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Nutrient inputs from an urbanized landscape may drive water quality degradation

Elizabeth W. Stoner[a,b,*], D. Albrey Arrington[b]

[a] Department of Natural and Applied Sciences, Bentley University, 175 Forest Street, Waltham, MA 02452, USA
[b] Loxahatchee River District, 2500 Jupiter Park Drive, Jupiter, FL 33458, USA

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ABSTRACT

Estuaries are increasingly affected by deteriorating water quality associated with a burgeoning human population. As such, there is a need to establish water quality baselines and elucidate whether shifts in water quality are attributed to anthropogenic activities or the dynamic nature of estuaries. Here we investigate an extensive water quality dataset collected from 2006 to 2015 within the Loxahatchee River, Florida watershed. Results indicate substantial spatial variation in water quality within the watershed, though most locations were in line with established state water quality standards. Chlorophyll *a* state nutrient criteria had the greatest number of exceedances over the period of record in brackish and marine river regions, while freshwater regions exhibited the most variable water quality conditions overall. Water quality appears to be largely influenced by suburban stormwater runoff, septic tank effluent, and relic row crop agricultural practices, though more work is required to identify point and non-point sources of nutrient loading. Most sites were phosphorus-limited, likely as an indirect result of anthropogenic activities, phosphorus adsorption to carbonate sediments, and freshwater phosphorus limitation. Systematic water quality monitoring efforts are critical to help resource managers improve the ecological integrity of estuaries.

1. Introduction

The ecological integrity of estuarine ecosystems is a primary concern as global environmental change intensifies (Vitousek et al., 1997; Worm et al., 2006; Jackson, 2008; Rabalais et al., 2009; Cloern et al., 2016). Anthropogenic disturbances including habitat modification, eutrophication, fragmentation, flood control, overexploitation of plants and animals, and introduction of non-native taxa, have all fundamentally affected estuarine and coastal marine ecosystems (Jackson, 2001, 2008; Kennish, 2002; Nilsson et al., 2005; Lotze et al., 2006; Worm et al., 2006; Diaz and Rosenberg, 2008; Rabalais et al., 2009). These disturbances often occur concomitantly and cause biodiversity loss, population declines, and shifts in valuable ecosystem services and functions (Vitousek et al., 1997; Jackson, 2001; Worm et al., 2006; Barnosky et al., 2012).

Estuarine ecosystems exhibit strong environmental gradients and are highly variable in space and time, making losses of biodiversity and ecosystem function difficult to identify (Villnäs and Norkko, 2011). It has become increasingly important to

* Corresponding author at: Department of Natural and Applied Sciences, Bentley University, 175 Forest Street, Waltham, MA 02452, USA.
E-mail address: estoner@bentley.edu (E.W. Stoner).

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quantify baseline water quality, including natural range of variability in estuaries compared to changes associated with anthropogenic activities (Boyer et al., 1997; Duarte et al., 2009; Villnäs and Norkko, 2011). Environmental monitoring programs can help identify the occurrence of shifting baselines in estuarine ecosystems and elucidate changes in spatial and temporal patterns (Boyer et al., 1997; Duarte et al., 2009), ultimately informing ecosystem-based management (Thrush and Dayton, 2010) and strategizing restoration efforts.

Over the last 60 years, the Loxahatchee River estuary, a subtropical, carbonate geologic system at the southern terminus of the Indian River Lagoon estuary in Martin and Palm Beach counties, Florida, has been increasingly influenced by anthropogenic activities, including nutrient loading and hydrologic regime shifts (i.e., channelization, flood control, and the regular dredging of the Jupiter Inlet) (McPherson and Sabanskas, 1980; VanArman et al., 2005). The Loxahatchee River drains a 435 km^2 watershed to the Atlantic Ocean through the Jupiter Inlet (VanArman et al., 2005). West of the Jupiter Inlet, the river widens into a large, centralized embayment that receives flow from three main tributaries: the Northwest Fork, North Fork, and Southwest Fork (South Florida Water Management District, 2006). The Northwest Fork is classified as having variable freshwater flows that differ substantially between the summer wet season and the winter dry season. The North Fork and Southwest Fork are more broadly classified as brackish systems. During very wet periods, excess freshwater is discharged from canal C-18 through the S-46 flood control structure into the Southwest Fork. In 1985, a 10.3 mile stretch of the Northwest Fork was designated as Florida's first national Wild and Scenic river, which is also an Outstanding Florida Waters and Aquatic Preserve (Florida Department of Environmental Protection and South Florida Water Management District, 2010). The Florida Department of Environmental Protection (DEP) has divided the river into nine different segments (‘‘regions") that vary in abiotic (e.g., salinity) and biotic (e.g., seagrass presence) characteristics. These include: marine waters, polyhaline waters, meso/oligohaline waters, the Wild and Scenic portion of the river, freshwater tributaries, freshwater canals, the Southwest Fork, the Intracoastal waterway-north (ICW-N), and the Intracoastal waterway-south (ICW-S).

The marine region of the river is driven by proximity to the ocean and strongly influenced by physical and chemical conditions of nearshore ocean waters. The polyhaline region is affected by freshwater flowing downstream from the Northwest Fork and saltwater flowing upstream from the inlet; however, during extremely wet periods the polyhaline region can be entirely driven by flood control releases passing through the Southwest Fork. The meso/oligohaline region is affected predominantly by freshwater flowing down the Northwest Fork, which includes flow over Lainhart Dam, tributary flow (Cypress Creek, Hobe Grove Ditch, and Kitching Creek) and substantial groundwater inputs (Swarzenski et al., 2006). Cypress Creek and Kitching Creek drain the largest expanses of natural lands within the watershed, while Hobe Grove Ditch drains the largest extent of active agricultural fields remaining in the watershed. The Wild & Scenic region is characterized by freshwater inputs from canal C-18 (hereafter referred to as the C-18). The C-18 is ~8 km long and provides flood control relief to southern and western portions of the watershed and receives flow from expansive undeveloped lands (e.g., Loxahatchee Slough, Grassy Waters preserve). During wet periods, the C-18 receives runoff from Jupiter Farms, a 15 square miles rural community that discharges base flow and stormwater runoff to the C-14 canal, and ultimately the Northwest Fork of the Loxahatchee River. The freshwater canal region represents a collection of disparate waterbodies, including ditches in Jupiter Farms and rural areas north and west of Jonathan Dickinson State Park. All of the freshwater canal sites, excluding C-18, are characterized as shallow drainage ditches. Under normal conditions, the Southwest Fork region is affected by inputs from Jones and Sims Creeks, which drain suburban landscapes, but under wet conditions is dominated by flood control releases from the C-18. The ICW-S region is affected by runoff from suburban coastal developments, while the ICW-N region receives significant flushing from marine waters and receives very little direct stormwater runoff.

The Loxahatchee River is encompassed by a diverse number of habitats including freshwater wetland, upland, riverine, estuarine, and marine environments (VanArman et al., 2005). The freshwater component of the river contains cypress communities, which provides refuge to a number of birds, mammals and reptiles (VanArman et al., 2005). The estuarine component of the river contains oyster reefs and seagrass beds, including the endangered Johnson's seagrass (*Halophila johnsonii* Eiseman) (Kenworthy, 1992). These ecosystems serve as important habitat for a number of species including the West Indian Manatee (*Trichechus manatus*), juvenile green sea turtle (*Chelonia mydas*), and commercially valuable fisheries such as snapper (*Lutjanus* spp.) and Florida stone crab (*Menippe mercenaria*). These ecosystems also help maintain ecosystem functioning via nutrient cycling, water filtration, and sediment stabilization (VanArman et al., 2005; Layman et al., 2014). Additionally, water discharged from the river enters the Indian River lagoon and nearshore coral reefs (VanArman et al., 2005). Deteriorating water quality stemming from issues related to the urbanization of the watershed and freshwater inflow with concomitant changes to salinity have driven shifts in cypress, seagrass, and oyster bed community composition and ecosystem function, highlighting a need for effective resource management and restoration (VanArman et al., 2005; Roberts et al., 2008; Parker et al., 2013).

Extensive water quality monitoring is a fundamental first step in establishing baseline water quality conditions and elucidating how anthropogenic activities influence the ecological integrity of a system, yet few peer-reviewed studies of water quality in the Loxahatchee River estuary exist (but see McPherson and Sonntag, 1984). Herein, we describe spatial water quality trends from a multi-parameter water quality monitoring dataset from the Loxahatchee River over the last decade, identifying areas of concern that may benefit from targeted efforts to improve water quality.

2. Materials and methods

2.1. Study area and water quality sampling

Water samples were collected at approximately 48 sites located in the Loxahatchee River, its major tributaries, and associated waters from June 2006 to September 2015 for a total of 53, 692 samples. Thirty-eight of the sites are sampled bi-monthly (every other month), while 10 stations are sampled monthly (Fig. 1). At each water quality monitoring station, physical water quality conditions including temperature, pH, conductivity, salinity, and dissolved oxygen (DO) were evaluated using a Hydrolab© multiprobe at the surface (30 cm depth), and where water depth exceeded 30 cm, at mid-depth and within 20 cm of the bottom. A secchi disk was used to assess water clarity at each station, and total water depth was recorded.

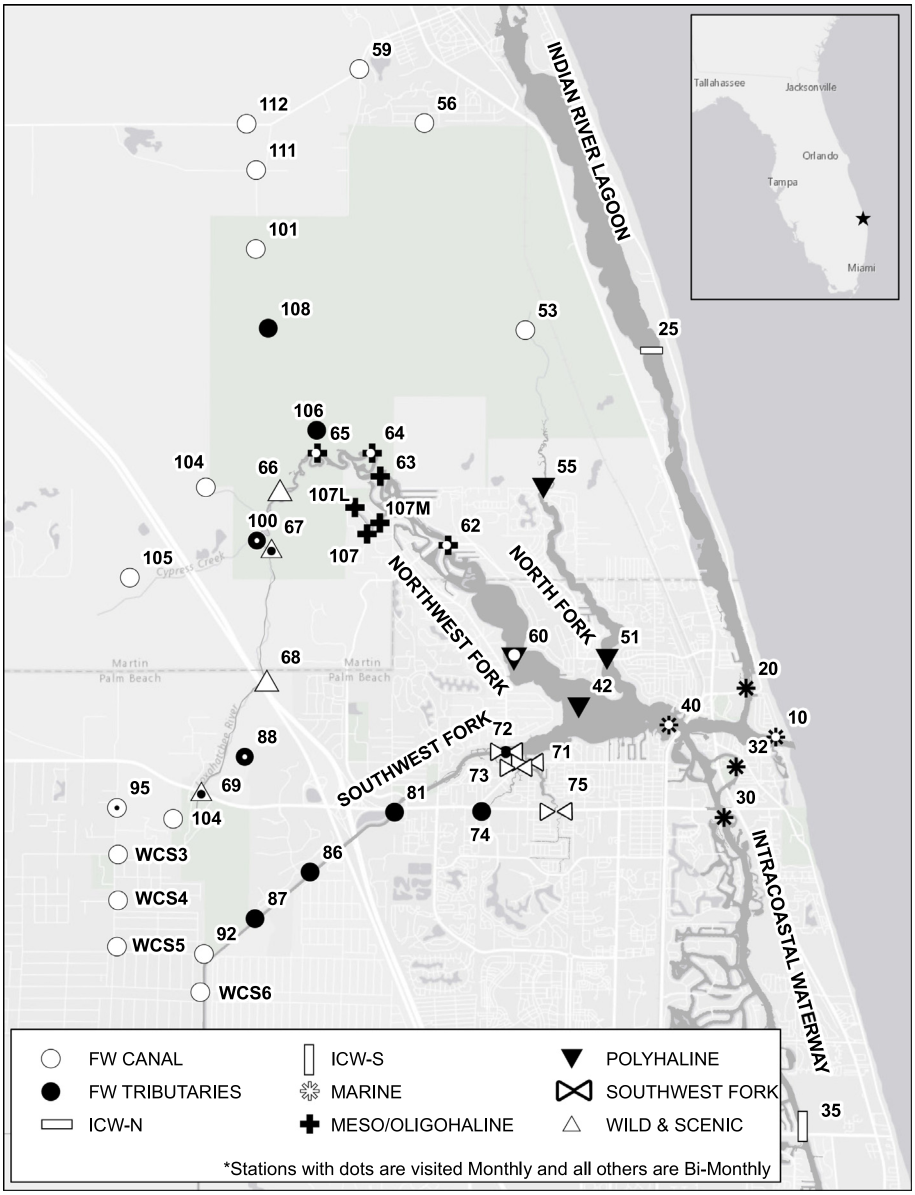

Fig. 1. Map of the Loxahatchee River watershed showing RiverKeeper water quality stations and their respective identification numbers. Different shapes represent the corresponding river region, and stations with a dotted symbol are visited monthly.

Water samples were collected from 10 cm below the surface using acid-washed HDPE plastic sampling bottles. These samples were analyzed for chlorophyll *a* (Chl *a;* standard method SM10200H), total organic carbon (TOC; standard method SM5310B), total nitrogen (TN = TKN+NO_2 + NO_3), total kjeldahl nitrogen (TKN; standard method EPA351.2), nitrate + nitrite (NO_2^- + NO_3^-; standard method EPA353.2), total phosphorus (TP; standard method SM4500-P E), turbidity (NTU; standard method EPA180.1), total suspended solids (TSS; standard method SM2540D), true color (PCU; standard method SM20120B), fecal coliform bacteria (cfu/100 ml; standard method SM10200H), and dissolved inorganic nutrients [orthophosphate (PO_4^{3-}; standard method SM 4500-P F) and ammonia (NH_3; standard method SM4500-NH3G)]. Samples collected for NO_2^- + NO_3^-, PO_4^{3-}, and true color were field filtered using Whatman© 0.45 μm membrane filters prior to analysis to remove particulate matter; water was filtered into 250 ml HDPE bottles and immediately placed on ice. Samples were refrigerated at 4 °C and analyzed within 48 h using a Lachat Flow Injection Analyzer. Water samples for NH_3, TKN, and TP were field-preserved to pH < 2.0 with sulfuric acid and transported on ice. Samples were refrigerated at 4 °C and analyzed within 28 days.

For NH_3 samples, all suspended solids and other potential sources of interference were removed through a distillation process and organic sources of nitrogen were converted to ammonium sulfate through a digestion process for TKN samples. Once samples were prepared, ~10 ml of sample for each analyte was transferred to a glass cuvette and analyzed via Lachat Flow Injection Analyzer. Chlorophyll *a* samples were collected in amber 2 L HDPE bottles, placed on ice, and filtered in dark conditions using Whatman© 0.47 mm diameter glass microfiber filters, then analyzed. Total organic carbon samples were collected in duplicate 40 ml glass vials and preserved with 1:1 hydrochloric acid. Fecal coliform bacteria were sampled to quantify bacterial load and indicate the potential for human health impacts; samples were collected using sterile Idexx© bottles using membrane filtration (0.45 μM pore size) and immediately placed on ice and transported back to the lab. Samples were analyzed within 8 h. Sample collection and field testing activities were performed in accordance with DEP Standard Operating Procedures for Field Activities (DEP-SOP-001/01, March 1, 2014).

2.2. Data analysis

In this study, we evaluated possible exceedances of TN, TP, and chlorophyll *a* across all site locations by computing their annual geometric means for the entire period of record (POR) and comparing them to Florida Department of Environmental Protection (DEP) and Environmental Protection Agency (EPA) Numeric Nutrient Criteria (hereafter NNC), which are state criteria for water quality thresholds. NNCs are computed as annual geometric means to reduce the potential influence of extreme temporal variation (i.e., from storm events) in water quality, and are used to maintain or achieve the desired health of a waterbody. Nutrient values may not exceed the NNC for any given river region more than once in a three-year period. In the Loxahatchee River, NNCs were established from 2013 to 2014 using a "reference period approach" in which data from the various river regions were evaluated from a period of time in which those regions were shown to be "healthy" or "unimpaired" (Florida Department of Environmental Protection Report to the Governor and Legislature, 2013). Fecal coliform bacteria concentrations are reported in context of bacteriological quality standards as provided by the EPA (Florida Department of Environmental Protection Chapter 62-302 Surface Water Quality Standards, 2010). All sampling protocol and lab analyses during the reporting period were in accordance with National Environmental Laboratory Accreditation (NELAC) requirements.

To understand the underlying spatial patterns in the distribution of the measured parameters from the Loxahatchee River, box and whisker plots were created following Caccia and Boyer, 2005. Outliers were suppressed to reduce figure compression. Pearson bivariate correlations were run between TN, TP, and chlorophyll *a* concentrations to assess nutrient limitation in the river (IBM SPSS V. 23.0). Additionally, to explore N and P limitation in the Loxahatchee River, molar TN:TP ratios were calculated for all water quality stations. Nutrient limitation in aquatic systems may be determined by several geochemical (e.g., sediment redox potential) and biotic (e.g., food web structure) factors that can influence the supply of N and P availability and nature of limitation in a given system (Elser et al., 2007). In the Loxahatchee River, nutrient limitation and water quality is likely to be determined in part by whether the river region is characterized by fresh, marine, or brackish water. To this end, we employed separate linear regressions with salinity as the predictor, and nutrient concentrations (TN, TP, nitrate-nitrite), chlorophyll *a*, color, and molar TN:TP as response variables (IBM SPSS v.23.0). Potentially affected river regions could then be assessed by determining which stations fell above the predicted salinity gradient and have elevated nutrient concentrations relative to upstream and downstream sources, indicative of localized nutrient loading.

3. Results

3.1. Overall water quality

The Loxahatchee River is a longitudinal system with opposing, dynamic forces acting on each end, i.e., freshwater flow from upstream and marine inputs from downstream. These forces create predictable spatial patterns in physical and chemical characteristics across the landscape (Table 1, Fig. 2). Overall, the Loxahatchee River is a warm and largely estuarine environment with a mean temperature of 25 ± 3.7 °C and mean salinity (across all regions) of 17.3 ± 14.4. Generally, freshwater conditions dominate upstream (river miles 16 to 9), marine conditions dominate downstream (river miles 1.5 to 0), and

Table 1
Mean (±SD) values for all physical parameters for 2006–2015 broken out by river region and season. Minimum-maximum ranges are given as raw data values across both seasons.

Region/Season	Temperature (°C)	Salinity (ppt)	Dissolved Oxygen (mg/L)	pH	Color (PCU)	Turbidity (NTU)	TSS (mg/L)	TOC (mg/L)
Marine								
Dry (*n* = 3207)	23.0 ± 1.9	33.9 ± 3.7	6.6 ± 0.6	7.9 ± 0.1	13.2 ± 11.8	3.3 ± 4.6	7.4 ± 8.7	2.4 ± 1.1
Wet (*n* = 3197)	28.1 ± 1.5	32.4 ± 4.8	5.9 ± 0.8	7.9 ± 0.1	16.2 ± 15.5	2.2 ± 2.4	5.2 ± 4.9	3.3 ± 2.0
Min-Max	16.8–31.9	7.0–39.5	0.7–8.6	7.2–8.4	2.5–100.0	0.1–52.6	0.6–120.0	0.5–13.0
ICW-N								
Dry (*n* = 569)	22.2 ± 2.0	33.6 ± 3.9	6.7 ± 0.7	7.9 ± 0.1	12.9 ± 11.5	3.2 ± 1.6	6.9 ± 4.1	2.5 ± 1.2
Wet (*n* = 574)	28.4 ± 1.7	33.5 ± 3.2	6.0 ± 0.6	7.9 ± 0.1	10.0 ± 6.0	2.0 ± 1.1	5.0 ± 2.9	2.3 ± 0.96
Min-Max	17.6–31.8	21.1–38.0	3.1–8.8	7.2–8.3	2.5–50.0	0.5–7.6	1–24.5	1.1–7.0
ICW-S								
Dry (*n* = 569)	22.2 ± 1.9	30.2 ± 4.4	6.1 ± 0.7	7.7 ± 0.2	19.4 ± 14.2	2.5 ± 1.1	6.1 ± 4.3	3.3 ± 1.0
Wet (*n* = 583)	29.1 ± 1.6	28.4 ± 4.6	5.2 ± 0.7	7.7 ± 0.1	22.2 ± 14.7	2.0 ± 0.7	4.5 ± 2.8	4.5 ± 2.3
Min-Max	16.4–32.0	14.6–35.9	3.0–7.8	7.0–8.2	5.0–65.0	0.6–6.0	1–20.3	2.0–8.7
Polyhaline								
Dry (*n* = 2749)	22.5 ± 2.4	28.3 ± 8.1	6.4 ± 0.8	7.8 ± 0.3	40.6 ± 47.8	3.2 ± 1.4	6.4 ± 5.1	5.1 ± 2.6
Wet (*n* = 2803)	28.3 ± 1.6	25.4 ± 9.5	5.3 ± 1.0	7.7 ± 0.3	70.5 ± 88.7	3.1 ± 1.5	5.7 ± 3.7	8.6 ± 4.3
Min-Max	14.2–32.8	0.2–38.8	1.5–8.6	5.8–8.4	5.0–800.0	0.8–9.2	1–43.5	1.2–25.0
Southwest Fork								
Dry (*n* = 2046)	22.4 ± 2.6	26.4 ± 7.2	5.8 ± 1.4	7.6 ± 0.2	31.0 ± 17.6	3.7 ± 2.1	6.8 ± 4.5	5.8 ± 2.3
Wet (*n* = 2048)	28.7 ± 1.6	22.8 ± 9.4	4.6 ± 1.5	7.6 ± 0.2	47.7 ± 27.5	3.7 ± 2.4	6.3 ± 4.3	8.8 ± 3.2
Min-Max	15.5–32.6	0.4–37.6	0.4–9.8	6.3–8.2	5.0–150.0	0.8–26.0	1–26.0	2.8–17.0
Meso/Oligohaline								
Dry (*n* = 4557)	21.7 ± 2.5	10.1 ± 8.6	5.5 ± 1.2	7.4 ± 0.2	51.8 ± 22.9	2.5 ± 1.1	4.1 ± 2.7	11.5 ± 2.9
Wet (*n* = 4547)	28.0 ± 1.8	7.6 ± 8.1	4.2 ± 1.1	7.3 ± 0.2	76.8 ± 44.2	2.6 ± 1.6	4.0 ± 2.7	13.9 ± 3.8
Min-Max	14.1–34.1	0.05–31.8	0.1–8.8	5.8–8.2	10.0–300.0	0.4–23.1	0.5–30.6	2.0–31.0
FW Tributaries								
Dry (*n* = 2179)	21.4 ± 2.6	0.53 ± 0.9	6.2 ± 1.8	7.5 ± 0.3	65.7 ± 36.5	2.7 ± 2.0	4.0 ± 2.9	14.3 ± 3.9
Wet (*n* = 2294)	27.8 ± 2.1	0.43 ± 0.9	4.6 ± 1.9	7.3 ± 0.4	89.8 ± 70.3	3.0 ± 2.5	4.7 ± 5.1	15.6 ± 4.8
Min-Max	13.1–33.7	0.07–11.0	0.28–13.3	5.9–8.5	13.0–450.0	0.3–23.4	0.5–53.6	2.0–37.0
FW Canals								
Dry (*n* = 3710)	20.9 ± 2.8	0.36 ± 0.1	4.7 ± 2.4	7.1 ± 0.4	84.1 ± 69.5	3.6 ± 3.7	5.2 ± 6.5	14.5 ± 6.2
Wet (*n* = 3800)	27.3 ± 2.0	0.31 ± 0.1	3.1 ± 2.0	7.0 ± 0.4	104.1 ± 86.0	4.5 ± 6.1	6.1 ± 10.0	16.1 ± 7.1
Min-Max	11.1–32.2	0.06–0.9	0.04–13.7	5.4–8.8	10.0–500.0	0.3–63.9	0.3–115.0	1.0–53.0
Dry (*n* = 569)	22.2 ± 2.0	33.6 ± 3.9	6.7 ± 0.7	7.9 ± 0.1	12.9 ± 11.5	3.2 ± 1.6	6.9 ± 4.1	2.5 ± 1.2
Wet (*n* = 574)	28.4 ± 1.7	33.5 ± 3.2	6.0 ± 0.6	7.9 ± 0.1	10.0 ± 6.0	2.0 ± 1.1	5.0 ± 2.9	2.3 ± 0.96
Min-Max	17.6–31.8	21.1–38.0	3.1–8.8	7.2–8.3	2.5–50.0	0.5–7.6	1–24.5	1.1–7.0
Wild and Scenic								
Dry (*n* = 2222)	21.2 ± 2.6	0.35 ± 0.31	5.6 ± 1.2	7.4 ± 0.3	53.5 ± 16.1	2.1 ± 1.6	2.9 ± 1.8	13.3 ± 2.1
Wet (*n* = 2225)	27.6 ± 1.7	0.35 ± 0.54	4.0 ± 1.2	7.3 ± 0.2	70.0 ± 30.5	2.2 ± 2.2	3.5 ± 4.8	14.7 ± 2.9
Min-Max	14.0–31.2	0.1–4.6	0.6–8.9	6.2–8.5	12.0–180.0	0.1–27.4	0.5–30.6	2.0–24.0

highly variable estuarine conditions occur in the middle of the river system (river miles 9 to 1.5). Mean DO was 5.2 ± 1.7 mg/L, or ~69% saturation; freshwater canals had both the highest and lowest reported DO concentrations over the period of record (0.04 mg/L and 13.7 mg/L, respectively; Table 1, Fig. 2B). Water clarity was generally quite high across all sites with a mean turbidity of 3.0 ± 3.1 NTU, mean color of 60.1 ± 58.5 PCU, and mean TOC concentrations of 10.8 ± 6.4 mg/L. Turbidity, color, and TOC were lowest in the marine portion of the river (0.1 NTU, 2.5 PCU, and 0.5 mg/L, respectively), and were highest in freshwater canals (63.9 NTU, 500 PCU, and 53 mg/L, respectively; Table 1, Fig. 2C, D, F).

3.2. Nitrogen and phosphorus parameters

Nutrient concentrations also exhibited predictable spatial variation across sampling locations (Fig. 3), though seasonal differences in N and P were less pronounced than seasonal shifts in physical parameters (Table 2). Overall, N and P were highest in freshwater tributaries and canals, and lowest in the marine and ICW-N portion of the river. Nonetheless, the minimum TN concentration observed during the period of record occurred in the large freshwater canal C-18. Salinity appears to be a driver of TN concentrations (Fig. 4A), though certain river regions demonstrated elevated total nitrogen concentrations compared to other water quality stations with the same salinity values, suggestive of possible localized nutrient loading. Approximately 23% of all RiverKeeper stations violated NNCs for TN at least once, though only 10% of the stations violated NNCs three times or more over the POR. Specifically, freshwater canals in the northeast portion of the watershed (stations 56, 59, 101, 111, and 112) routinely exceeded NNC, with all five sites exceeding the TN NNC three or more years over the POR

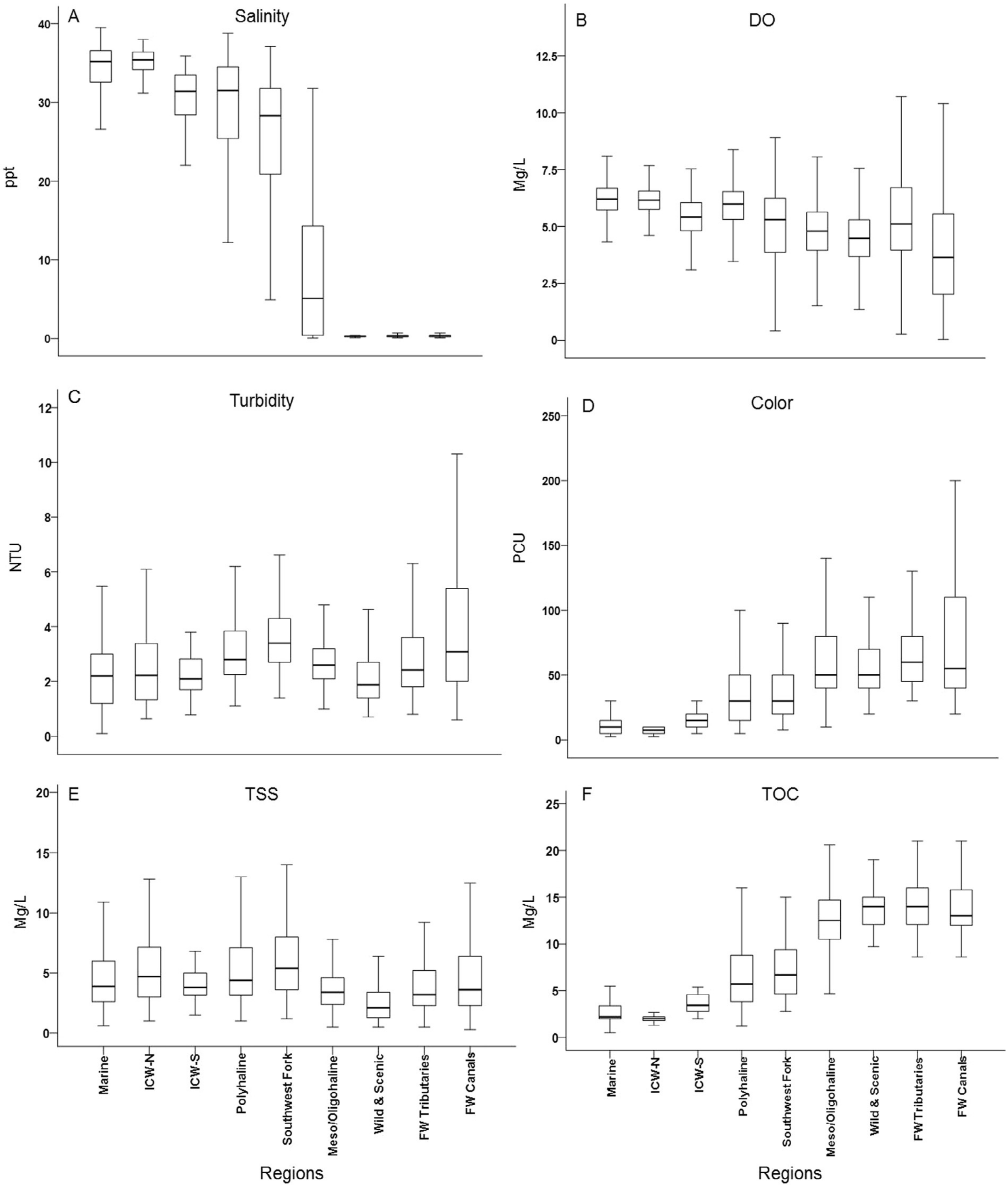

Fig. 2. Physical parameter data across pooled across the period of record (2006–2015) for each river region of the Loxahatchee River. Parameters are A) salinity (ppt), B) dissolved oxygen (mg/L), C) turbidity (NTU), D) color (PCU), E) total suspended solids (mg/L), and F) total organic carbon (mg/L). The center horizontal line of the box is the median of the data, while the top and bottom of the box represent the 25th and 75th percentile, respectively. The top and bottom of the whiskers represent the 5th and 95th percentile, respectively.

(Fig. 5A). Stations 56 and 59 exceeded NNCs 100% and 80% of the time, respectively (Fig. 5A). Mean TKN concentrations averaged 0.88 ± 0.51 mg-N/L; freshwater canals had both the highest and lowest reported values (0.10 and 4.7 mg-N/L, respectively; Fig. 3B). Mean NH_3 levels averaged 0.08 ± 0.08 mg-N/L; freshwater canals had the highest reported values (0.12 ± 0.11 mg-N/L) and the ICW-N had the lowest reported values (0.04 ± 0.01 mg-N/L; Fig. 3C). Mean $NO_2^- + NO_3^-$ concentrations

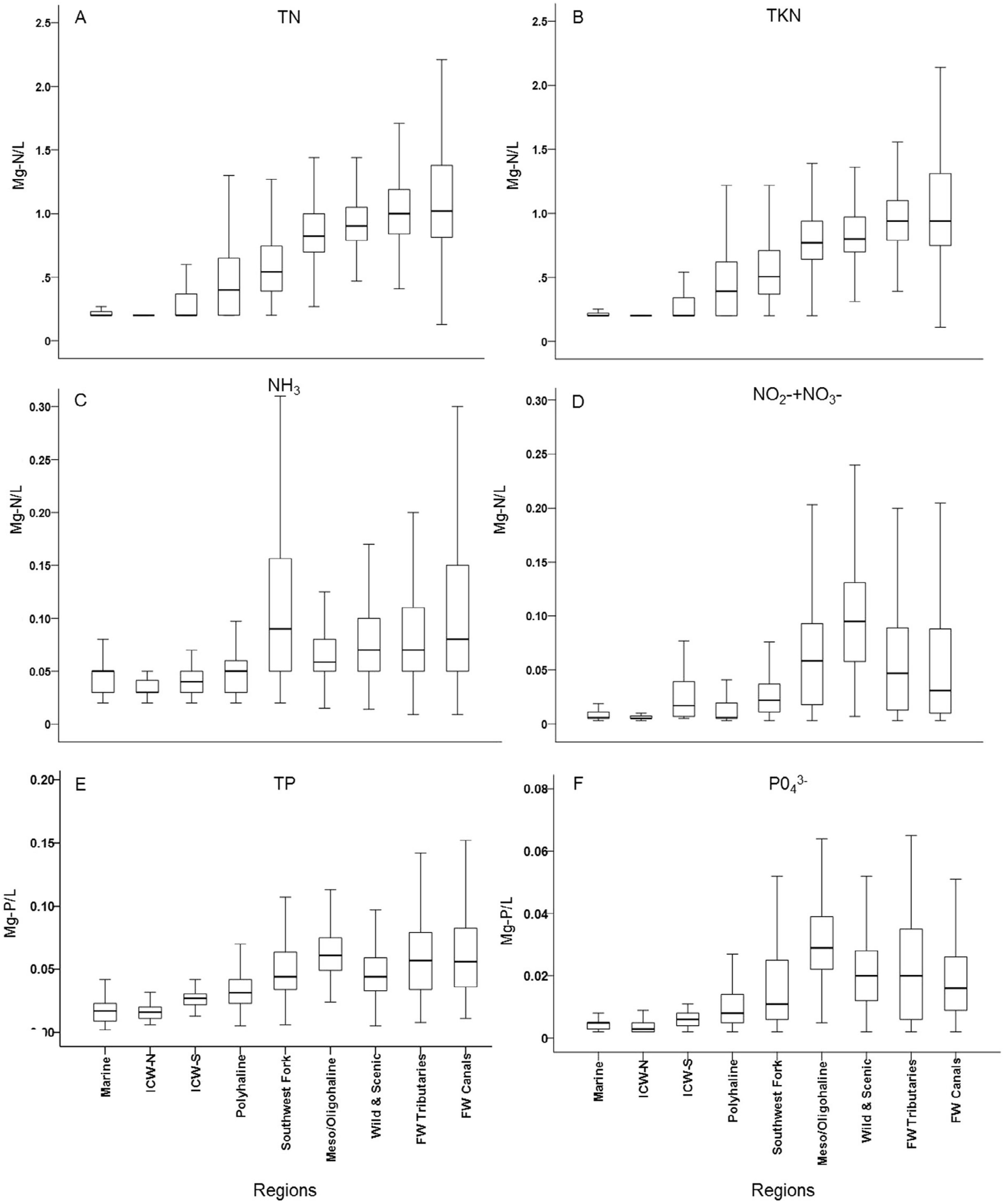

Fig. 3. Nutrient data across pooled across the period of record (2006–2015) for each river region of the Loxahatchee River. Parameters are A) total nitrogen (mg-N/L), B) total Kjeldahl nitrogen, C) ammonia (mg-N/L), D) nitrite + nitrate (mg-N/L), E) total phosphorus (mg-P/L), and F) Ortho-phosphorus ($P0_4^{3-}$). The center horizontal line of the box is the median of the data, while the top and bottom of the box represent the 25th and 75th percentile, respectively. The top and bottom of the whiskers represent the 5th and 95th percentile, respectively.

averaged 0.04 ± 0.05 mg-N/L across the river. Surprisingly, the Wild and Scenic portion of the river had the highest mean nitrate concentrations of any river region (0.10 mg-N/L), though freshwater canals yielded the highest individual NO_2^- + NO_3^- value of 0.67 mg-N/L (Fig. 3D).

Table 2
Mean (±SD) values for all chemical parameters for 2006–2015 broken out by river region and season. Minimum-maximum ranges are given as raw data values across both seasons. Florida DEP and EPA's numeric nutrient criteria (NNC) for total nitrogen (TN), total phosphorus (TP), chlorophyll *a* concentrations (Chl *a*), and fecal coliform bacteria for each river region and percent exceedances of NNC (% samples ≥NNC) for those parameters are presented in bold face type. BD signifies that nutrient concentrations were below the machine detection limit.

Region/Season	TN (mg-N/L)	$NO_2 + NO_3$ (mg-N/L)	NH_3 (mg-N/L)	TKN (mg-N/L)	TP (mg-P/L)	PO_4^{3-} (mg-P/L)	Chl *a* (ug/L)	Fecal coliform (cfu/100 ml)
Marine								
Dry (*n* = 2046)	0.31 ± 0.32	0.01 ± 0.01	0.06 ± 0.04	0.36 ± 0.32	0.02 ± 0.02	0.005 ± 0.005	2.5 ± 2.0	9.1 ± 14.0
Wet (*n* = 2063)	0.31 ± 0.25	0.01 ± 0.01	0.05 ± 0.03	0.31 ± 0.24	0.02 ± 0.01	0.005 ± 0.006	3.3 ± 2.7	23.3 ± 69.7
Min-Max	0.2–2.4	BD-0.14	0.02–0.45	0.2–2.4	BD-0.34	BD-0.062	1.0–16.3	1.0–53.0
NNC limit	0.63	–	–	–	0.032	–	1.8	800
% Exceedances	9.3				16.2		67.3	0
ICW-N								
Dry (*n* = 328)	0.36 ± 0.37	0.01 ± 0.01	0.04 ± 0.01	0.35 ± 0.37	0.02 ± 0.01	BD	3.4 ± 2.8	1.7 ± 1.7
Wet (*n* = 329)	0.28 ± 0.19	0.01 ± 0.008	0.04 ± 0.01	0.28 ± 0.19	0.01 ± 0.01	BD	2.2 ± 3.0	1.6 ± 1.4
Min-Max	0.2–2.1	BD-0.09	BD-0.09	0.2–2.08	BD-0.08	BD-0.02	1.0–16.9	1.0–9.0
NNC limit	0.49	–	–	–	0.02	–	1.90	800
% Exceedances	15.3				43.1		43.1	0
ICW-S								
Dry (*n* = 309)	0.38 ± 0.35	0.04 ± 0.03	0.05 ± 0.01	0.36 ± 0.34	0.03 ± 0.01	0.008 ± 0.005	3.8 ± 2.5	12.8 ± 11.5
Wet (*n* = 309)	0.37 ± 0.18	0.02 ± 0.02	0.05 ± 0.04	0.36 ± 0.18	0.03 ± 0.01	0.007 ± 0.006	6.3 ± 5.2	30.6 ± 66.0
Min-Max	0.2–1.6	BD-0.19	BD-0.19	0.2–1.6	0.01–0.08	BD-0.026	1.0–25.3	1.0–310.0
NNC limit	0.66	–	–	–	0.04	–	4.70	800
% Exceedances	12.3				21.5		39.6	0
Polyhaline								
Dry (*n* = 1445)	0.52 ± 0.44	0.02 ± 0.02	0.06 ± 0.05	0.51 ± 0.43	0.03 ± 0.02	0.008 ± 0.006	4.7 ± 2.8	66.4 ± 130.1
Wet (*n* = 1499)	0.72 ± 0.52	0.01 ± 0.01	0.06 ± 0.05	0.71 ± 0.52	0.04 ± 0.02	0.01 ± 0.01	7.7 ± 6.6	88.7 ± 160.6
Min-Max	0.2–3.2	BD-0.18	BD-0.44	0.2–3.2	BD-0.2	BD-0.09	1.0–42.1	1.0–1260.0
NNC limit	0.80	–	–	–	0.03	–	4.0	800
% Exceedances	24.6				58.4		65.9	1.1
Southwest Fork								
Dry (*n* = 1381)	0.56 ± 0.35	0.03 ± 0.03	0.13 ± 0.10	0.53 ± 0.34	0.04 ± 0.03	0.01 ± 0.01	8.7 ± 5.2	397.0 ± 697.3
Wet (*n* = 1445)	0.82 ± 0.47	0.02 ± 0.02	0.09 ± 0.07	0.80 ± 0.46	0.05 ± 0.03	0.01 ± 0.02	15.2 ± 13.9	374. 6 ± 462.2
Min-Max	0.2–2.8	BD-0.26	BD-0.61	0.20–2.8	0.006–0.40	BD-0.13	1.0–97.9	6.0–4280.0
NNC limit	1.26	–	–	–	0.075	–	5.5	800
% Exceedances	9.6				15.7		79.9	15.1
Meso/Oligohaline								
Dry (*n* = 2480)	1.0 ± 0.57	0.06 ± 0.04	0.07 ± 0.07	0.95 ± 0.5	0.06 ± 0.06	0.02 ± 0.02	5.2 ± 3.9	286.5 ± 547.4
Wet (*n* = 2564)	1.1 ± 0.54	0.05 ± 0.04	0.07 ± 0.08	1.1 ± 0.5	0.10 ± 0.13	0.05 ± 0.09	8.0 ± 7.1	392.1 ± 1046.1
Min-Max	0.2–4.1	BD-0.32	BD-0.94	0.2–4.0	0.01–1.4	BD-1.0	1.0–61.9	8.8–8800.0
NNC limit	1.26	–	–	–	0.075	–	5.5	800
% Exceedances	27.7				29.6		48.3	8.8
FW Tributaries								
Dry (*n* = 2124)	1.0 ± 0.32	0.07 ± 0.06	0.09 ± 0.08	0.94 ± 0.31	0.07 ± 0.14	0.04 ± 0.16	6.9 ± 8.2	159.2 ± 383.4
Wet (*n* = 2271)	1.1 ± 0.38	0.04 ± 0.04	0.08 ± 0.07	1.0 ± 0.36	0.10 ± 0.20	0.06 ± 0.22	10.4 ± 11.6	177.8 ± 345.7
Min-Max	0.2–2.5	BD-0.43	0.009–0.74	0.2–2.4	BD-2.5	BD-2.5	1.0–78.6	1.0–4800.0
NNC limit	1.54	–	–	–	0.12	–	20.0	800
% Exceedances	10.1				7.7		10.3	2.8
FW Canals								
Dry (*n* = 3693)	1.0 ± 0.43	0.07 ± 0.08	0.11 ± 0.12	1.0 ± 0.43	0.05 ± 0.04	0.01 ± 0.01	8.12 ± 14.4	167.5 ± 568.7
Wet (*n* = 3787)	1.2 ± 0.55	0.04 ± 0.05	0.12 ± 0.11	1.2 ± 0.56	0.08 ± 0.06	0.02 ± 0.02	12.1 ± 17.2	283.2 ± 860.2
Min-Max	0.13–4.7	BD-0.67	0.009–1.0	0.10–4.7	BD-0.64	BD-0.24	1.0–177.5	1.0–1250.0
NNC limit	1.54	–	–	–	0.12	–	20.0	800
% Exceedances	18.6				12.1		10.1	5.5
Wild and Scenic								
Dry (*n* = 2051)	0.96 ± 0.30	0.10 ± 0.05	0.08 ± 0.05	0.86 ± 0.30	0.04 ± 0.02	0.01 ± 0.008	2.8 ± 3.3	85.1 ± 84.4
Wet (*n* = 2105)	1.0 ± 0.34	0.08 ± 0.04	0.08 ± 0.06	0.94 ± 0.34	0.06 ± 0.03	0.02 ± 0.02	4.1 ± 3.3	179.6 ± 500.1
Min-Max	0.2–2.6	0.007–0.26	BD-0.50	0.23–2.5	BD-0.33	BD-0.12	BD-26.7	3.0–4700.0
NNC limit	1.54	–	–	–	0.12	–	20.0	800
% Exceedances	7.7				3.5		0.9	2.3

Similar to total nitrogen, phosphorus concentrations exhibited a negative correlation with salinity (Fig. 4C), with maximum TP concentrations reported from freshwater tributaries (2.58 mg-P/L). Specifically, mean TP concentrations were highest from station 88 (0.75 ± 0.51 mg-P/L); minimum TP values were reported from the marine region of the river (0.002 mg-P/L; Fig. 3E). Total phosphorus NNC exceedances were not region-specific, unlike total nitrogen exceedances which were

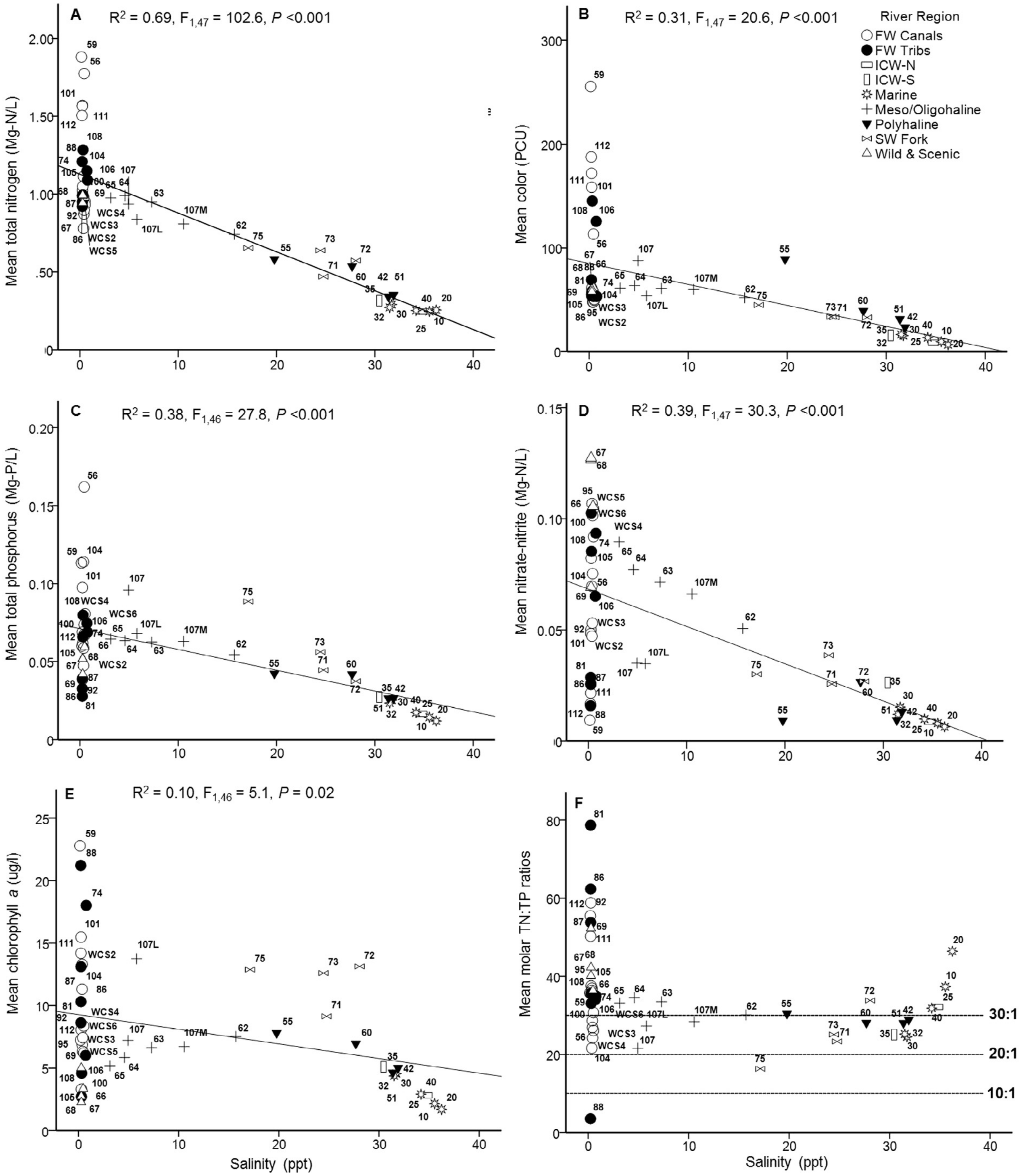

Fig. 4. Separate linear regressions for the period of record (2006–2015) across all water quality stations with salinity as the predictor variable and mean A) total nitrogen (mg-N/L), B) color (PCU), C) total phosphorus (mg-P/L), D) nitrite-nitrate (mg-N/L), mean chlorophyll *a* (ug/L), and F) molar TN:TP ratios as response variables. Station 88 had a mean TP concentration of 0.78 mg-P/L, and is not shown because the Y-axis is truncated to more clearly display the remaining points. A line denotes a significant relationship (at $\alpha = 0.05$) between salinity the response variable.

concentrated in freshwater canals. Approximately 23% of the RiverKeeper stations violated TP NNCs at least once over the POR, while only 12.5% of stations violated NNCs three or more times. Stations 56 (freshwater canal), 55, and 60 (polyhaline) exceeded region-specific NNCs 100, 100, and 90% over the POR respectively, while stations 107 (meso/oligohaline), 75 (Southwest Fork), and 88 (freshwater tributary), all exceeded region-specific NNCs 70, 66.6, and 50% over the POR,

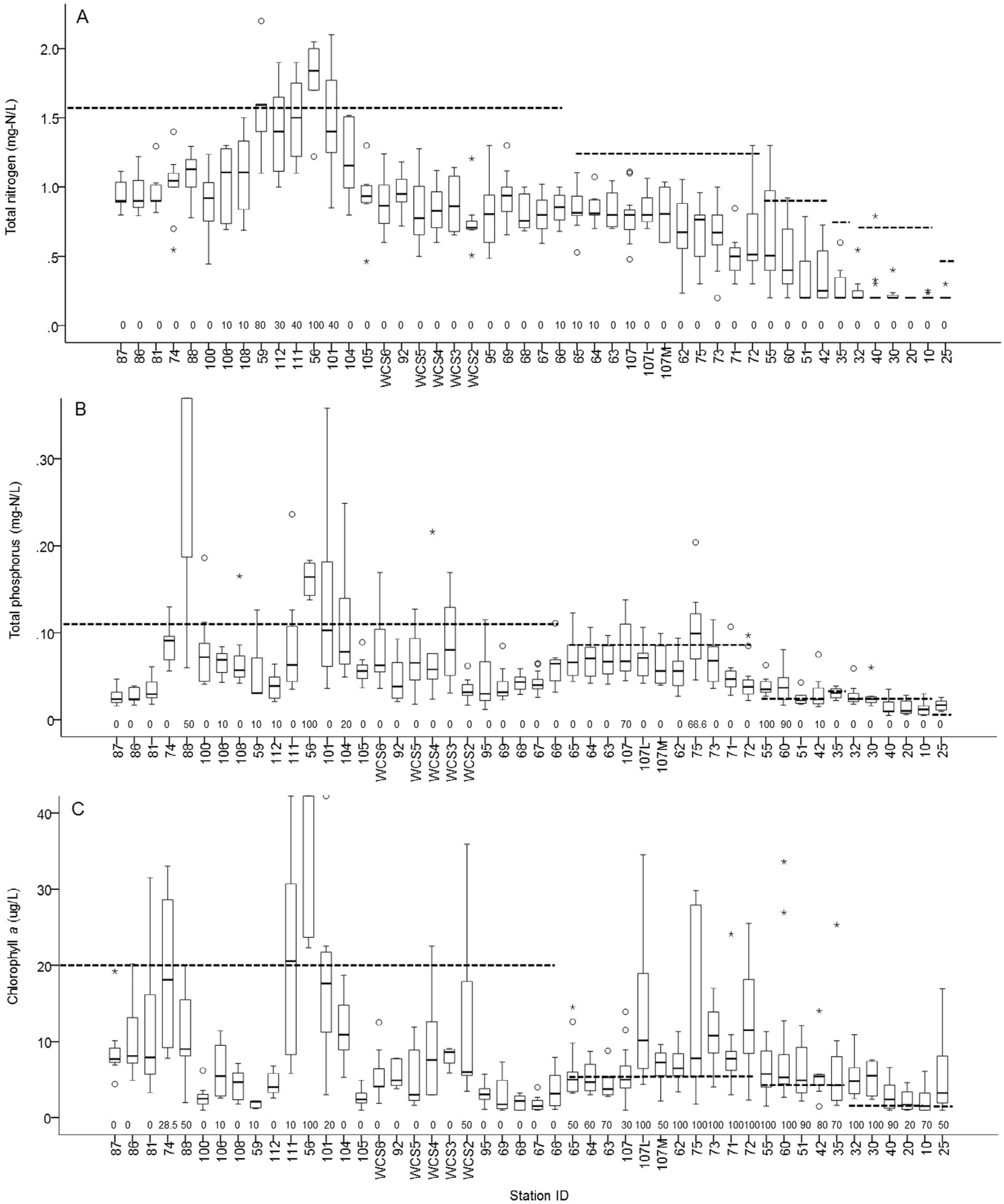

Fig. 5. A) Total nitrogen (mg-N/L), B) total phosphorus (mg-P/L), and C) chlorophyll *a* data pooled across the period of record (2006–2015) across all of the RiverKeeper stations. Stations are organized along a gradient of salinity (upstream-downstream). Numeric nutrient criteria are indicated by the dotted line for each river region, and the percentage of nutrient criteria exceedances for each station are indicated above the station identifier.

respectively (Fig. 5B). Ortho-phosphate (PO_4^{3-}), which is the bioavailable form of phosphorus to primary producers, averaged 0.02 ± 0.08 mg-P/L; PO_4^{3-} exhibited a maximum concentration of 2.5 mg-P/L in freshwater tributaries and a minimum value of 0.02 mg-P/L from all regions except for the meso/oligohaline portion of the river (0.05 mg-P/L; Fig. 3F).

3.3. Algal productivity

Chlorophyll *a* concentrations, indicative of the productivity and trophic condition of estuaries, coastal and oceanic waters (Boyer et al., 2009), averaged 7.3 ± 10.3 μg/L across the river. Minimum reported concentrations ranged from 0.9 μg/L in the Wild and Scenic portion of the river to a maximum value of 177.5 μg/L in freshwater canals, however this abnormally high reading was taken from a sample collected at Kitching Creek at 138th Street (Station 111) in a stagnant pool adjacent to agricultural fields during the dry season. Chlorophyll *a* values had the greatest number of NNC exceedances of the three parameters (TN, TP, Chlorophyll *a*); 62.5% of the stations violated NNCs at least once and 50% of the stations violated NNCs three times or more over the POR. In fact, all of the stations within the Southwest Fork (75, 73, 71, and 72) exceeded the NNC 100% of the time, and all stations within the polyhaline river region (55, 60, 51, 42) exceeded the NNC between 80 and 100% of the time. Five out of the six meso/oligohaline sites (65, 64, 63, 107L, 107 M, and 62) exceeded the NNC between 50 and 100% of the time over the POR. Additionally, station 56 (freshwater canal) violated the chlorophyll *a* NNC 100% of the time over the POR. Surprisingly, almost all of the stations in the marine portion of the river (10, 30, 32, 40) exceeded the region-specific NNC (between 70 and 100% over the POR), in addition to stations 25 (ICW-N) and 35 (ICW-S) that exceeded NNCs 50% and 70% of the time, respectively. Total nitrogen only explained 15% of the variation in chlorophyll concentrations ($r = 0.15$, $P < .001$) though TP exhibited a slightly stronger relationship with chlorophyll *a* ($r = 0.27$, $P < .001$).

3.4. Bacteria concentrations

Fecal coliform bacteria concentrations averaged 159.65 ± 345.92 cfu/100 ml across the river. Minimum reported concentrations were 1 cfu/100 ml in all river regions except within the meso/oligohaline and Wild and Scenic portions of the river (8 and 2 cfu/100 ml, respectively). Maximum reported concentrations were found in the meso/oligohaline river region (15 ,200 cfu/100 ml). The single day state water quality criteria for the Loxahatchee River is <800 cfu/100 ml (2010 version of Florida Statute 62-302). Samples collected for fecal coliform had low exceedances across all river regions; ~15% of the samples collected from the Southwest Fork exceeded water quality criteria, but few or no exceedances were reported for other river regions (Table 2).

3.5. Spatial variation in water quality and limiting nutrients

Linear regressions indicated that the gradient of salinity throughout the river was a predictor of water column nitrogen, phosphorus, and color, and a weak but significant predictor of chlorophyll *a* (Fig. 4). Total nitrogen concentrations were most tightly associated with salinity ($r^2 = 0.69$; Fig. 4A). Freshwater tributaries and canals exhibited the highest TN concentrations, while marine and ICW-N and ICW-S river regions yielded the lowest TN concentrations. Color, total phosphorus, and chlorophyll *a* exhibited a similar pattern as TN, though the relationships were more variable (Fig. 4B, C, E). Stations 59 and 56 (located in freshwater canals) in the northern portion of the watershed had some of the highest mean TN, TP, color and chlorophyll concentrations of any site. Nitrate-nitrite was also highest in low salinity river regions; interestingly, monitoring stations 66 and 67 within the protected Wild and Scenic portion of the river yielded the highest mean nitrate-nitrite values. The meso-oligohaline sites also exhibited elevated nitrate-nitrite values compared to other river regions (Fig. 4D).

Ratios of TN to TP indicate overall P limitation in the water column throughout the river (34.5 ± 12.7; Fig. 4F). The minimum TN:TP ratio was 3.53 (indicating N limitation) from station 88. The maximum TN:TP ratio was 78.6 (indicating strong P limitation) from station 81, located along the C-18 (Fig. 1). Mean TN:TP ratios from this study are most comparable with mean reported N:P ratios from the Indian River lagoon estuary system (41.10 ± 2.13:1), offshore Palm Beach County reef systems (34.8 ± 14.9:1), as well as values reported from Florida Bay (range: 20–140:1), a waterbody that is located from the Florida Everglades to the southern end of the Florida Keys (Table 3).

4. Discussion

Our findings indicate that there is predictable upstream/downstream spatial variation in water quality parameters, with nearly all having a significant negative relationship with salinity (i.e., nearshore marine waters are more oligotrophic than upstream freshwaters). Nonetheless, our results suggest that several regions have impaired water quality, likely as a result of anthropogenic activity. For instance, stations 81, 92, and 69 represent a linear, upstream-to-downstream sequence of stations in which relatively high quality fresh water flows from the C-18 (station 81) to the C-14 canal (station 92) and then to Northwest Fork (station 69). As water originating from the C-18 flows into and through the C-14 canal, it is mingled with runoff from Jupiter Farms, a rural area with low-density houses utilizing on-site wastewater treatment and disposal systems. Our results show that mean concentrations of TP increase sequentially as water moves downstream from stations 81 to 92 to 69 (0.028 mg-P/L, 0.038 mg-P/L, and 0.042 mg-P/L, respectively) and $NO_2^- + NO_3^-$ (0.029 mg-N/L, 0.05 mg-N/L, and 0.069 mg-N/L, for stations 81, 92, and 69 respectively), which is suggestive that nutrients are entering the water in the Jupiter Farms region. Similarly, station 75 (Jones Creek at Indiantown Rd) shows elevated TP concentrations relative to salinity-derived projections (see Fig. 4). Taken together, these data suggest elevated phosphorus concentrations in Jones Creek and the Northwest Fork are derived from upstream nutrient loading. However, it is imperative that future research endeavors more clearly

Table 3
Comparison of reports with Nitrogen: Phosphorous (N:P) molar ratios across different estuarine and coastal marine waterbodies in Florida. N:P ratios are reported either as Total Nitrogen:Total Phosphorus (TN:TP) or Total Dissolved Nitrogen: Total Dissolved Phosphorus (TDN:TDP), and are expressed in means (±SD) unless otherwise indicated.

Source	Salinity (ppt)	TN:TP ratio	Location
Janicki Environmental, Inc. (2011a)	NR	5.8–20:1	Sarasota Bay, Florida
Janicki Environmental, Inc. (2011b)	NR	4.6–10.5:1	Tampa Bay, Florida
Sigua et al. (2000)	NR	≤10-41:1	Indian River Lagoon, Florida
Lapointe et al. (2012)	22.67 ± 9.29	41.4 ± 22.3	Indian River Lagoon, Florida (Peck's Lake)
Lapointe et al. (2015)	6.0–42.9	TDN:TDP = 10.8–176.8:1 (Mean) 41.10 ± 2.13	Indian River Lagoon, Florida
Lapointe et al. (2012)	3.37 ± 5.8	TDN: TDP = 11.7 ± 9.5:1	St. Lucie Estuary, Florida
McPherson and Sonntag (1984)	~0–38	7.9–22.9:1	Loxahatchee River, Florida
Present study	0.05–39.5	34.5 ± 12.7:1	Loxahatchee River, Florida
Lapointe (2007)	NR	TDN:TDP = 34.8 ± 14.9:1	Offshore reef sites, Palm Beach County
Lapointe (2007)	NR	TDN:TDP = 32.1 ± 10:1	Offshore reef sites, Martin County
Briceño et al. (2014)	8.5–15.5	209.7–225.1:1	Southern Everglades, Florida
Sutula et al. (2003)	~0–30	127–216:1	Southern Everglades, Florida
Fourqurean et al. (1993)	38–50	20–140:1	Florida Bay, Florida
Collado-Vides et al. (2007)	27.9–39.7	(Median) 58.0:1	Florida Keys, Florida
Lapointe (2007)	NR	TDN: TDP = 51.5 ± 12.2:1	Abaco, The Bahamas
Briceño and Boyer (2013)	36.2–37.0	96:1	Bermuda

establish non-point and point-sources of nutrient pollution in these river regions, as we did not identify specific causes of elevated nutrient availability relative to other river regions.

Overall, freshwater portions of the watershed exhibited the most variability in nutrient concentrations, with nearly all freshwater canal sites (open circles in Fig. 4) showing elevated nutrient concentrations compared to other river regions. For instance, station 56, a freshwater canal station, appears to be influenced by an adjacent community that utilizes septic tanks and is downstream from a golf course, driving elevated nitrogen and phosphorus concentrations. In fact, station 56 exceeded TN, TP, and chlorophyll *a* NNCs 100% of the time over the POR. Stations 101, 111, and 112, also freshwater canal stations, exhibited elevated nitrogen and phosphorus concentrations likely stemming from the prevalence of landscape nurseries that are adjacent to- and upstream from these sites. Offsite drainage from relic farm fields may also have contributed nitrogen and phosphorus to these stations. Station 88, a site located in a drainage ditch adjacent to a relic row-crop agricultural field has experienced substantially elevated chlorophyll concentrations stemming from P-enriched sediment, a result of chronic fertilizer application (Loxahatchee River District unpublished data). Mean total phosphorus concentrations at station 88 were over 4 times greater than the next most phosphorus-enriched site (station 56), and exceeded TP NNC 50% of the time over the POR.

McPherson and Sonntag (1984) also demonstrated that freshwater portions of the river experienced the highest nitrogen, phosphorus and total organic carbon loads (75 metric tons N, 2.7 metric tons P, and 1000 metric tons of organic carbon, respectively), though they partially attribute these high loading rates to storm activity and intensified stormwater runoff during the sampling period. Sediment loading to the river has been especially problematic; following the creation of the C-18, sediment delivery from the canal has increased from 0 to >600 tons a^{-1} with an accumulation of two meters of muck in the C-18 (Jaeger and Hart, 2001; Jaeger et al., 2009). Although anthropogenic activities likely drove observed patterns of elevated nutrient concentrations across freshwater portions of the watershed, one surprising finding was that the highest $NO_2^- + NO_3^-$ concentrations among all sample sites were from the relatively pristine Wild and Scenic river region (see Fig. 3D). While these stations most likely receive elevated $NO_2^- + NO_3^-$ from Jupiter Farms, it appears that extensive shading by the largely intact cypress canopy in this portion of the river reduces algal productivity and associated nutrient uptake, which is consistent with slower rates of nutrient uptake in forested watersheds (Newcomer Johnson et al., 2016). However, more research is necessary in order to confirm whether this mechanism is driving elevated nitrate concentrations.

The Loxahatchee River exhibited strong P-limitation across the majority of our sampling sites (59.7% of sites have mean TN:TP molar ratios >30:1). These skewed TN:TP ratios appear driven by elevated TN values (compare Fig. 3A and E), suggesting nitrogen loading may be impacting certain river regions, especially freshwater canals. Florida DEP guidelines for Florida estuaries (2002) indicate that any molar TN:TP ratio <10:1 represents N limitation, ~20:1 represents co-limitation, and 30:1 or greater represents P limitation (Florida Department of Environmental Protection, 2002). TN:TP molar ratios from this study are comparable to reported TN:TP ranges from the Indian River Lagoon, Florida Bay, and offshore Palm Beach County reef systems. Freshwater portions of the river exhibited strong P-limitation, which is often characteristic of freshwater systems (but see Elser et al., 2007) as well as reflective of nitrogen loading from septic tank, agricultural, and stormwater runoff (Paerl et al., 2014). Interestingly, most marine portions of the river also yielded molar TN:TP ratios consistent with P-limitation. It is well-understood that in carbonate systems, including the Loxahatchee River estuary (Swarzenski et al., 2006), phosphorus can act as the limiting nutrient though this may also be a function of the budget of gains and losses of N and P availability (Short, 1987; Fourqurean et al., 1992; Fourqurean and Zieman, 2002; Ferdie and Fourqurean, 2004; Caccia and Boyer, 2005). Specifically, biogenic carbonate mud can act as sink for P through adsorption to carbonate sediments (Fourqurean et al., 1993). Parts of Florida Bay also exhibit P-limitation, largely driven by P adsorption to carbonate sediment (Fourqurean et al., 1993). Additionally, the northern Indian River Lagoon is P-limited, though this may be a function of anthropogenic enrichment of nitrogen. Work conducted by Lapointe et al., (2015) suggests that the northern segments of the Indian River Lagoon, Mosquito Lagoon, and Banana River are highly enriched with total dissolved nitrogen (TDN) as a result of nitrogen pollution from septic systems contributing to the elevated TDN:TDP ratio and subsequent harmful algal blooms in the region.

In the Loxahatchee River estuary, effluent from septic systems has been found to impact surface water quality (Village of Tequesta vs. Loxahatchee River Environmental Control District, 714 So.2d 1100 at 1101, Fla 4th DCA, 1998) and likely plays a role in driving elevated TN:TP ratios. Septic system leachate and other non-point sources of pollution are especially problematic in coastal, low-lying regions of Florida, which are often at sea level, have porous carbonate geology, and shallow groundwater systems (Lapointe et al., 2012). For instance, Station 107 in the meso-oligohaline portion of the river has routinely exhibited elevated nitrogen, phosphorous and chlorophyll *a* concentrations, as this site is adjacent to a region of the watershed where homes continue to rely on septic tanks. Unpublished data from the Loxahatchee River District demonstrates the presence of sucralose in surface water samples from Station 107, which is commonly used as an indicator of septic tank effluent (Oppenheimer et al., 2011). Problems may arise after heavy rain events, in which the high water table and porous substrate allows movement of septic effluent including nutrients, bacteria, viruses and other contaminates from shallow groundwater to surface waters, ultimately degrading water quality, aquatic species abundance and diversity, and ecosystem function (Caccia and Boyer, 2005; Lapointe et al., 2012). Recently, in the Indian River Lagoon estuary, elevated nutrient loads from more than an estimated 300,000 active septic tanks in the lagoon watershed have been attributed to harmful algal blooms and seagrass loss (Lapointe et al., 2015). However, it should be noted that while septic tank leachate is of concern in the Loxahatchee River (Lapointe and Krupa, 1995), this source of water quality degradation is diminishing because the Loxahatchee River District has been systematically converting homes off septic systems and onto the regional sanitary sewer system over the past 40 years.

Urban stormwater may also play a large role in influencing water quality in the Loxahatchee River. The negative impacts of stormwater runoff are well-established, and include increased loading of nutrients, bacteria, sediments and other pollutants (Schillinger and Gannon, 1985; Lee and Bang, 2000; Vaze and Chiew, 2004). Approximately 25% of the Loxahatchee River watershed is urbanized, including golf courses, residential areas, and impervious surfaces (Florida Department of Environmental Protection and South Florida Water Management District, 2010). During major stormwater events, massive amounts of freshwater are passively discharged from the terrestrial landscape to the estuary by numerous stormwater management systems, often operated at the neighborhood scale, and by a large, regional flood control system managed by the South Florida Water Management District. For instance, stormwater likely affected water quality in the Sims and Jones Creek area (within the Southwest Fork). While stormwater discharges and flood control releases clearly load nutrients and bacteria to the estuary, the principle impact is often significant and prolonged deviations in estuary salinity (Ridler et al., 2006; Wan et al., 2015). Additionally, the mean residence time of the Loxahatchee River estuary (along a linear transect from the confluence of Kitching Creek and the Loxahatchee River to the Jupiter Inlet) is ~1 day (Swarzenski et al., 2006) compared to other nearby systems such as the Indian River Lagoon that has a mean residence time of ~1 year (Kamerosky et al., 2015), and as such, nutrients from stormwater may be flushed rapidly from the Loxahatchee River to near-shore waters. However, it should be noted that the Southwest and North Forks have longer mean hydraulic residence times, allowing phytoplankton time to assimilate nutrients and accumulate increased chlorophyll *a* concentrations observed in these river regions (Loxahatchee River District unpublished data).

An encouraging finding was that only 10% of the stations violated TN and TP numeric nutrient criteria (NNCs) three times or more over the period of record (POR). When assessing nutrient concentrations in the context of numeric nutrient criteria, only a small fraction of sites were impaired relative to established benchmarks. Ten percent of sites exceeded total nitrogen NNC thresholds more than once in ten years, and all were freshwater sites. Fifteen percent of sites exceeded total phosphorus NNC thresholds more than once in 10 years. However, despite relatively low NNC exceedances for TN and TP, chlorophyll *a* concentrations frequently exceeded NNCs in both the marine and brackish water river regions. While water quality in the Loxahatchee River clearly has room for improvement, we believe the excessive chlorophyll *a* exceedances are indicative of overly conservative chlorophyll *a* targets. It is imperative that numeric limits for chlorophyll *a* are biologically meaningful, in other words, nutrient criteria should meet habitat requirements for aquatic flora and fauna living within those regions. For instance, dense submerged aquatic vegetation (SAV) have been found to be negatively associated with chlorophyll *a*, as increased phytoplankton productivity diminishes light penetration leading to a decline in SAV (Boyer et al., 2009). In Chesapeake Bay, chlorophyll *a* concentrations generally need to fall below 15 μg/L in order for SAV to survive, while in Tampa Bay, chlorophyll *a* concentration targets must fall between 4.6 and 13.2 μg/L in different segments of the bay to help meet long-term seagrass coverage goals (Greening and Janicki, 2006). In brackish and marine portions of the Loxahatchee River where seagrasses are the most abundant, chlorophyll *a* concentrations generally fall below these SAV thresholds, yet in the marine portion of the Loxahatchee River where chlorophyll *a* NNC is 1.8 μg/L, NNCs were violated 70%–100% of the time over the entire POR. It should also be noted that there is no known public perception that water clarity (and elevated chlorophyll *a* concentrations) in the marine and ICW-N/S portions of the river is poor; in fact, contact recreation activities which include primary contact (e.g., swimming) and secondary contact (e.g., fishing, Smith et al., 2015) are abundant in in these areas. While improving water quality in the Loxahatchee River is a primary concern, unrealistically low chlorophyll *a* NNCs may result in spending limited water quality improvement funds on unnecessary projects (i.e., projects to lower annual geometric mean chlorophyll *a* concentrations from 2.5 mg/L to >1.8 mg/L; see Table 2 chlorophyll *a*, Marine). Thus, we suggest projects to improve water quality should be explicitly focused on areas with impaired water quality relative to state NNCs, especially in river regions with point-sources of contamination. Additionally, more rigorous evaluation of specific drivers of water quality degradation are required, as well as more intensive statistical analyses to identify explicit causality between anthropogenic activity and water quality. Such focused efforts will allow natural resource managers to utilize often-limited resources to improve water quality and engender additional public support for future projects.

5. Conclusions

The Loxahatchee River estuary may undergo rapid change in the next decade as global anthropogenic activities increase and threats including climate change and sea level rise become reality in Florida. These stressors, combined with local threats to the river, including on-site wastewater treatment (septic) system effluent and urban stormwater runoff, may degrade the ecological integrity of the estuary including critically-important habitats such as oyster reefs and seagrass beds that are experiencing declines in some parts of the river (Loxahatchee River District unpublished data). Data presented herein suggest local, site-specific water quality improvement projects should be implemented to ameliorate elevated nitrogen and phosphorus concentrations. Moreover, these projects must be structured to address actual source of water quality impairment (e.g., urban stormwater runoff, septic system effluent, relic agriculture inputs). In addition to conducting water quality improvement projects, future work should identify causality between possible sources of nutrient pollution and water quality throughout the river, elucidate potential interaction effects between local and global stressors, and how these effects may exacerbate degradation of estuarine ecosystem health. To this end, it is imperative that water quality continue to be monitored to ensure that resource managers have the information necessary to identify water quality impacts and justify funding of targeted water quality improvement projects.

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Appendix A. Supplementary data

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