatic Data Center for Metcalf Field Airport, Toledo, OH, USA—the closest station to Ottawa National Wildlife Refuge.

Water Quality Measurements

Lab analyses included turbidity, phycocyanin, chlorophyll-*a*, *E. coli*, total phosphorus, and total nitrogen. All parameters were measured in duplicate and the mean value of the duplicates was calculated. Turbidity was analyzed using a Hach 2100P portable turbidity meter (Hach Company, Loveland, CO, USA). Phycocyanin and chlorophyll-*a* were analyzed using a handheld Turner AquaFluor fluorometer (Turner Designs, Sunnyvale, CA, USA). Total phosphorus and total nitrogen were each measured using USEPA approved Method 8190 for total phosphorus (Hach PhosVer 3 acid persulfate digestion method) and Method 10206 for total nitrogen (Hach dimethylphenol method). In order to determine *E. coli* concentrations, duplicate water samples (100 mL) were passed through sterile 0.45 μm pore size mixed cellulose ester filter membranes (Pall Corporation, Ann Arbor, MI, USA). The filter membranes were placed on Difco® modified mTEC agar (Becton, Dickinson and Co., Sparks, MD, USA). Plates were incubated for 2 h at 35 °C and then at 44.5 °C for 18–20 h. Following incubation the plates were counted for *E. coli* as indicated by magenta colored colonies and the mean of the sample duplicates was calculated.

Statistical Analyses

Statistical analyses were performed with the IBM® SPSS® (Release ver. 20.0.0; SPSS Inc.) statistics package. Analyses included: Spearman's Rank Order correlation to determine the relationship between environmental variables and *E. coli* and total phosphorus levels, respectively; ANOVA and Tukey's tests were used to determine statistically significant differences by site location for *E. coli* and total phosphorus; and multiple linear regression using backward selection (exclusion criteria $p \leq 0.10$) to explore significant relationships between environmental variables and *E. coli* and total phosphorus separately. *E. coli* and total phosphorus data were log-transformed to normalize values prior to ANOVA and regression analyses.

Results

Escherichia coli, total nitrogen, and total phosphorus, as well as multiple water and meteorological variables, showed considerable spatial and temporal variations during the study period (Table 1). Temporal variations of *E. coli* levels and total phosphorus concentrations are shown in Figs. 2 and 3, respectively. *E. coli* levels varied by site and were found in all water samples collected from sites 1 and 2, but were not detected during one of the sampling collections at site 3 (5.9%) and two (11.7%) of the sampling collections from site 4. Site 1 *E. coli* levels ranged from 33 to 2,535 CFU/100 mL (mean = 507 CFU/100 mL), site 2 levels ranged from 12 to 2,349 CFU/100 mL (mean = 450 CFU/100 mL), site 3 levels ranged from 1 to 290 CFU/100 mL (mean = 60 CFU/100 mL), and site 4 levels ranged from 0 to 62 CFU/100 mL (mean = 10 CFU/100 mL). Total phosphorus concentration at site 1 ranged from 209 to 1,050 μg/L (mean = 535 μg/L), at site 2 from 135 to 482 μg/L (mean = 233 μg/L), at site 3 from 23 to 127 μg/L (mean = 63 μg/L), and at site 4 from 11 to 89 μg/L (mean = 41 μg/L). Total nitrogen concentration at site 1 ranged from 40 to 62 μg/L (mean = 48 μg/L), at site 2 from 16 to 69 μg/L (mean = 40 μg/L), at site 3 from 0 to 50 μg/L (mean = 19 μg/L), and at site 4 from 0 to 40 μg/L (mean = 18 μg/L).

Based on Spearman's Rank Order correlation, *E. coli* and total phosphorus both showed significant correlations across multiple indicators (Table 2). *E. coli* showed significant correlations ($p \leq 0.01$) with total phosphorus ($r = 0.689$), phycocyanin ($r = 0.387$), chlorophyll-*a* ($r = 0.554$), turbidity ($r = 0.552$), specific conductivity ($r = 0.381$), dissolved oxygen ($r = -0.479$), pH ($r = -0.462$) and sampling site number ($r = -0.748$). Total phosphorus was significantly ($p \leq 0.01$) correlated with total nitrogen ($r = 0.612$), phycocyanin ($r = 0.488$), chlorophyll-*a* ($r = 0.820$), turbidity ($r = 0.534$), specific conductivity ($r = 0.723$), dissolved oxygen ($r = -0.536$), pH ($r = -0.623$), water temperature ($r = -0.278$ at $\alpha = 0.05$), and sampling site number ($r = -0.899$).

ANOVA results indicated there was a significant difference between sites for *E. coli* (F (3, 64) = 31.264, $p < 0.001$), as well as for total phosphorus (F (3,52) = 84.397, $p < 0.001$). Tukey's test showed significant differences ($p < 0.01$) in *E. coli* levels for all pairwise comparisons of sites except for sites 1 and 2 ($p = 0.96$) and significant differences ($p < 0.001$) in total phosphorus concentrations for all pairwise comparisons of sites except for sites 3 and 4 ($p = 0.06$).

A multiple linear regression model ($R^2 = 0.579$) to predict log-transformed *E. coli* levels showed a significant association with the following environmental variables: dissolved oxygen ($p = 0.025$), dew point ($p = 0.040$), barometric pressure ($p = 0.009$) (Table 3). A second multiple linear regression model ($R^2 = 0.809$) to describe log-transformed total phosphorus concentration included significant associations with: specific conductivity ($p = 0.036$), pH ($p < 0.001$), barometric pressure ($p = 0.019$), precipitation from the day of sampling ($p = 0.005$), UV index ($p = 0.018$), and turbidity ($p = 0.03$) (Table 4).

Discussion

This study provides information about the water quality influencing ecoservices provided by a near-shore wetland in western Lake Erie on an adjacent swimming beach. Study findings support the hypothesis that fecal indicator bacteria and nutrient levels within a near shore wetland and swimming beach are reduced along the hydrological gradient. For instance, surface waters flowing into the wetlands at ONWR during the summer frequently exceeded their recommended (*E. coli* = 235 CFU/100 mL (single sample primary contact, USEPA)) and target (total P = 15 μg/L (Ohio Phosphorus Task Force)) levels at the upstream sites (sites 1 and 2), but then decreased to levels near target or below recommended levels at downstream locations (sites 3 and 4) indicating that *E. coli* and total P levels were lower in

Table 1. Summary of Measurements Across all Sampling Sites at Ottawa National Wildlife Refuge and the Lake Erie Beach from May Through September 2012

	Site 1	Site 2	Site 3	Site 4	All sites
E. coli (CFU/100 mL)					
Mean	507	450	60	10	257
Median	150	117	32	5	64
Range	33–2,535	12–2,349	1–290	0–62	0–2,535
Total P (μg/L)					
Mean	535	233	63	41	218
Median	529	208	57	30	131
Range	209–1,050	135–482	23–127	11–89	11–1,050
Total N (μg/L)					
Mean	48	40	19	18	34
Median	44	42	8	16	40
Range	40-62	16–69	0–50	0–40	0–69
Phycocyanin (μg/L)					
Mean	62	85	47	51	61
Median	52	80	37	29	49
Range	33–137	40–168	11–171	15–279	11–279
Chlorophyll-*a* (μg/L)					
Mean	34	28	8	8	19
Median	32	24	5	3	10
Range	10–76	8–68	1–27	2–58	1–76
Turbidity					
Mean	59.0	148.9	39.4	23.9	67.8
Median	42.4	116.5	36.2	22.1	39.9
Range	17.3–244.0	39.6–559.0	6.7–125.5	6.1–65.0	6.1–559.0
Water temperature (°C)					
Mean	24.0	25.6	26.1	26.0	25.4
Median	24.6	26.0	25.7	25.5	25.5
Range	17.3–28.4	17.0–28.9	17.9–30.9	22.5–30.6	17.0–30.9
Specific conductivity (μS/cm^3)					
Mean	822	473	389	375	515
Median	789	454	388	379	427
Range	706–1,000	333–708	284–485	283–433	283–1,000
pH					
Mean	8.16	8.19	8.78	8.75	8.47
Median	8.10	8.25	8.79	8.74	8.53
Range	7.63–8.72	7.44–9.28	8.28–9.33	8.32–9.20	7.44–9.33
Dissolved oxygen (mg/L)					
Mean	6.4	7.7	10.3	10.1	8.7
Median	5.6	7.9	10.3	10.1	9.3
Range	2.7–11.3	3.4–12.5	7.2–13.1	7.5–13.8	2.7–13.8
Precipitation—day of sampling (cm)					
Mean					0.36
Median					0.01
Range					0–5.21
Precipitation—1 day before sampling day (cm)					
Mean					0.35

Table 1. continued

	Site 1	Site 2	Site 3	Site 4	All sites
Median					0.03
Range					0–2.92
Precipitation—2 days before sampling day (cm)					
Mean					0.11
Median					0.01
Range					0–1.47
Precipitation—3 days before sampling day (cm)					
Mean					0.36
Median					0.02
Range					0–1.83

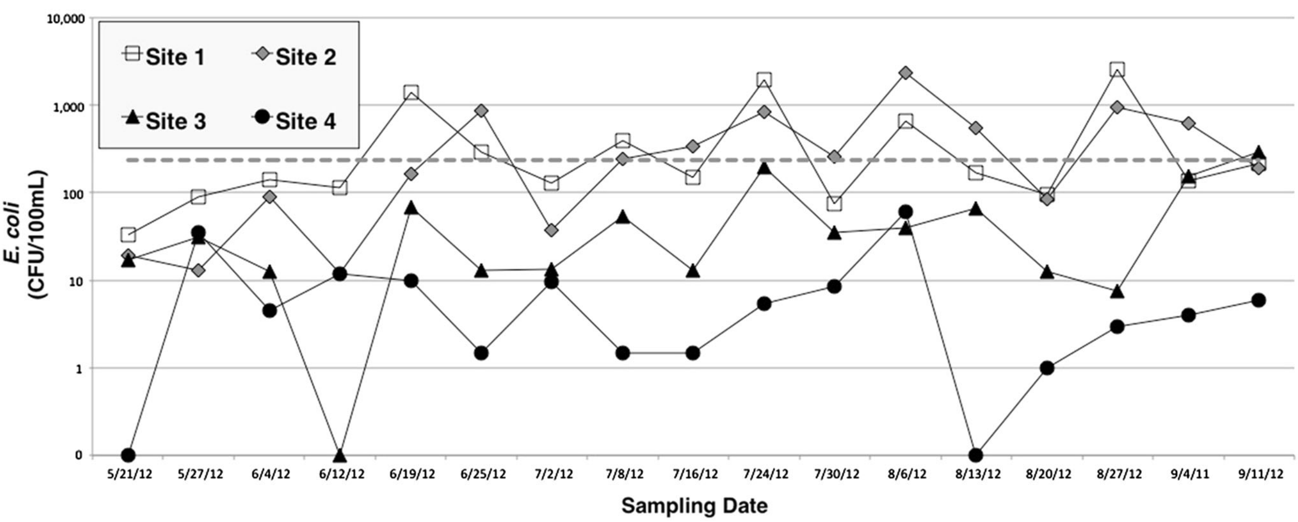

Figure 2. Temporal variation of *E. coli* concentrations (densities) from the 4 study sites at Ottawa National Wildlife Refuge and the adjacent Lake Erie beach from May 21, 2012 through September 11, 2012 (*dashed line* U.S. EPA single sample maximum (235 CFU/100 mL)).

water flowing out of the wetlands than in water flowing into the wetlands. Weekly trends indicate ONWR wetlands consistently reduce *E. coli* and total phosphorus levels to safer ranges prior to water reaching Lake Erie and nearby recreational waters. Based on the summer mean values for site 1 (inflow) and site 3 (outflow), *E. coli* and total P both showed 88% reductions, and total N was reduced by 60%. Our findings imply that during the 2012 summer swim season the ONWR wetlands provided important water quality ecoservices by reducing total P and *E. coli* from unsafe to safer levels before water entered Lake Erie. Total N also exhibited the same pattern; however, we were unable to test all of our weekly samples, thus this limitation hinders our ability to conclude the same decreasing trend is consistent over the entire study period. Furthermore, the method of sequential sample collection may have confounded site and time of day effects; however, this was done in an attempt to control time of day variability within each site and it is unlikely that there is a large "time of day" effect. Even so, randomized sample site collection could have been included to avoid this potential effect and we recommend future studies take this into consideration.

Multiple mechanisms may be responsible for decreasing *E. coli,* and total P. Slowed water flow, UV irradiation, vegetation (i.e., wetland plants and root systems), soil composition, and microbial organisms typically provide the mechanisms in which wetlands reduce contaminants (USEPA 2013). By slowing water flow and dissipating energy, wetlands provide time for contaminants to be broken down by bacteria and sediments to be filtered by aquatic plant root systems. Elevated pH may have contributed to lower *E. coli* concentrations at downstream locations.

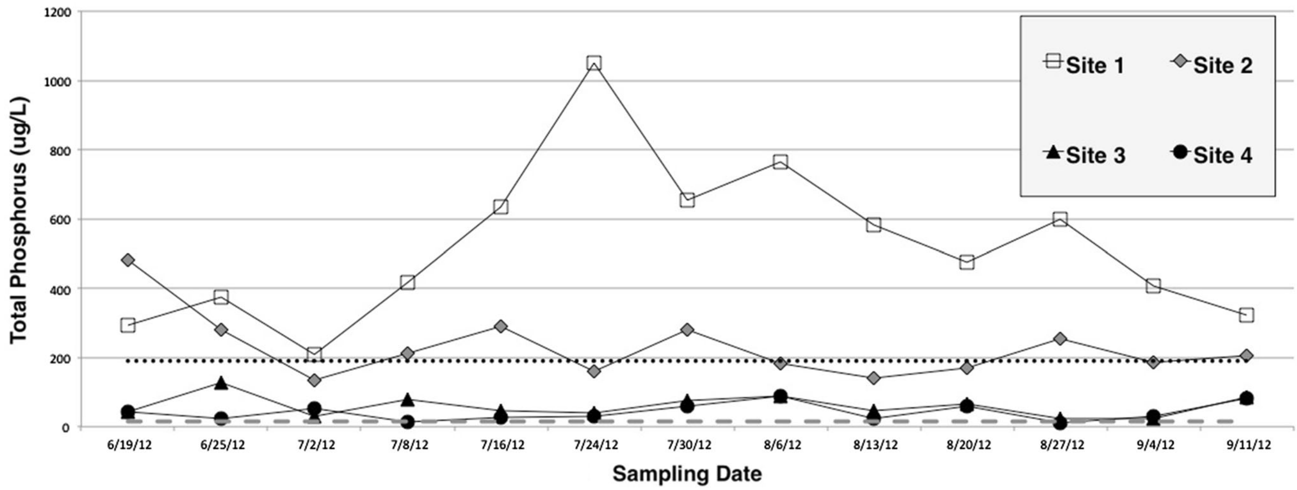

Figure 3. Total phosphorus (μg/L) for Ottawa National Wildlife Refuge sampling sites measured from May 21, 2012 through September 11, 2012 (*dashed line* Phosphorus Task Force target level (15 μg/L); *dotted line* 10 y Ohio drainage ditch mean (190 μg/L) (Ohio State University unpublished study data)).

Table 2. Spearman Correlations Between Water Quality Metrics (*E. coli*, total P) and Environmental Parameters

	E. coli	Total P	Total N	Phycocyanin	Chlorophyll-*a*
E. coli	1				
Total P	0.689**	1			
Total N	0.403	0.612**	1		
Phycocyanin	0.387**	0.488**	0.519*	1	
Chlorophyll-*a*	0.554**	0.820**	0.654**	0.790**	1
Turbidity	0.552**	0.534**	0.539**	0.663**	0.645**
Specific conductivity	0.381**	0.723**	0.730**	0.230	0.642**
Dissolved oxygen	−0.479**	−0.536**	−0.471*	−0.089	−0.208
pH	−0.462**	−0.623**	−0.491*	−0.114	−0.424**
Water temperature	−0.186	−0.278*	−0.206	−0.047	0.144
Sampling site	−0.748**	−0.899**	−0.622**	−0.432**	−0.729**

* Indicates significance at $\alpha = 0.05$, ** Indicates significance at $\alpha = 0.01$.

Table 3. Final Model Using Multiple Linear Regression for Predicting Log-transformed *E. coli* Levels Using Environmental Parameters

Independent variable	Coefficient	Standard error	*P* value
Dissolved oxygen	−0.190	0.080	0.025
Dew point	0.185	0.085	0.040
pH	−0.851	0.434	0.061
Barometric pressure	5.169	1.829	0.009
Precipitation—sampling day	−0.643	0.341	0.071
UV index	−0.502	0.291	0.097
Intercept	−140.465	53.614	0.015

E. coli data were log-transformed.

Table 4. Final Model Using Multiple Linear Regression for Predicting Log-transformed Total P Levels Using Environmental Parameters

Independent variable	Coefficient	Standard error	*P*-value
Turbidity	0.001	0.001	0.03
Specific conductivity	0.001	<0.001	0.036
pH	−0.725	0.154	<0.001
Barometric pressure	1.426	0.569	0.019
Precipitation—sampling day	−0.222	0.072	0.005
UV index	−0.165	0.065	0.018
Intercept	−32.699	16.777	0.063

Total P data were log-transformed.

Changes in pH can lead to damage to biota and changes to biochemical processes (Eriksson et al. 2002, Australian and New Zealand Environment and Conservation Council 2000). Additionally, increasing pH leads to decreased growth of *E. coli* (Parhaud and Rao 1974). The decreasing trends were consistent, even as additional biological, nutrient, water, and meteorological variables all exhibited variability across time and space during the study period. The few exceptions to the overall pattern occurred when the typical direction of water flow in the wetland was reversed by a seiche—a periodic phenomenon observed in all of the Great Lakes, especially in Lake Erie due to its physical characteristics (Herdendorf 1987; Mitsch and Gosselink 2007).

Awondo et al. (2011) estimated a \$6.19 million aggregate annual economic benefit from the construction of a wetland to filter and remediate contaminated ditch water at a nearby Lake Erie beach (Maumee Bay State Park); however, their study based their economic valuation on the assumption, without uncertainty, that a wetland adjacent to a swimming beach would prove successful at lowering *E. coli* levels to safe concentrations. Our study provides support for their findings by showing that wetlands adjacent to a Lake Erie swimming beach do indeed improve water quality to levels acceptable for direct human contact and exposure.

Significant Spearman's correlations were observed for both *E. coli* and total phosphorus ($\alpha = 0.01$). High levels of *E. coli* indicate the presence of fecal contamination, thereby suggesting the potential for pathogens and elevated health risks. Phosphorus is an important nutrient, especially in the Western Basin of Lake Erie, because it frequently results from nonpoint source agricultural runoff and can result in algal blooms and deteriorated water quality (OEPA 2010). Dissolved oxygen was the only environmental variable that was significantly correlated with *E. coli* concentrations that also appeared in our final multiple linear regression model. As dissolved oxygen increased, *E. coli* concentrations decreased. This result is likely not representative of cause and effect, but rather is thought to be correlative in nature and due to the strong correlation between increasing DO, decreasing *E. coli* counts, and site number. Turbidity ($\rho = 0.534$), specific conductivity ($\rho = 0.723$), and pH ($\rho = -0.623$) were the only environmental variables that we found to be significantly correlated and also in the model used to predict total P. As turbidity and specific conductivity increased and pH decreased, total P was elevated. Barometric pressure was a significant predictor of *E. coli* and total P in each respective model. Whitman and Nevers (2008) also observed barometric pressure as a variable that could explain *E. coli* concentrations in another nearby Great Lake (Lake Michigan). Barometric pressure is directly related to dissolved oxygen and is also associated with changes in atmospheric conditions that can result in alterations to wind speed and wave height, among other environmental shifts. Thus, collectively, subtle changes to multiple barometric pressure-related variables affecting physicochemical water properties may explain its inclusion in both of our models.

Finally, although sites were arbitrarily numbered upstream to downstream one through four, we observed a significant ($\alpha = 0.01$) negative correlation between both *E. coli* and total P and site number. This indicates that the levels of contaminants were closely related to site location, with sites farther downstream exhibiting lower levels.

Conclusions

Based on these data and what is known about ecosystem services provided by wetlands, it appears that the ONWR wetlands, even with the presence of abundant wildlife, function in a capacity that support improving water quality parameters to safe and acceptable levels for direct contact by nearby beachgoers. This would indicate that a healthy near-shore wetland ecosystem provides ecoservices that counteract the influence of large wildlife populations and nearby agricultural contaminants, thus preserving and providing a safe recreational water environment. Furthermore, this supports the idea that wetland environments can exist, and be conserved or reestablished in close proximity to surface waters that serve as drinking and direct contact recreational water sources—an option that is economical and efficient. For example, according to recent work in the Eagle Creek Watershed outside of Indianapolis, Indiana, USA, almost 3,000 sites were identified, where wetlands could be restored or engineered to gather almost one-third of the watershed area's runoff while covering only 1.5% of the watershed's area (Babbar-Sebens et al. 2013). A decade earlier, Mitsch et al. (2001) estimated that the creation and restoration of 2 million hectares of wetlands was needed, mostly in Midwestern USA agricultural states, to cause a significant reduction in the Gulf of Mexico Hypolimnetic eutrophication known as hypoxia.

Although the avian contribution and pathogen co-occurrence are still yet to be determined, it is suspected that their contribution will largely be offset by the greater ability of the wetland area to filter and cleanse surface water. Physical and hydrometeorological factors may acutely reintroduce microbial pathogens into surface water. However, the same processes (e.g., settling, absorption, adsorption, etc.) that promote reductions in pathogen concentrations are anticipated to act following the reintroduction, ultimately managing, and minimizing the number of pathogens over the long-term. Finally, it should be noted that the findings from this work further support evidence that intact ecosystems function in a disease-regulating role (MEA 2005, McFarlane et al. 2012).

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