Groundwater seepage nutrient loading in a recently dug wet detention stormwater pond

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Abstract Most of the 10,000 urban wet stormwater ponds found in southwest Florida were constructed post 1980 to protect State waters. Ideally, the impounded polluted water runoff is detained, phyto-remediated and released at the right time at mandated acceptable pollutant levels to the above and underground hydrosystems. However, most studies seem to show the poor performance for these ponds to treat surface runoffs while their groundwater connection is very largely overlooked. This one-year study examined, at high spatiotemporal resolution, the groundwater seepage nutrient loading of a 0.47 ha karstic wet detention pond which is nutrient rich despite a small mostly pervious underused watershed. This 7,000 m^3 water body behaved as a seepage pond (i.e. the pond did not overall recharge the aquifer) with groundwater fluxes typical of other lakes in Florida. Fluxes were positively correlated with rainfall during the dry season but not during the rainy season. Higher fluxes in the northeastern portion than in the southwestern portion were in agreement with the subsurface flow pattern in the region. Groundwater nutrient concentrations were high for total phosphorus and typical for total nitrogen. Groundwater nutrient loading could explain the resulting eutrophic conditions of the pond.

Keywords Florida, groundwater seepage, nutrient loading, stormwater pond

Introduction

Since the early 1980s, in the face of past significant environmental degradation (e.g. Porter and Porter 2002), the State of Florida mandated that actions be taken to reestablish natural hydropatterns and prevent pollutants (especially nutrients) from reaching natural hydrosystems. In particular, Chapter 62-40 of the Florida Administrative Code was enacted so that stormwater runoff was slowed down in order to i) prevent erosion, ii) allow siltation/sedimentation prior to reaching natural hydrosystems, iii) promote soil filtration for pollutant removal, and iv) promote aquifer recharge. Through Chapter 62-40, stormwater pollutants were to be reduced by 80% with respect to the State Water Quality Standards. This figure was changed to a 95% reduction when such stormwater emptied into an Outstanding Florida Waterway (OFW). Several different types of stormwater management systems exist and range from swales to dry and wet detention and retention ponds placed judiciously to intercept stormwater and provide flood protection as well as fill for construction. In Lee

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County, Florida, these systems are widely used since this heavily developed region borders the coasts and large (e.g. Caloosahatchee River) or small coastal rivers (Imperial River) emptying into OFWs (e.g. Estero Bay). Although the total number of these systems is unknown, a census of all the wet urban and agricultural wet ponds accounted for 7,632 water bodies in 2012 (e.g. Thomas 2014) for a total surface area of 57.2 km^2 or 1.8% of the County's footprint. It is unknown whether these ponds function adequately as studies are rare (e.g. Harper and Baker 2007) or not readily available (e.g. non-disclosed studies or unpublicized ones). Harper and Baker (2007) report that wet detention ponds are the least efficient and often do not meet the 80% pollutant reduction while wet retention ponds overall meet that requirement but that dry retention ponds are better. A more recent study on wet ponds in the City of Naples, located in the adjacent southern Collier County (AMEC 2012), showed that most ponds were well below 80% pollutant reduction for Total Phosphorus (TP) and Total Nitrogen (TN) with often negative retention rates, especially for copper. This suggests that stormwater ponds could export more pollutants than they receive as they age.

Residential ponds (e.g. ponds in London, UK) (Birch and McCaskie 1999) were often built so as to increase the shoreline available for adjacent houses leading to excessive nutrient loading from fertilized lawns and impervious surfaces. These nutrients led to the development of macrophytes and microphytes, which were then suppressed with herbicides and algaecides, especially copper based algaecides. Deposition of dead macrophytes and microphytes and shoreline erosion due to a lack of rooted macrophytes in the littoral zone led to decreased water storage and overall pond life (e.g. Thomas 2014). It is noteworthy that pond pollutant and hydraulic retention are based on surface water runoff only (e.g. AMEC 2012) but the underground components are often not taken into consideration. This might explain why dry and wet retention ponds appear to be better at sequestering pollutants (Harper and Baker 2007).

Groundwater has a significant, but unseen influence on the ecology of natural lakes and coastal environments since it can be an important source of water and nutrients to these systems (Kang et al. 2005). This is especially true south of Lake Okeechobee where soils are porous (e.g. karstic) and groundwater tables shallow (e.g. Schiffer 1998, Lee et al. 2014). Most groundwater seepage studies involving direct seepage measurement are rare and rely on hydrologic data (e.g. water level), precise topographic maps and modeling (e.g. Grubbs 1995) but uncertainties remain (e.g. Lee and Swancar 1997). Direct measurements in Florida include natural lakes located north of Lake Okeechobee since very few natural lakes exist south of it. Examples include Lake Tohopekaliga (Belanger and Mikutel 1985, Belanger et al. 1985), Lake Conway and Apopka (Fellows and Brezonik 1980) and more recently Lake Jessup (Harper 2011). Information from indirect groundwater seepage measurements made on detention ponds are only available for three detention ponds in West Central Florida (Pinellas County, Fernandez

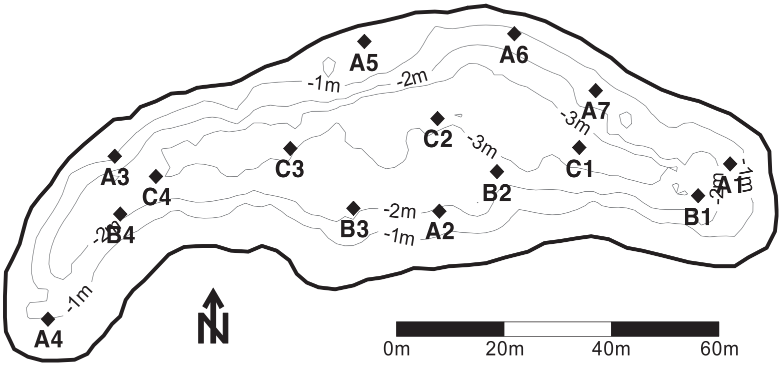

Figure 1. Bathymetry of the pond studied with the 0 m isobaths delineating the pond when full (3/3/2013). Closed diamonds represent the positions of the seepage meters. Isobaths units are in meters. Note that meters A5 through A7 included were out of the water during the dry season.

and Hutchinson 1993) and one pond in Central Florida (Orange County, McCann and Olson 1994).

Directly measuring groundwater fluxes can be difficult, but groundwater seepage meters are valuable using "less inventive water budgets" (Deevey 1988) even though spatial variation can be high within each system (e.g. Brock et al. 1982, Shaw and Prepas 1990).

This study aims to examine with groundwater seepage meters (Lee 1977) groundwater fluxes in a 3 year old eutrophic wet detention pond and to document whether the pond acts as a source of water and nutrients to the surficial aquifer or as a sink for water and nutrients. Furthermore, groundwater seepage is generally heterogeneous spatially and temporally. This study thus also purposes to examine spatiotemporal variability using numerous seepage meters per acre of pond and various temporal scales ranging from monthly to seasonal.

Materials and Methods

Study site. The wet detention pond surveyed from 03/2013 to 02/2014 is an oblong, East-West oriented, 0.47 ha, 3 years old eutrophic detention pond located within Florida Gulf Coast University campus (17N 422079mE 2927505mN, Figure 1 and Figure 2). The pond is bordered to its north and west by a 16-acre flat lot paved with pervious crushed limestone that makes the foundations of the solar panels field. It is bordered to its south by preservation lands high enough for scattered slash pines to be established and low enough for the establishment of a short hydroperiod wetland (Figure 2). To the east, the pond is immediately bordered by an elevated dirt road. The pond has a shoreline development index of 1.49, a volume of 8,400 m^3, a mean depth of 1.8 m and a maximum depth of 3.8 m (Figure 1). Prior to being dug, the excavation site roughly laid within the center of an 84 ha zone delineated by roads which includes disturbed pinelands scattered with short-hydroperiod wetlands (Figure 2). At a larger scale, the main campus, with 13 manmade ponds, is bordered to its north by a retired borrow mine pit of about 210 ha and 5.6 m in mean depth (Lakes Miromar and Como). Its shores are heavily urbanized by single family homes (Figure 2). The rest of the constructed portion of

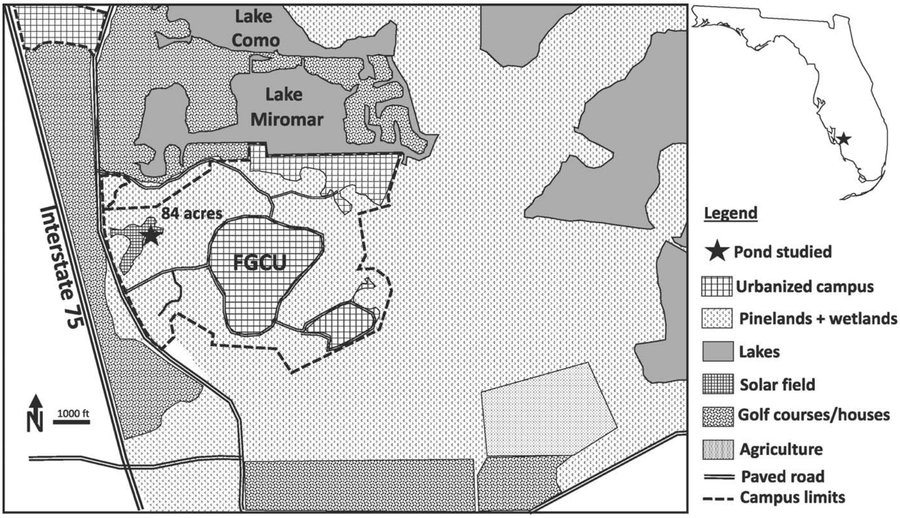

Figure 2. Location of the studied pond and description of the land uses surrounding it. Redrawn to scale from Google Earth Pro satellite imaging (3/31/2014).

the campus is built within disturbed pinelands and short-hydroperiod wetlands. To the east, these lands are bordered by borrow pit mine lakes and to the south and the west by golf course communities (Figure 2).

Seepage meters location. Water fluxes whether positive (i.e. groundwater influx or seepage) or negative (i.e. groundwater recharge) were assessed from March 2013 to February 2014 using 12 to 15 seepage meters. Because it was expected that most groundwater influxes would occur within the littoral zone (e.g. Fellows and Brezonik 1980, Brock et al. 1982), seven meters (A1-A7) were placed nearly equidistant from each other within the 0-1 m depth zone (Figure 1). This shallow zone utilized all seven meters when water levels were high from August to November 2014, six meters (all but A6) in December 2014 when water levels began to drop and four meters (A1 through A4) during the rest of the study. These four meters were always used as they were submerged during the entire year and positioned in the southern ¾ portion of the pond (meters A1-A4, Figure 1). The littoral zone of the northern quarter of the pond was much steeper and rockier and provided an inadequate seal of the meters with the pond bed in the median portion of this shallow 0-1 m depth zone. Locations further up the bank, however, provided an adequate seal for the meters during the rainy season when the pond water level was higher. The depth zones between 1-2 m and >2 m each received four meters placed at regular distance intervals (meters B1-B4 and C1-C4 respectively, Figure 1).

Meter construction and positioning. Groundwater seepage meters have been used to understand the interconnection between groundwater and surface water in various water bodies including lakes (e.g. Boyle 1994), wetlands (e.g. Harvey at al. 2000), rivers (e.g. Libelo and Macintyre 1994), and coastal marine systems (e.g. Lewis 1987). A variety of designs have been used, dating back to the 1940s (e.g. Israelson and Reeve 1944) but it was not until Lee's 1977 study that an easy, affordable, and accurate way to consistently measure groundwater seepage was developed. Each meter consisted of a 55 gallon steel drum half encapsulating 0.26 m^2 of pond bed (Lee 1977). Each meter was cut unevenly at the base so that when the base was driven down into the pond's bed to create a good seal, the top of the meter was slightly tilted. This allowed gas bubbles to vent out through a 1.27 cm diameter outlet connected to a clear vinyl tube which was positioned at the highest point of the meter with respect to the pond's bed. Water fluxes were assessed by rubber strapping a clear 15 cm×30 cm plastic bag (1.5 mm thick) to the end of the vinyl tube. Collection bags were thin walled to reduce resistance to flow (Shaw and Prepas 1989, Asbury 1990, Murdoch and Kelly 2003). Harvey et al. (2000) found that larger diameter connection materials reduced resistance of flow allowing for more accurate measurements. Bags were placed via SCUBA or snorkel to prevent disturbance of surrounding sediment. Each bag was prefilled with 500 ml of deionized water and care was taken so that no bubbles were trapped in the bag when it was connected to the vinyl tube. Bag deployments were set to 24 h for the monthly seepage meter assessment. Bags were retrieved by SCUBA and chilled in an ice chest. The water volume in each bag was then measured to the nearest ml and, in the event of a net water gain from May 2013 to February 2014, water was transferred into a 100 ml PTFE bottle which was filled to the top and subsequently frozen at −18°C.

Nutrients analysis. Nutrient analyses were performed for all bags which received groundwater with the exception of March and April 2013. Once thawed, the water from the collection bag was analyzed within 6 months with a Cary-100 spectrophotometer for TP (APHA 2012) and TN (Bachmann and Canfield 1996). A long holding time of the samples in the freezer does not affect the analyses of TP (Lambert et al. 1992) and TN (Bachmann and Canfield 1996). The water concentration of the groundwater influx was then corrected from the dilution occurring in the prefilled bag with deionized water. The groundwater nutrient influxes (mass loading) were calculated by multiplying the water flux by the nutrient concentration (mg/m^2/d).

Weather. A Davis Vantage Pro2 weather station located at about 400 m to the east of the pond logged rainfall every 10 min.

Computations and statistics. Water flux (m/day or 1000×l/m^2/d) was calculated as $\Delta V/(\Delta t \times A)$, where ΔV (m^3) and Δt (days) were the changes in net volume in the bag and net time, respectively, while A was the surface area encapsulated by the seepage meter (m^2). A correction coefficient of 1.25 was applied to all flux velocities to account for the resistance to water flow the meter's components generate (e.g. Asbury 1990, Harvey et al. 2000, Murdoch and Kelly 2003). The spatial variability of the water flux was assessed through mapping with Surfer 12 (www.goldensoftware.com) using the Kriging method and the adequate variogram model to spatially interpolate the data. Surfer was also used to calculate the net daily water gain or loss (l/d) for the pond within the polygon of interpolation. The daily net gain or loss of water and nutrient influx for the whole pond was calculated through extrapolation outside the polygon of interpolation using the correction factor "whole pond/polygon of interpolation" surface areas. The average water flux was determined by dividing the daily water gain or loss by the surface area of pond bed that day. Each daily flux was then expressed on a monthly basis by multiplying the daily flux by the number of days of the month. All resulting twelve monthly fluxes were then summed to estimate the yearly net groundwater exchange. This net exchange was then further divided by the yearly average volume of the pond to determine the yearly percent groundwater contribution. Daily nutrient influxes for the meters were computed by multiplying the daily water flux by the concentration of groundwater nutrients (i.e. nutrient mass loading in mg TP or TN/m^2/day). The mass of nutrients entering the pond was then computed daily by multiplying the average nutrient concentration by the daily groundwater flux to the pond (mg/d). This daily groundwater flux was finally divided by the pond volume to get the additional equivalent nutrient concentration (mg/l) brought to the pond. The cumulative monthly direct rainfall collected on the planar surface of the pond was calculated by multiplying the planar surface area of the pond for a given month and the total rainfall amount for the same month. All cumulative monthly rainfall volumes were then combined to estimate the yearly total volume of rainfall. Histograms, scatterplots and regressions were conducted in Microsoft Excel 2010 and averages are presented along with their respective standard deviation.

Results

Water exchanges. Water fluxes ranged from −2.0 l/m^2/d (10/2013, meter A4) to 7.04 l/m^2/d (01/2014, meter A2) when all data are pooled together over space and time. With one exception, all maps of water fluxes exhibited higher values in the north to northeastern portion of the pond (Figure 3) than its south to southwestern portion. The one exception was in 01/2014 when higher water fluxes were observed at meters A4 and A2. This seepage event was marked with significant rainfall prior to and during the water seepage collection period (50.8 mm accounting for 78% of the precipitation in January). When water fluxes were averaged over the pond surface area, water fluxes ranged from −0.28 l/m^2/d (06/2013) to 1.47 l/m^2/d (01/2014, Figure 4). These figures equate to −0.18‰ and 0.89‰ water exchanges per day with the overall pond water volume. Water fluxes were positive 9 out of 12 months. They were positive during the dry season when there was low precipitation and negative or minimal during the rainy season (Figure 5). The resulting yearly groundwater recharge was 531 m^3 (i.e. pond water losses) and groundwater influx (i.e. pond water gains or seepage) was 984 m^3 or 13.6% of the average pond volume for the year. The net water exchange between the pond and the groundwater was 453 m^3 or 6.3% of the average pond volume. The yearly volume of rainfall over the pond surface was 5,280 m^3 or 73% of the average pond volume. There was a positive linear correlation between the amount of rainfall during the dry season and the average water flux for the whole pond ($P=0.02$, Figure 5). In contrast, no correlation was found during the rainy season (Figure 5).

Groundwater nutrient loading. Groundwater nutrient concentrations did not exhibit a clear seasonal pattern (Figure 6). It was 2.83+2.96 mg/L and 0.27+0.23 mg/L for TN and TP, respectively. Nitrogen groundwater seepage loading increased from 05/2013 with 2.01+1.23 mg/m^2/d to 4.93+5.60 mg/m^2/d in 11/2013 (Figure 7). TP groundwater seepage loading similarly increased from 0.21+0.09 mg/m^2/d in 05/2013 to 0.92+0.49 mg/m^2/d in 02/2014 (Figure 7). Thus the additional nutrient loading on a liter of pond water basis for the period 05/2013-02/2014 was 0.019+0.021 mg/l/d and 0.0014+0.0018 mg/l/d for TN and TP, respectively (Table 1).

Discussion

This study is unique since groundwater seepage was measured at high spatiotemporal resolution with 32 seepage meters per hectare and in a 0.47 ha wet manmade detention pond instead of a lake. As a comparison, Harper (2011) used 0.006 meters per hectare (40 in Lake Jesup with 6,475 ha) while this figure was 0.003 meters per hectare (25 in Lake Tohopekaliga with

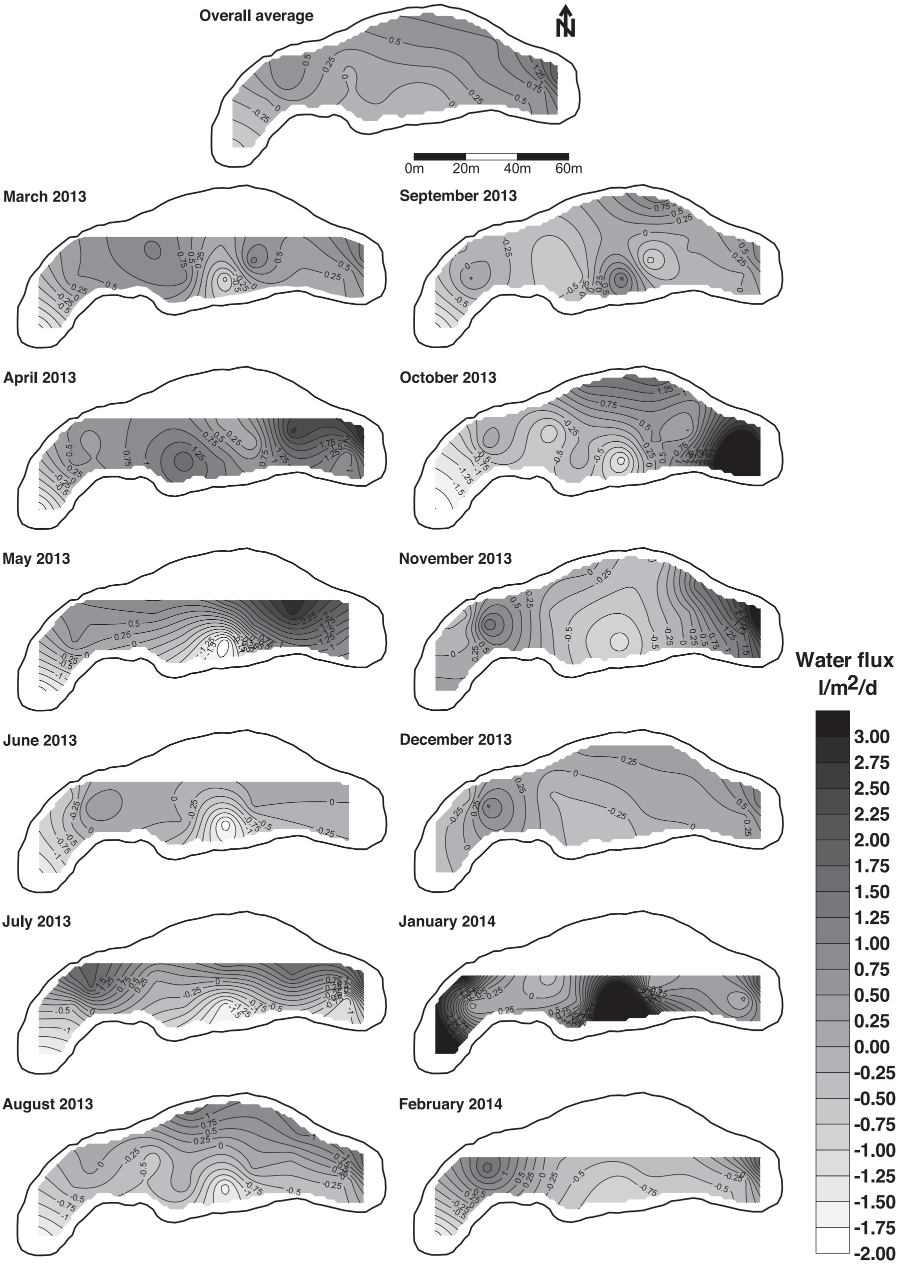

Figure 3. Spatial variations of water fluxes from March 2013 through February 2014. The overall average fluxes are also depicted in the top map.

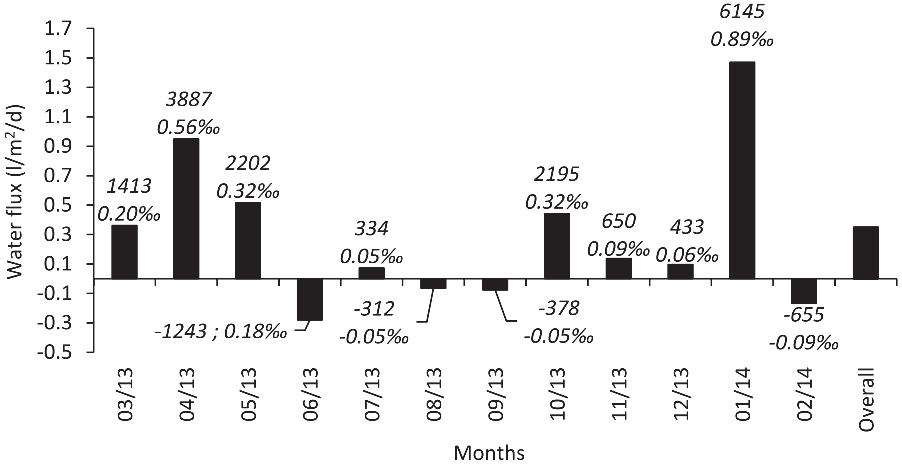

Figure 4. Average water fluxes (column graph) as measured over a 24 h period and each month from March 2013 to February 2014. The overall average water fluxes for all the months combined are also shown. Data values in italics above each column represent the overall water gained or lost in l/d and the ‰ gain or loss of the overall pond water volume per day.

9,186 ha) in Belanger et al. (1985) and even less in Fellows and Brezonik (1980) investigations (Lake Apopka with 12,464 ha and Lake Conway with 711 ha). The high density of seepage meters allowed precise mapping of groundwater movement in a northeastern to southwestern pattern. This pattern is in agreement with the general groundwater flow direction in the region (e.g. Bennett 1992). Overall, the pond was a seepage pond (as defined in Lee et al. 2014) because it had a positive net groundwater inflow. However, this groundwater inflow was about 12 times less than direct rainfall onto the planar surface of the pond. According to Lee et al. (2014), most lakes of the peninsular

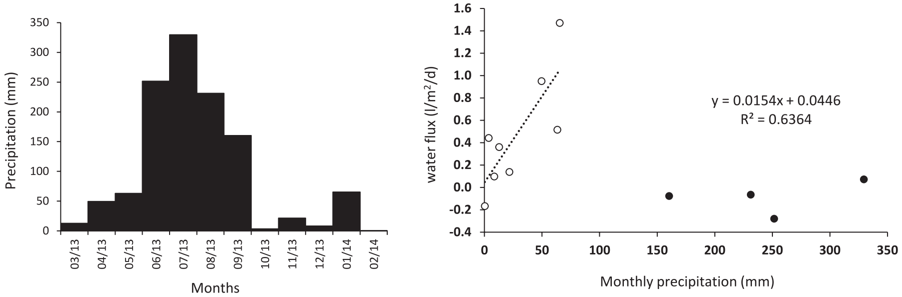

Figure 5. Monthly precipitation at FGCU campus from 03/13 to 02/2014 (left) and regression between the water flux and the monthly precipitation for the dry months (open circles, $P=0.018$) and wet months (closed circles, $P>0.05$).

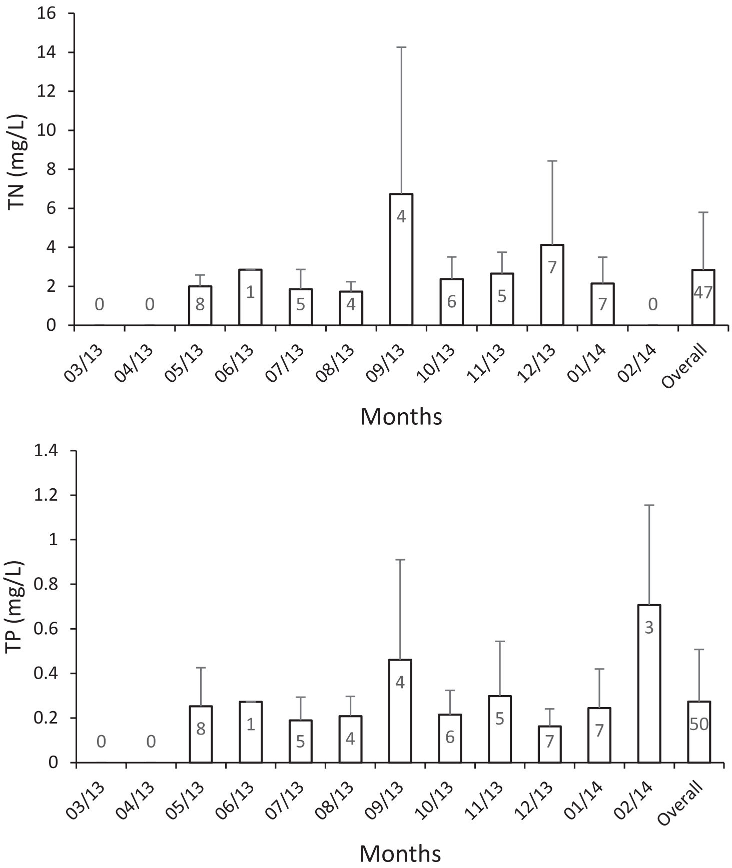

Figure 6. Average TN (top) and TP (bottom) water concentrations coming from the seepage meters and calculated from one 24 h assessment each month from May 2013 to February 2014 (the number of replicates is encapsulated in the column, zero means that nutrients were not considered early in the project).

Florida have more evaporation than precipitation, i.e. a negative net precipitation which is compensated by a positive net groundwater inflow. A water budget for this pond would have been useful to concretely verify these assertions, but evaporation pans (or a net radiometer), as well as a precise water level recorder, were not available. We attempted to conduct statistics to compare water fluxes of the shallow versus deeper portion of the ponds with the expectation that shallow meters would have higher values than that of the deeper meters (e.g. Belanger et al. 1985). This proved to be challenging to do because of the aforementioned spatial northeastern to southwestern groundwater flow pattern. Also, the absence of meter data during the dry season (meters were out of the water) made it difficult to run a repeated measure ANOVA using time as the repeating factor and the various meters per depth

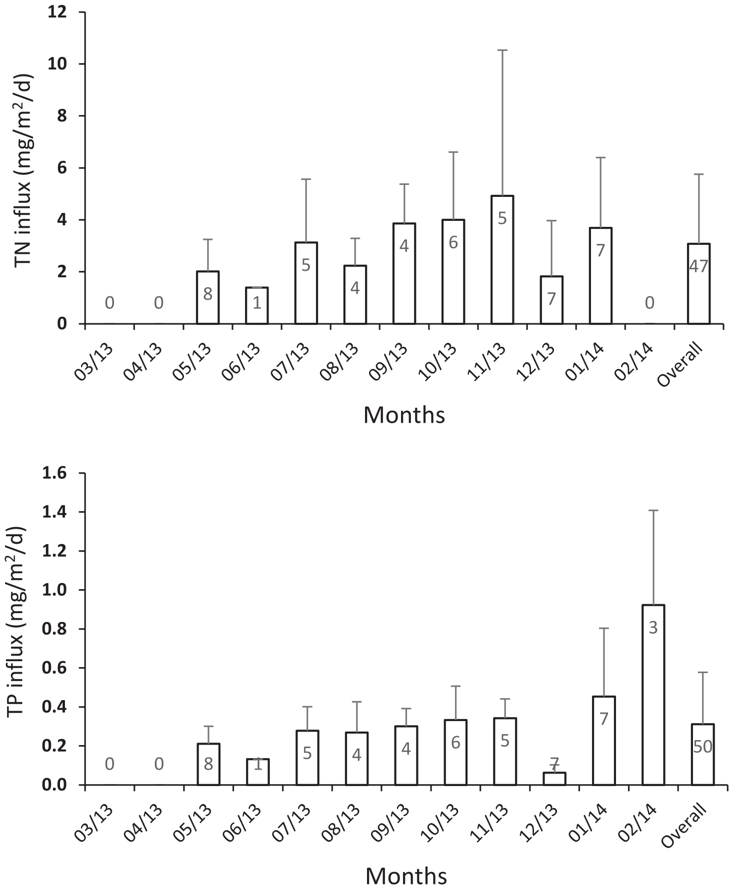

Figure 7. Average TN (top) and TP (bottom) influxes calculated from one 24 h assessment each month from May 2013 to February 2014 (the number of replicates is encapsulated in the column, zero means that nutrients were not considered early in the project).

as the group subjects. Nevertheless, there was enough data collected to assert that this pond is a seepage pond and, as such, it does not recharge the aquifer as mandated.

Most studies focusing on groundwater seepage establish a hydrological budget and in particular assess the percentage of groundwater contribution to the water sources (and water sink) of the water body considered. In this study, because no hydrological budget was made, the amount of water exchanged compared to the volume of the pond was used to give a percentage of water exchange per day over time. Our percentages are thus difficult to compare with those in the literature. To put the study pond into perspective, a high-end estimate of percentage groundwater contribution could be calculated by not including rainfall runoff to the pond. The pond is mostly surrounded by

Table 1. Contribution of groundwater TN and TP on a per liter basis to the pond water per month and overall for the pond water capacity that month.

	Average Additional [TN]		Average Additional [TP]	
Month	mg/l/month	g/month	mg/l/month	g/month
03/13	N/A	N/A	N/A	N/A
04/13	N/A	N/A	N/A	N/A
05/13	0.019	131.4	0.0017	11.5
06/13	no influx	no influx	no influx	no influx
07/13	0.002	18.5	0.0001	1.0
08/13	no influx	no influx	no influx	no influx
09/13	no influx	no influx	no influx	no influx
10/13	0.019	155.8	0.0009	7.1
11/13	0.007	51.6	0.0006	4.8
12/13	0.007	53.5	0.0001	1.0
01/14	0.059	394.8	0.0049	32.4
02/14	no influx	no influx	no influx	no influx

pervious flat surfaces and an elevated dirt road to its east which blocks runoff. Only its south portion should thus receive runoff, but it is believed that this would be limited to the rainy season when water levels are high enough (which is an event we did not visually notice). The groundwater inflow contribution could then be calculated as the ratio between the groundwater seepage divided by the sum of the volumes of direct rainfall precipitation falling over the planar surface area of the pond and the groundwater inflow. This calculation yields an estimate of 15.7% groundwater contribution to the pond. Despite the value representing a maximum estimate of groundwater contribution (because runoffs were not included), it is within the order of magnitude found in Florida lakes (e.g. Belanger et al. 1985).

The correlation of rainfall with net groundwater inflow during the dry season, and the lack of such a relationship during the rainy season, was particularly conspicuous. Seepage lakes in Florida increase in water level nearly immediately after precipitation over their watershed (e.g. Lee et al. 2014). The lack of such a relationship in the study pond during the rainy season may be due in part to water table elevation differences between the two seasons. During the dry season, rapid evaporation may have drawn down the pond level below the level of the surrounding water table, creating a positive hydraulic gradient, drawing water into the pond through the littoral areas (Darcy's Law). Sporadic rain events on the surrounding landscape could have increased, via rain infiltration, the water table level even more, creating a larger hydraulic gradient and more groundwater inflow. Conversely, during the wet season, surface runoff and direct precipitation occurred often and this potentially raised the level of the pond high enough to reduce the head difference and even temporarily increase pond levels above the surrounding water table, allowing slight seepage. The implementation of piezometers around the pond along transects across elevation gradients could determine the head differences between the pond water level and surrounding water table, which would test this hypothesis.

The contribution of nutrient loading via groundwater seepage compared to the pond's overall nutrient load is difficult to estimate because of the lack of a hydrological budget and the analysis of water column nutrients during the study. As such, a nutrient budget was not made. Based on unpublished investigations by the authors involving measurements of Secchi disk depths and water total chlorophyll concentrations, the pond surveyed is high mesotrophic to eutrophic on the Carlson trophic status index scale (1977) but its immediate watershed is fertilizer free and very likely reduced in size. Thus, it is hypothesized that groundwater inflow should be responsible for its relatively high nutrient status especially for a young wet detention pond. The nutrient concentration in the groundwater inflow recorded is high for TP when compared to other wet ponds of ages ranging from 1 to 30 years and surrounded by residential and commercial lands (Fernandez and Hutchinson 1993). However, note that groundwater samples were taken from wells (their study) instead of seepage meters bags (this investigation). Groundwater inflow collected from groundwater seepage meters often overestimate nutrients inputs (e.g. Belanger et al. 1985) since meters create a sediment confinement potentially leading to sediment anoxia, which promotes the dissociation of orthophosphates from the reduced iron. As such, adjacent groundwater wells should have been used to draw groundwater samples. This additional phosphorus input was found to be twice higher in the Belanger et al. study (1985), but even if this correction were to be used, our TP in groundwater would still remain high and could explain the pond's nutrient status. This source of phosphorus in groundwater remains unknown since the campus lands (including lawns) northeast of the pond are not fertilized with a few exceptions such as the soccer and football fields which are 1,000-2,000 m away. It is doubtful that the heavily vegetated lands and wetlands found northeast of the pond would release nutrients to the groundwater as the labile pool of nutrients should be sequestered by the plants and algae thus creating a refractory nutrient pool. Further, the land immediately east-northeast of the pond was scraped down to the limestone to create a short hydroperiod oligotrophic reclaimed wetland. Finally, because of the direction of the groundwater flow found in this study, the nearby western and southern golf courses cannot be considered as groundwater nutrient sources.

In conclusion, this study provides a detailed insight into connections between a wet detention pond and its groundwater. Overall, the water body studied was a seepage pond and this assertion should be verified for other ponds in the region. The large number of meters and sampling effort documented the high spatial heterogeneity of the groundwater flux (fluxes were higher in the northeastern portion of the pond than its southwestern portion which agreed with the general subsurface flow pattern in the area). This study would have greatly benefited from a hydrological budget which would have included all the water sources and sinks to the pond as well as the use of piezometers judiciously placed to validate the general groundwater flow pattern. Shoreline meters should also have ideally been relocated as the shoreline was receding during the dry season. The establishment of a nutrients budget including nutrients loading via runoff, rainfall and pond water nutrients as well as, ideally, the groundwater nutrients taken from a groundwater well adjacent to each seepage meter would have best determined why this pond is nutrient rich despite the efforts undertaken at Florida Gulf Coast University (FGCU) to prevent its eutrophication. These types of studies can be helpful in understanding why some ponds remain nutrient rich despite management efforts to reduce surface nutrient loading via runoff and internal loading via sediment dredging. Studies of groundwater nutrient loading in urban stormwater ponds are also important because the numbers of these ponds are steadily increasing over time.

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