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Non-Point Sources (Septic Tanks) of Surface Water Nutrient Pollution: A Review and a Study of Taylor Creek, Okeechobee County, Florida

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Abstract

This study investigated the impact of high-density septic systems (aka Onsite Sewerage and Disposal Systems, OSTDS) along the canals located in the communities of the lower Taylor Creek area on water quality at the northern periphery of Lake Okeechobee. Using sucralose as an anthropogenic tracer, we investigated the septic derived non-point sourcing of nutrients which feed harmful algal (cyanobacterial) blooms (HABs) in Lake Okeechobee and adjacent waters.

The subdivisions investigated were Treasure Island (TI) and Taylor Creek Isles (TCI) located to the east and west of Taylor Creek. TI homes are all on septic tanks whereas TCI is serviced by a municipal vacuum sewerage system.

TI canals had 5.3 times the mean concentration of sucralose relative to TCI canals. On a yearly basis, the Treasure Island sites away from Taylor Creek had 2.25 times the total phosphorus and 1.20 times the total nitrogen compared to the Taylor Creek isles sites. An extensive literature review of non-point pollution is included.

Keywords: non-point pollution, septic tanks, ammonia, phosphorus, algal blooms, sucralose

1. Introduction

1.1 The Problem

The use of septic tanks, also called Onsite Sewerage Treatment and Disposal Systems (OSTDS), is widespread in Florida and elsewhere (LaPointe et al., 1990, 1992; Miller, 1992; Whitlock et al., 2002; Meeroff and Morin, 2005; Herren and Lapointe, 2016).

Effluents from septic tanks lead to the pollution of surface and ground waters with pharmaceuticals (Coble, 1981; Alhaijar et al., 1988; Chen, 1988; Carrara et al., 2008; Standley et al., 2008; Ejhed et al., 2012; Phillips et al., 2015), fecal coliforms (Cogger et al., 1988; Griffin et al., 1999; Scarlatos, 2001; Tanji et al., 2001; Frenzel and Couvillion, 2002; Whitlock et al., 2002; Jamieson et al., 2003; Kelsey et al., 2003; Glassmeyer et al., 2005; Karathanasis et al., 2006; Servais et al., 2007; Lizarraga-Mendiola et al., 2013; USGS, 2017;), and primary plant nutrients, namely nitrogen and phosphorus (Lapointe and Matzie, 1996; Macintosh et al., 2011; Mechtensimer, S., and Toor, G.S., 2017; Mockler et al., 2017; Liao et al., 2019;).

The pollution of surface waters with primary plant nutrients, notably nitrogen and phosphorus, is increasing worldwide (Carpenter et al., 1998; Smith et al., 1999; Bricker et al., 2007; Elser et al., 2007; Dodds et al., 2009; Guignard et al., 2017). Nutrients can be and often are addressed within watershed management programs through processes termed best management practices or BMPs (Gunsalus et al., 1992; Sims et al., 2000; FDACS, 2011; FDEP, 2013), though lag-times between implementation and detection of impacts can range from years to decades (Meals et al., 2010).

In the October 2016 United States Environmental Protection Agency report entitled "National Nonpoint Source Program", it was stated; "Of all the waterbodies across the nation that have been assessed and a possible source of impairment identified, 85% of rivers and streams and 80% of lakes and reservoirs are polluted by nonpoint sources." (USEPA, 2016).

Under the United States Clean Water Act Section 502, General Definitions, it states; "The term 'point source' means any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural stormwater discharges and return flows from irrigated agriculture." (USEPA, 2019). It is the last sentence in this definition that generates the idea of 'non-point' sources (NPS). That is, "Nonpoint source pollution, on the other hand, comes from disperse overland flow associated with rain events." (Pierce et al., 1998). Nonpoint nitrogen and phosphorus pollution is a well-known worldwide problem (Carpenter et al., 1998; Lankoski and Ollikainen, 2013; Xia et al., 2020) but is not limited to overland flow from rain events. That is, septic tank sources, including drain field effluents as well as leaking septic tanks, are indeed "non-point" sources and are well documented pollution sources (Canter and Know, 1984; Hayes et al., 1990; Scarlatos, 2001; EPA, 2002; Jin et al., 2004; Zhang et al., 2011; Lapointe et al., 2015; Cooper et al., 2016; Barile, 2018).

Many process-based mathematical models exist and utilize input data including nutrient concentrations, water flow, soil types, weather, and numerous other parameters in order to develop and/or characterize BMP efficiencies. Such programs include the Soil and Water Assessment Tool (SWAT) developed by the United States Department of Agriculture (Arnold et al., 1998, 2010; Neitsch et al., 2011; Shen et al., 2015). Several other models also exist (Tuo et al., 2015; Liu et al., 2019) for the assessment of basin and catchment scale studies.

1.2 South Florida – Nutrients and Algal Blooms

South Florida has been and still is experiencing nutrient (N, P) excesses in the surface waters and sediments of Lake Okeechobee (Havens, 1995; Walker and Havens, 1995; Havens and East, 1997; Recheigl, 1997; FDEP, 2001, 2018, 2019; Fisher et al., 2001; Havens et al., 2005; Engstrom et al., 2006; Byrne and Wood, 2011; Pollman and James, 2011; US-ACE, 2016; Zhou and Struve, 2016), coastal estuaries (Lapointe et al., 1990, 2012, 2015; Lapointe and Clark, 1992; Lapointe and Krupa, 1995; Pant and Reddy, 2001; Phlips et al., 2002; Liu et al., 2009; Tarnowski, 2014; Duersch and Louda, 2017;), and the Greater Everglades (Childers et al., 2003; Bruland et al., 2007; Louda et al., 2015; Reddy et al., 2011). Sources include sewerage, notably septic systems (aka OSTDS, Onsite Sewerage Treatment and Disposal Systems: Badruzzaman et al., 2012; FDOH, 2013; Meeroff et al., 2014; Lapointe et al., 2017), agricultural operations (Boggess et al., 1993; Stuck et al., 2001; Entry and Gottlieb, 2014; Duersch et al., 2017, 2020, 2021) and a growing equestrian industry (Louda et al., 2021).

The following quote is from a US-EPA Funding Opportunity (Number EPA-G2017-STAR-A1) with the pertinent sections underlined: *"The occurrence of HABs" {Harmful Algal Blooms} is increasingly common in inland freshwater ecosystems. HABs have been recorded in the waters of all 50 states. (NOAA, 2016), Yet basic questions of HAB occurrence, extent, intensity, and timing are largely unanswered (Ho and Michalak, 2015; U.S. EPA, 2015; NSTC, 2016;)."*

The June-July 2016 catastrophic bloom of the toxic cyanobacterium *Microcystis aeruginosa* in Lake Okeechobee and its downstream effects on the coastal estuaries of southern Florida has received considerable local and national press. Examples from the hundreds of press releases include: "Lake O algae blooms balloons by 500%" (P.B. Post, 2016) and "Florida Declares State of Emergency over Influx of 'God-Awful' Toxic Algae" (Guardian, 2016). Lake Okeechobee's blooms (e.g. 2005) within the list of World problems have also been noted in the journal Science (Stone, 2011). Earlier (e.g. 1986) drastic cyanobacterial blooms in Lake Okeechobee were due to the anatoxin producing diazotrophic (Nitrogen-fixing) species *Anabaena flos-aquae* and reductions in phosphorus loading since then appears to hold those blooms at bay (Rechcigl and Bottcher, 1995; Rechcigl, 1997). However, as seen in 2005, 2016 and 2018, continual dual (N, P) nutrient pollution, especially nitrogen, does now favor the non-diazotrophic blooms of *Microcystis aeruginosa.* Blooms of this cyanobacterium produce large amounts of the hepatotoxin microcystin (Carmichael, 1992, 1994; Dawson, 1998; Bischoff, 2001; Yokoyama and Park, 2003; Blaha et al., 2009; Bortoli and Volmer, 2013; Lone et al., 2015; Loftin et al., 2016).

Nutrients, specifically nitrogen and phosphorus species, are the primers and drivers of algal blooms, be they toxic or non-toxic. HABs produce a lot of organic matter that settles and undergoes aerobic breakdown, depleting oxygen in the water. Resultant hypoxic and anoxic conditions lead to fish kills (Carousel and Russo, 2002; Thornson and Quigg, 2008; Hu and Ou, 2013; Clark et al., 2017; Hounshell and Paerl, 2017). Concerning nutrient drivers, the Redfield ratio (C:N:P ~ 106:16:1: Redfield, 1934, 1958) of N:P provides a measure of nutrient quantity and stoichiometry that is useful in assessing the relative importance of N vs. P-limitation (Lapointe et al., 1992). This is particularly appropriate for assessing OSTDS groundwater-borne sewage pollution that can deliver nutrient pollution at high N:P ratios as a result of selective adsorption of P onto soil particles (Bicki et al., 1984; Weiskel and Howes, 1992), especially so within the calcium/magnesium carbonates of Florida.

Since *M. aeruginosa* is a non-diazotrophic (non-nitrogen-fixing) cyanobacterium, it requires 'fixed' N (e.g. nitrite, nitrate, ammonia, urea etc.). Classic thought and data on the Redfield-Richards Model (Redfield Ratio: Redfield 1934, 1958) N:P ratios reveal that "low" N:P ratios (*e.g.* <~20:1) favor nitrogen-fixing cyanobacteria such as *Anabaena flos-aquae* and *Aphamenozon flos-aquae* which bloomed in Lake Okeechobee in the 1980-90s (Rechcigl and Bottcher, 1995; Rechcigl, 1997).

Anthropogenic Nitrogen loading is cited as main cause of the upswing in *Microcystis* blooms worldwide (Paerl et al., 2014). However, without dual nutrient (N, P) controls (Paerl, 2009; Xu et al., 2010; Paerl et al., 2011; Beaulieu et al, 2013) eutrophication and resultant blooms obviously cannot be controlled without algaecides or other drastic chemical measures that can destroy entire ecosystems.

Lake Okeechobee, a Class I freshwater lake, is the largest in Florida and the second largest freshwater lake in the United States It releases water to both the east (St. Lucie Canal) and west (Caloosahatchee River) and their associated estuaries. The health of Lake Okeechobee and the underlying causes of its impairments have been a controversial topic for decades. Due to nutrients transported from upstream agricultural and urban sources, the quality of the water flowing into the lake has been degraded.

South Florida's Kissimmee-Okeechobee-Everglades ecosystem (KOE) extends from the headwaters of the Kissimmee River in the north to Florida Bay in the south. Lake Okeechobee and its watershed are key components of KOE. The lake receives freshwater input from several streams, including the Kissimmee River, and sixteen other tributaries, such as Taylor Creek (Byrne and Wood 2011). Taylor Creek (TC) is a tributary to the lake and passes through both agricultural and residential areas. Treasure Island (TI) is a community to the east side of the creek and is currently using on-site sewage treatment and disposal (OSTD; aka septic tanks) systems to treat its wastewater effluent. This area has high ground water levels and pollution from septic effluents is increased (Paevy and Groves, 1978). The community to the west, Taylor Creek Isles (TCI), is being served mainly by a municipal vacuum sewer system with only a few remaining active septic tanks. The Taylor Creek area was the object of the present study which is aimed at discerning the extent of septic tank pollution which then eventually flows into Lake Okeechobee.

1.3 Non-Point Pollution Tracers

A wide variety of tracing methods have evolved to assess sources, directions, and quantities of sewerage pollution (Meeroff and Morin, 2005; Meeroff et al., 2014). "Transport Modelling" in which chloride (Cl^-), electrical conductivity, numerous groups of bacteria and viruses (biological tracing) has been reported (Alhajajar et al., 1988; Ahmed et al., 2006). The stable isotopes of carbon ($_6C^{13}$) and nitrogen ($_7N^{15}$) have been used to discriminate sewerage sources in a variety of ecosystems (Bicki et al., 1984; Lapointe and Krupa, 1995a-b; Belanger et al., 2007; Risk et al., 2008; Lapointe et al., 2015). Natural N-fixation source values are close to 0‰ (Heaton, 1986; France et al., 1998), atmospheric N typically ranges from -3‰ to +1‰ (Paerl and Fogel, 1994) and synthetic fertilizer N ranges from -2‰ to +2‰ (Bateman and Kelly, 2007). N sources are all N-15 depleted relative to enriched values of +3‰ to +19‰ for human sewage (Heaton, 1986; Costanzo et al., 2001). However, in areas that will have runoff contaminated with cow manure, having $d^{15}N$ values of +3 to +33 (Lee at al., 2011; Wong et al., 2018), the use of N-15 data to conclude human sewerage input is tenuous at best. Additional tracers that have been used include sulfur hexafluoride, fluorescein, rhodamine-WT, and a bacteriophage (Virus) PRD-1 (see Hardena et al., 2008 and references therein).

The compound sucralose (trade name Splenda) is almost ideal as a tracer. Sucralose is a very common food and beverage additive (Gloria, 2003; Gardner et al., 2012) and the vast majority passes through the human digestive tract without metabolism or absorption (Roberts et al., 2000). It is present in virtually every domestic wastewater discharge at detectable levels (10 to 40 parts per billion [ppb] ng/L), does not occur naturally, has low toxicity, is highly soluble in water, is not effectively metabolized or removed by wastewater treatment processes (Oppenheimer et al., 2011; Tran et al., 2014; Subedi and Kannan, 2014), is highly stable (Quinlan and Jenner, 2006), and persists in the environment with a 1- to 2-year half-life (Robertson et al., 2016). Sucralose does undergo some degradation at temperatures above 120°C (248°F: de Oliveira et al., 2015), well above any exposure in the environments considered herein. "DEP's monitoring of sucralose has helped identify sites for more intensive study, track contaminant migration routes in surface water and groundwater, and distinguish between abatable and non-abatable sites based on the impacts of human activities." (FDEP, 2019). Sucralose is being used in more foods, increasing the levels of sucralose exponentially (Soh et al., 2011; Malisova et al., 2015; Sylvetsky and Rother, 2016). Sucralose degradation through wastewater treatment facilities has also been demonstrated to be minimal in full-scale sewerage facilities and laboratory-scale aerobic biodegradation reactors (Neset et al., 2010; Torres et al., 2011). Sucralose has been shown to pass through septic tanks and their drainfields and into adjacent surficial waters

easily (Yang et al., 2017; Spoestra et al., 2020; Troxell et al., 2022). Since sucralose deteriorates at a slow rate in natural waters, it can be detected for far distances past the point of introduction (Buerge, et al., 2011; Troxell et al., 2022). Sucralose has been successfully used since 2012 in several local studies (Tarnowski, 2014) to pinpoint areas of OSTD systems. The only waters with measurable levels of sucralose were waters with anthropogenic waste introduction (Mawhinney et al., 2011). FDEP's monitoring of sucralose has helped track contaminant transport routes in surface and groundwater and identify sites for more intensive study for sites based on the impacts of human activities (FDEP, 2018). Furthermore, it should be evident that when monitoring other elements (nitrogen, phosphorus, etc.) in any given water column, definitive points of origin are most always difficult to detect whereas sucralose is directly associated with human consumption and excretion. Sucralose is not an additive in fertilizer nor is it found in the foods eaten by fish, otters, birds, or other animals in and around a typical Florida surface water body.

1.4 Purpose of the Present Study

The Okeechobee Utility Authority (OUA) initiated this study as a part of its consideration of and planning for the upgrade of the Treasure Island community to a municipal sewer system. This conversion, leading to the abandonment of septic tanks in the Treasure Island area has the high potential of reducing pollutants, notably nutrient (N, P), loads into the lake. To address this management and water quality concern, we designed and conducted a 14-month surface water quality-monitoring study which included 15 sampling sites. The purpose of this study was to investigate the impact of high-density (OSTD) septic systems along the canals located in the communities of the lower Taylor Creek area on water quality at the northern periphery of Lake Okeechobee. Using sucralose as an anthropogenic tracer, we investigated the septic derived non-point sourcing of nutrients that can feed the harmful algal (cyanobacterial) blooms in Lake Okeechobee and adjacent waters.

The data collected during the studies presented here was instrumental in the recent successful application to the State and Federal Governments for funding to the Okeechobee Utility Authority. These funds are earmarked for the installation of 2,430 new connections to municipal vacuum sewerage lines. This will eliminate the use of septic systems (OSTDS) in the Treasure Island and Taylor Creek Isles sections of lower Taylor Creek at the northern end of Lake Okeechobee and greatly decrease the input of nitrogen and phosphorus to Taylor Creek and Lake Okeechobee.

2. Methods

2.1 Area of Study and Sampling Sites

Figure 1 is a map of the state of Florida with an arrow directing the reader to an enlargement of Lake Okeechobee in Figure 2. Taylor Creek is highlighted in red and the area of study (The Treasure Island / Taylor Creek Isles subdivisions) is circled in red.

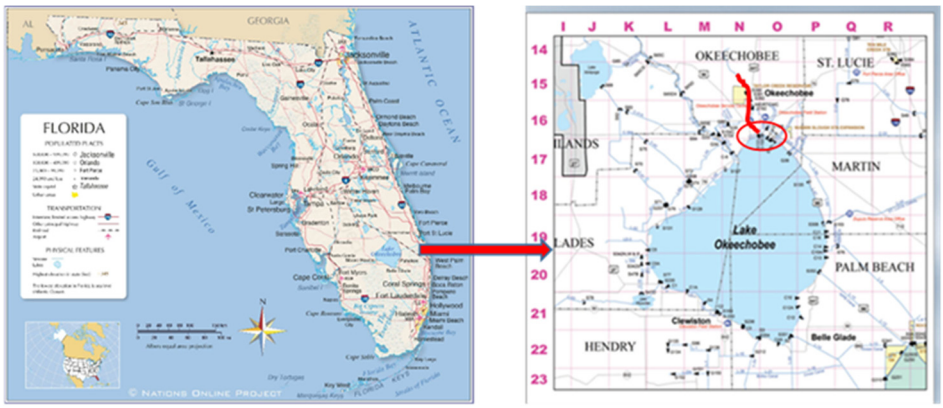

Figure 1 (left). Map of Florida. From Nations Online (www.nationsonline.org/oneworld/map/USA/florida_map.htm)

Figure 2 (right). Expansion of the Okeechobee City, Lake Okeechobee with Taylor Creek (red line) and The Treasure Island / Taylor Creek Isles area (red circle) indicated. S193 and S133 control structures at the southern end of Taylor Creek have Taylor Creek outflow into Lake Okeechobee. Map from South Florida Water Management website (www.sfwmd.gov)

Figure 3 is a Landsat image of the area of study, showing the sites we sampled. The abbreviations therein are: TC = Taylor Creek, TI = Treasure Isles, and TCI = Taylor Creek Isles.

Figure 3. Sampling sites along Taylor Creek (TC-1 to TC-3), Taylor Creek Isles (TCI-1 through TCI-6) and Treasure Island (TI-1 through TI-6). (Map from Google Earth. Data from Lansat/Copernicus)

Table 1 contains the latitudinal and longitudinal locations of the 15 sites studied. Latitude and longitude values were confirmed onsite with a Garmin #172 GPSMAP Global Positioning System.

Table 1: Site locations by Latitude and Longitude

Site	Latitude		Longitude
TC-1	27° 13' 20.12" N	x	80° 48' 36.49" W
TC-2	27° 13' 26.40" N	x	80° 48' 10.40" W
TC-3	27° 12' 32.83" N	x	80° 47' 53.19" W
TI-1	27° 13' 28.95" N	x	80° 47' 59.10" W
TI-2	27° 13' 11.39" N	x	80° 47' 52.39" W
TI-3	27° 13' 30.27" N	x	80° 47' 52.01" W
TI-4	27° 12' 55.48" N	x	80° 47' 39.77" W
TI-5	27° 12' 53.60" N	x	80° 47' 27.93" W
TI-6	27° 13' 11.48" N	x	80° 47' 08.69" W
TCI-1	27° 13'01.85" N	x	80° 48' 00.76" W
TCI-2	27° 12' 54.96" N	x	80° 48' 01.48" W
TCI-3	27° 12' 40.17" N	x	80° 48' 27.85" W
TCI-4	27° 12' 43.90" N	x	80° 48'17.27" W
TCI-5	27° 12' 44.02" N	x	80° 48' 04.43" W
TCI-6	27° 12' 54.80" N	x	80° 48' 29.38" W

Latitudes and longitudes from Google Maps

2.2 Sampling

Sampling was performed using a Coast Guard Auxiliary inspected 15-foot outboard motorboat which was equipped with a depth finder, GPS, and VHF radio. Water samples were collected at each site by submerging inverted critically cleaned and HPLC grade water triple rinsed 500 mL amber polypropylene rectangular bottles (Thermo-Scientific # 20090016) to a depth of 0.3 m and then rotating them to fill. The bottles were then placed on ice in a cooler for transport to the FAU lab for filtering within 4-6 hours of collection.

Duplicate water samples for sucralose analyses at each site were collected in similar fashion using 60 mL amber polypropylene bottles (Thermo-Scientific #3120850002). The sucralose samples were placed on ice in a separate (Styrofoam) cooler and frozen with 4-6 hours of collection. Frozen samples for sucralose analysis were shipped overnight by FedEx to the Environmental Research Analytical Laboratory (EARL) of Florida International University (FIU). Sucralose analysis procedures are given in a following section.

2.3 Analyses

On-site Ammonia was measured (HACH TNT830; 0.015-2.00 mg/L NH_3-N) on unfiltered waters samples using a HACH DR1900 portable spectrophotometer.

At the FAU laboratory, water was filtered through Whatman GF/F filters until just before clogging. The volume filtered was recorded and the filters were folded in half, blotted, reblotted, folded in quarters, reblotted, sealed in aluminum foil and frozen.

Pigments, for total chlorophyll determinations, were extracted according to Hagerthey et al. (2006). Ultraviolet visible absorption spectra of pigments were recorded on a Perkin-Elmer Lambda-2 spectrophotometer. Total chlorophyll-a was calculated using the SCOR-UNESCO equation (See Louda and Monghkonsri, 2004).

Primary plant nutrients, nitrogen and phosphorus, were analyzed in the filtrates. All tests utilized reagent kits from the HACH Chemical Company (www.hach.com). These were performed using a HACH DR5000 spectrophotometer and a digital reactor block (DRB200) for the total nitrogen and total phosphorus tests requiring heated digestion procedures. All tests are EPA certified and were verified (QA/QC) against the following NIST-traceable standards: Phosphate (1 mg/L #256949), Mixed parameter (PO_4 = 10/mg/L; NH_3 = 10 mg/L; NO_3 = 6 mg/L; TN = 7 mg/L: # LCA721), nitrate (10m/L #30749).

Total nitrogen was analyzed using the HACH TNT-826 reagent set which included a half-hour persulfate digestion at 120°C. Total phosphorus was analyzed using the HACH USEPA PhosVer 3 with acid persulfate digestion method kit (TNT-LR # 2742645) that included a half-hour digestion at 150°C. Soluble reactive phosphorus (SRP) was analyzed using the HACH phosphorus-reactive TNT-LR kit (#2742545).

Analyses of HACH NIST-traceable standards served to verify each test. Analyses of HACH deionized water (#27248) provided the zero reading and adjustment for method background readings, if needed. All tests performed well with R-squared values > 0.98 and y ~ 1.0x. It is noted here that the total nitrogen test is detailed by HACH Chemical Company to be valid only above 1.0 mg-N per liter.

Samples for sucralose analyses were shipped frozen and on-ice overnight with chain-of custody paperwork to the Environmental Research Analytical Laboratory (EARL) of Florida International University (FIU) in Miami Florida. At FIU-EARL multi-matrix ultra-trace analysis by SPE HPLC high-resolution mass spectrometry was performed. That procedure is based on the U.S. Geological Survey (USGS) method O-2060-01 and has a detection limit of 11 ng sucralose/L (Furlong et al., 2001 cf. Batchu et al., 2015; Loos et al., 2009).

3. Results

3.1 Sucralose

A preliminary 6-site sampling of the Taylor Creek area was performed in June of 2019. These sites and the sucralose data obtained are shown in Figure 4.

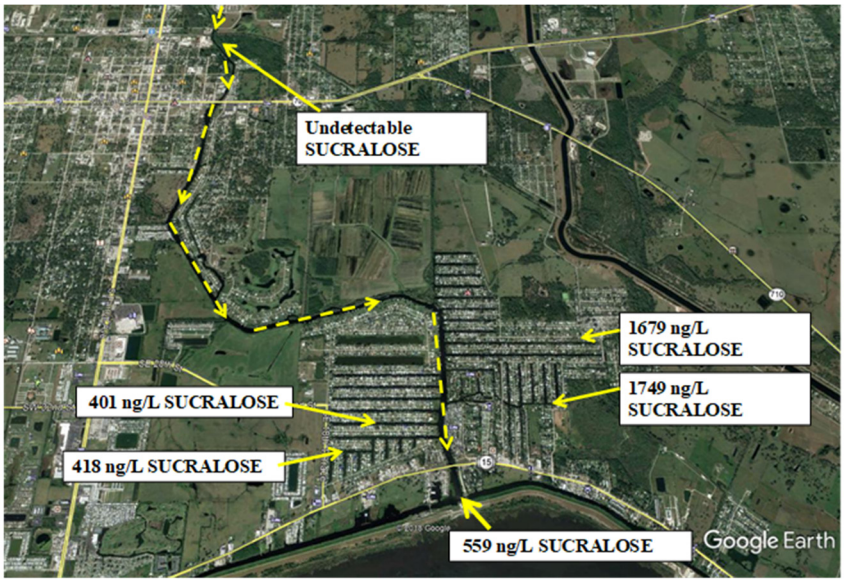

Figure 4. Map of the Taylor Creek area showing June 2019 preliminary sites and sucralose data. (Figure taken from Google Earth)

The main points to be concluded from this small study preceding the full 2019-2020 study are as follow: First, the Taylor Creek site north of Okeechobee City had sucralose below the 11ng/L detection level. Then as Taylor Creek flows south through Okeechobee City towards Lake Okeechobee it gains sucralose from the city of Okeechobee as well as both the Treasure Island (TI) and Taylor Creek Isles (TCI) sites. The TI sites, totally on septic systems (aka OSTDS), canals had sucralose levels nominally four-fold higher than the TCI sites that are mainly on municipal sewerage.

Following the preliminary study. we proceeded to the 14 month – 15 site study. As can discerned from the sucralose data plotted in Figure 5, the vast majority of sucralose in these areas were present in the canals at sites TI-4/-5/-6 with lower, yet still above Taylor creek values at TI-2/-3. Looking at Figure 3, one can surmise that the sucralose enrichment at the interiors Treasure Island sites (TI-4/-5/-6) flow into Taylor Creek via sites TI-2 and TI-3. The lowest overall sucralose concentrations were at Taylor Creek Isles sites TCI-3/-4/-6, the farthest from Taylor Creek itself and within the subdivision that is more than 90% on vacuum municipal sewerage. Immediately obvious is the fact that the inland Treasure Island canals are about five times (5x, 500%) as enriched in sucralose as are the Taylor Creek Isles canals. It then follows that other septic tank / drainfield leachates would also be enriched in the Treasure Island sites.

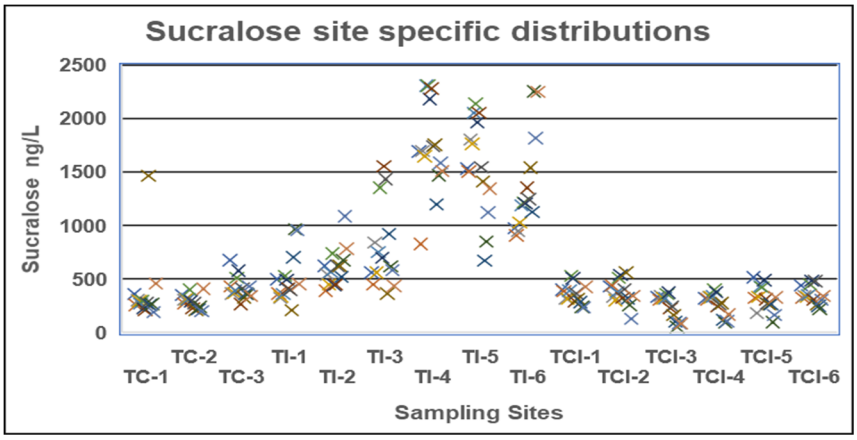

Figure 5. Sucralose contents in the 15 sites sampled. Each site has 14 data points

3.2 Total Nitrogen

Figure 6 is a plot of the total nitrogen (TN) in the canal waters at all sites during the 14 month study. Values ranged between 0.5 to 2.5 mg N/L with 3 anonymously higher (3.0-4.0 mg N/L) samples. Fertilizers and/or agricultural runoff may have been responsible for the higher values but that cannot be proven here.

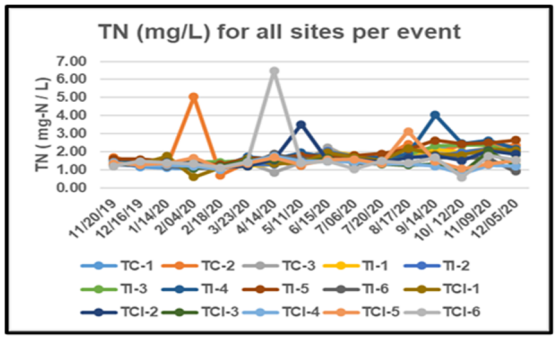

Figure 6. Plot of total nitrogen for all sites sampled

Examining the total nitrogen (TN) in the canals farthest away from Taylor Creek itself, we found that Treasure Island canals (Figure 7, left) had approximately 1.5 to 1.7 times (50 – 70 % more) of the amount of nitrogen as did the Taylor Creek Isles canals (Figure 7, right).

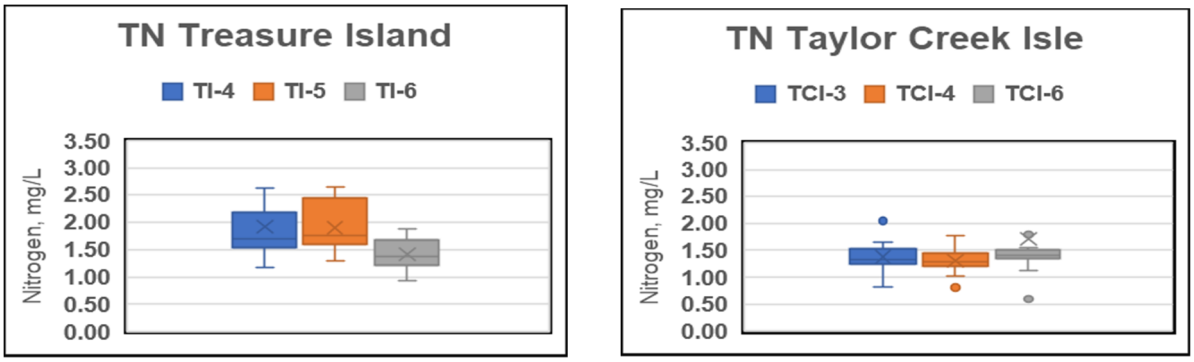

Figure 7. Box and whisker plots of total nitrogen for the sites to the east (TI, left) and west (TCI, right) for the full 14-month study

3.3 Phosphorus

As discerned from the data plotted in Figure 8, soluble reactive phosphorus (SRP) was found to be the major component of total phosphorus (TP) in all cases. The lowest phosphorous concentrations were detected during the warmer summer months, a period of much less tourist population and non-resident home occupation. The highest values correspond to the winter tourism seasons which also corresponds with the highest rains and septic drainfield leeching.

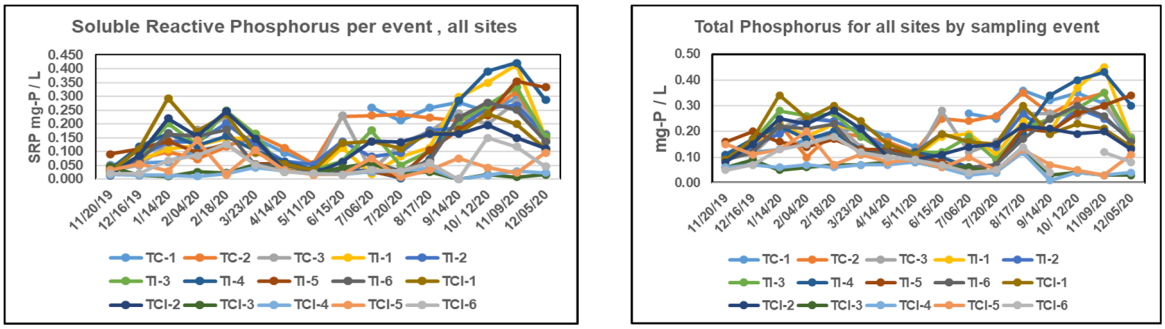

Figure 8. Total (left) and soluble reactive (right) phosphorous measured at all sites

Figure 9 contains box-and-whisker plots of the total phosphorous (TP) in the canal sites farthest from Taylor Creek itself (see Figure 2). On a yearly basis, TP values in the Treasure Island canals average two to four times those of the Taylor Creek Isles canals. Septic tank and drainfield leeching is taken as a significant source of phosphorus to these waterways which eventually flow into Taylor Creek and through water control structures into Lake Okeechobee.

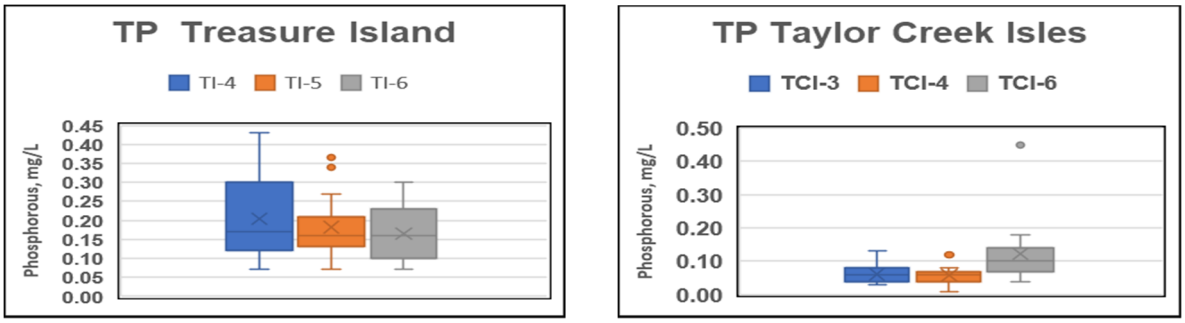

Figure 9. Total phosphorous (TP) plotted for the sites in each sub-division (TI, left and TCI, right) which are farthest from Taylor Creek itself (see Figure 2) for the full 14-month study

3.4 Ammonia

Figure 10 presents the ammonia concentrations for all sites throughout the 14-month survey. January 2020 lacks ammonia data due to an instrument failure. The elevated ammonia values around July and the Winter months correlates to increased rainfall.

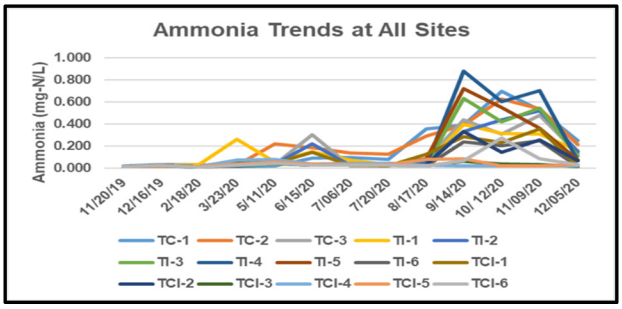

Figure 10. Plot of ammonia concentrations in all sites throughout the 14-month study. January 2020 lacks ammonia data

Heavy rains in the July and September through December 2020 period increased flushing of septic drainfields, as noted from the trends in Figure 10. Additionally, increased winter populations likely lead to increased septic tank utilization.

In Figure 11, we have restricted data to include only those sites that are deeper into each subdivision and thus well removed from Taylor Creek itself. This allows examination of the effect of runoff and leeching without the mixing (averaging) effects of Taylor Creek.

Figure 11a reveals that the Treasure Island sites have higher year-round ammonia concentrations as compared to Taylor Creek Isles sites (Fig. 11b).

Examining these sites during the heavier rains of September through December 2020 (https://www.sfwmd.gov/science-data/dbhydro), it becomes clear that the Treasure Island sites leech significant quantities of ammonia from septic tank drainfields (Fig. 11c). Values were from 0.2 to 0.9 mg ammonia per liter. During these heavy rain periods the Taylor Creek Isles canals (Fig. 11d) had very low ammonia. Besides providing nitrogen as a nutrient for algal growth, ammonia is quite detrimental to aquatic organisms such as fish (McKenzie et al., 2008; Milne et al., 2017).

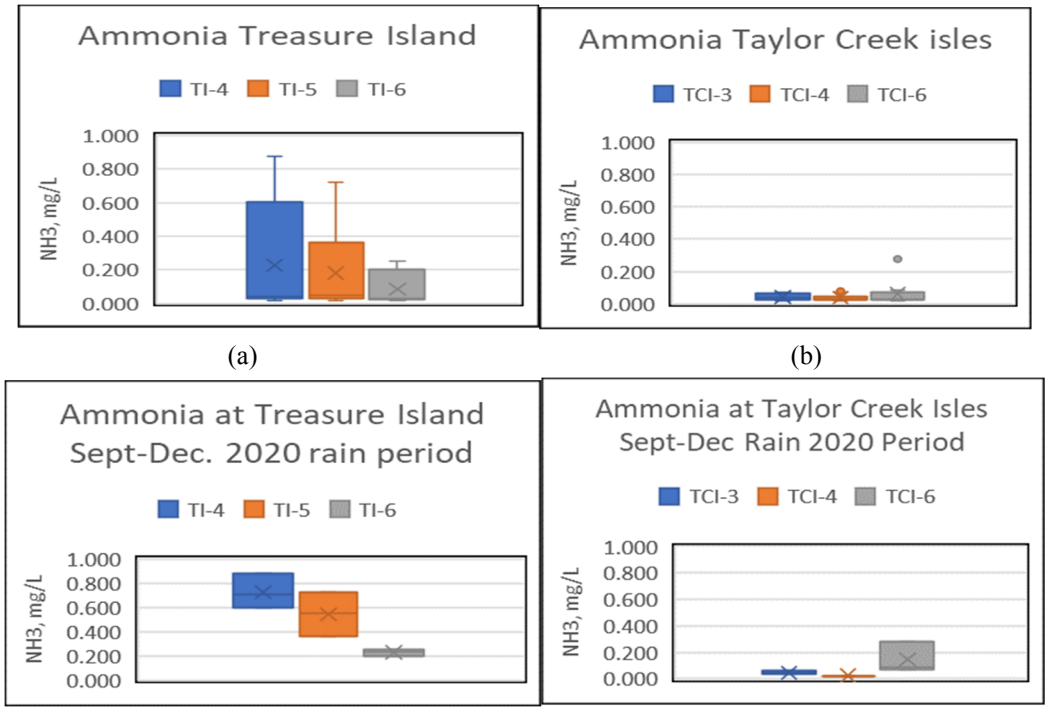

Figure 11. Box and whisker plots of the ammonia concentrations in the sites of Treasure Island and Taylor Creek Isles which ae well removed from Taylor Creek itself. (a & b) Overall data for the full 14-month study. (c & d) Data from these sites restricted to the heavy rain period of September through December 2020

4. Discussion

In the present study, considering the sites away from Taylor Creek proper (i.e. TI-4/-5/-6 and TCI-3/-4/-6), it was found that that the *Treasure Island canals had 5.3 times the mean concentration of sucralose relative to the Taylor Creek Isles canals*. This is based on the mean concentrations in TI (1,646 + 223.4 ng/L) and TCI (313+ 44.1 ng/l). Sites in the TI (TI-1/-2/-3) and TCI (TCI-1/-2/-5) areas close to Taylor Creek itself reflected their respective drainages mixing with TC waters. Taylor Creek 'reference' sites (TC-1/-2), those before encountering TI or TCI drainage, had a mean sucralose concentration of 280 + 57.8 ng/L). After traveling through the TI / TCI area, the TC site closest to Lake Okeechobee (TC-3) had a mean sucralose concentration of 426+ 113.2 ng/L, reflecting a 52% increase in sucralose.

During and following the heavy saturating rains of September-October 2020, strong increases in soluble reactive phosphorus (SRP) and ammonia were recorded for the inland Treasure Island sites (TI-4-/5-/-6). This is taken as an indication that drainfields from corresponding septic tanks were flushed through soils and into the canals more rapidly than during drier periods. The *Treasure Island sites away from Taylor Creek had 2.25 times (125% more) the total phosphorus and 1.20 times (20% more) the total nitrogen compared to the Taylor Creek isles sites.*

The data and conclusions derived from the present study aided the Okeechobee Utility Authority in securing state funding in the amount of $ 24,500,000.00 towards the full cost of $32,000,000.00 for the conversion of 2,200 – 2,400 units in the Treasure Island subdivision from septic systems to vacuum municipal sewerage system. Design and construction are completed within 24-36 months. This conversion will undoubtedly lead to a decrease in surface water nutrient pollution and additional monitoring in the future will take place.

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