Science of the Total Environment 872 (2023) 162232

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Leveraging green infrastructure for efficient treatment of reclaimed water

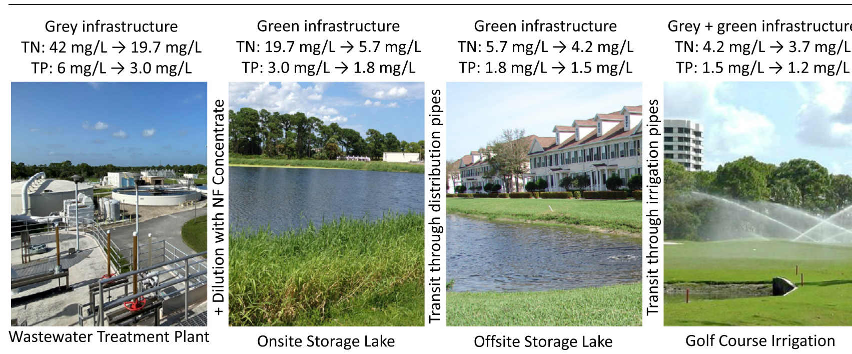
D. Albrey Arrington [a,*], Rachel Joy Harris [a], Craig A. Layman [b], Dylan G.E. Gomes [c]

[a] Loxahatchee River District, 2500 Jupiter Park Drive, Jupiter, FL 33458, United States of America
[b] Center for Energy, Environment & Sustainability, Wake Forest University, Winston-Salem, NC 27106, United States of America
[c] National Academy of Sciences NRC Research Associateship Program, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA 98112, United States of America

HIGHLIGHTS

- Water scarcity necessitates practical, sustainable water reuse practices.
- Green infrastructure significantly reduced reclaimed water nutrient concentrations.
- Nutrient levels were similar to those of advanced wastewater treatment.
- Fertilization should be reduced proportionally to nutrients in irrigation water.
- Irrigation with reclaimed water did not result in downstream eutrophication.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jay Gan

Keywords:
Eutrophication
Irrigation
Nitrogen
Phosphorus
Storage lakes
Wastewater

ABSTRACT

Global water scarcity necessitates creative, yet practical, solutions to meet ever-growing demand. Green infrastructure is increasingly used in this context to provide water in environmentally friendly and sustainable ways. In this study, we focused on reclaimed wastewater from a joint gray and green infrastructure system employed by the Loxahatchee River District in Florida. The water system consists of a series of treatment stages for which we assessed 12 years of monitoring data. We measured water quality after secondary (gray) treatment, then in onsite lakes, offsite lakes, landscape irrigation (via sprinklers), and ultimately in downstream canals. Our findings show gray infrastructure designed for secondary treatment, integrated with green infrastructure, achieved nutrient concentrations nearly equivalent to advanced wastewater treatment systems. For example, we observed a dramatic decline in mean nitrogen concentration from 19.42 mg L^{-1} after secondary treatment to 5.26 mg L^{-1} after spending an average of 30 days in the onsite lakes. Nitrogen concentration continued to decline as reclaimed water moved from onsite lakes to offsite lakes (3.87 mg L^{-1}) and irrigation sprinklers (3.27 mg L^{-1}). Phosphorus concentrations exhibited a similar pattern. These decreasing nutrient concentrations led to relatively low nutrient loading rates and occurred while consuming substantially less energy and producing fewer greenhouse gas emissions than traditional gray infrastructure—at lower cost and higher efficiency. There was no evidence of eutrophication in canals downstream of the residential landscape whose sole source of irrigation water was reclaimed water. This study provides a long-term example of how circularity in water use can be used to work toward sustainable development goals.

1. Introduction

Green infrastructure is broadly defined as utilizing any natural aspect of the environment—and the desired services those features provide—as part of human infrastructure (Benedict and McMahon, 2006; Palmer et al.,

* Corresponding author.
E-mail address: albrey@lrecd.org (D.A. Arrington).

http://dx.doi.org/10.1016/j.scitotenv.2023.162232
Received 30 September 2022; Received in revised form 8 February 2023; Accepted 9 February 2023
Available online 14 February 2023

2015). Examples range broadly, including tree cultivation, green roofs, vegetation coverage for erosion prevention, stormwater detention ponds, and wetland construction. Green infrastructure systems are increasingly employed concomitant with urbanization. In Florida alone there are >75,000 stormwater ponds and lakes, accounting for 2.7 % of urban land cover as of 2020 (Sinclair et al., 2020). While stormwater ponds are not a panacea for water quality concerns (Harper and Baker, 2007), they contribute many ecosystem services (Taguchi et al., 2020), including nutrient retention and removal from water (e.g., Ament et al., 2022; Ryan et al., 2010; Troitsky et al., 2019). For example, in Florida stormwater systems with a detention time of 14 days removed approximately 20–40 % of total nitrogen and 60–70 % of total phosphorus (Harper and Baker, 2007). In Minnesota, annual nutrient retention for phosphorus was >48 % and for nitrogen >58 % in three urban stormwater detention ponds, with variation in retention tied closely to hydrology and pond storage capacity (Janke et al., 2022). Stormwater ponds are common in coastal urban environments, contributing to nutrient removal through sedimentation (Lusk and Chapman, 2021; Schroer et al., 2018), macrophyte uptake (Schwammberger et al., 2020), and nitrification and denitrification (Rivers et al., 2018; Yazdi et al., 2021).

The extension of green stormwater systems to the green management of reclaimed wastewater seems obvious, yet there are few studies of full-scale systems in urban settings. Recycling treated wastewater is an ancient practice (Angelakis et al., 2018) that is resurging due to increasing water conservation needs (Almuktar et al., 2018; Maniam et al., 2022; Partyka and Bond, 2022; Rao et al., 2022). In this study, the reclaimed water we refer to is treated wastewater plant effluent that is eventually recycled to meet landscape irrigation needs and to offset groundwater withdrawals. In the recycling process, green infrastructure systems are the lake ecosystems in which treated wastewater is stored. In addition, the landscape (e.g., turf grass, shrubs, trees, riparian buffers) comprises terrestrial green infrastructure (Lee et al., 2004). These components are used to complement traditional gray infrastructure, e.g., mechanical filtration, aeration, disinfection by chlorination, and an underground transport pipe system. Studies that address the link between treated wastewater and storage systems tend to look at the effects of the influent on the ecology of the recipient water body (Chen et al., 2017; Liu et al., 2021; Luo and Li, 2018; Yang et al., 2022). For example, attention has been directed to establishing threshold values of nutrients that, when exceeded, may cause unwanted effects such as eutrophication and toxic algal blooms (Song et al., 2022; Sun et al., 2022). Others have documented impacts of elevated salt content on crop production (Liu et al., 2023).

An under-studied, alternative perspective may have equally important management implications, i.e., how do reclaimed water storage lake ecosystems mediate water quality, thereby affecting ecosystems where the water is reused? Mechanisms of nutrient retention in reclaimed water lakes likely vary among systems and environmental conditions and could involve sedimentation, phytoplankton, macrophytes, wetlands, microbial communities, and biogeochemical processes. Regardless of the mediating mechanisms, evidence that water quality may be significantly improved as reclaimed water flows through green infrastructure has globally important management implications.

The incorporation of green infrastructure into reclaimed water recycling projects has other advantages. For example, gray infrastructure advanced treatment methods are often associated with intense energy demands, high greenhouse gas emissions, environmental contamination (e.g., heavy metals), and poor cost efficiency (Amann et al., 2022; Zhang et al., 2021)—all of which are improved by integrating green infrastructure (Jayasooriya et al., 2017; Sturiale and Scuderi, 2019; Wang et al., 2020). Letting natural ecological processes operate reduces the chemical, electric, and labor demands typically associated with gray infrastructure. If reclaimed water reuse avoids negative externalities (e.g., downstream eutrophication) due to achieving acceptable nutrient loading rates, then the reuse of reclaimed water may meet irrigation and nutrient demands for landscaping or agricultural purposes, thereby reducing the demand for additional fertilizer application (Liu et al., 2023; Narain-Ford et al., 2021; Partyka and Bond, 2022; Rao et al., 2022; Zhu and Dou, 2018; Zurita and White, 2014). In these ways, optimized reclaimed water reuse programs are consistent with the philosophy and practice of a sustainable, circular economy (Estevez et al., 2022).

In this study, we focused on the reclaimed wastewater gray and green infrastructure system employed by the Loxahatchee River District (LRD) in Florida. Reclaimed water in this system has been thoroughly evaluated and well characterized (Arrington and Dent, 2008; Stanford et al., 2021; Stanley et al., 2009). The reclaimed water system consists of a series of treatment stages for which we assessed 12 years of monitoring data. We measured water quality after secondary treatment through standard gray wastewater infrastructure, then in green infrastructure—including onsite lakes, offsite lakes, and landscape irrigation (via sprinklers)—and ultimately in downstream canals. Specifically, we had the following hypotheses:

- Nitrogen and phosphorus concentrations decline as reclaimed water moves through gray and green infrastructure systems.
- Nitrogen and phosphorus concentrations at the end of our gray and green reclaimed water systems (i.e., when water emerges from sprinkler heads) are comparable to nitrogen and phosphorus concentrations in reclaimed water following advanced wastewater treatment consisting entirely of gray infrastructure.
- Because of lower nutrient concentrations achieved through the gray and green infrastructure system, unwanted ecosystem-level impacts are avoided, i.e., no eutrophication of downstream canals.

We assess these hypotheses with a robust, long-term dataset. Also, we provide a model framework for the use of reclaimed water that adheres to water quality standards, meets regional demand for irrigation water, and increases efficiency relative to wastewater treatment relying solely on gray infrastructure—all while avoiding unwanted environmental effects and minimizing costs.

2. Material and methods

2.1. Study area

The Northwest Fork of the Loxahatchee River is one of two rivers in Florida designated as a National Wild and Scenic River and as such receives special protections. Urbanization, drainage, stabilization, deepening of Jupiter inlet, dredging, and habitat loss have degraded the watershed (Stoner and Arrington, 2017; VanArman et al., 2005). Altered hydrology, increased water withdrawals from the natural system, and sea level rise have exacerbated saltwater intrusion (VanArman et al., 2005). Saltwater flows into the watershed from the Atlantic Ocean via Jupiter Inlet, a natural inlet identifiable in the oldest maps of Florida. Ecological degradation spawned plans to safeguard the Loxahatchee River from additional harm, including defining minimum flows necessary to sustain the river and regulatory efforts that limit the amount of water withdrawn from the watershed (Florida Administrative Code Rule 40E-2.091 and 40E-8.221(4)). Additionally, the development of alternative water supplies, such as using reclaimed water to meet nonpotable water demands, is a statewide goal and has been promoted within the watershed to safeguard existing surface water and groundwater (403.064 and 373.250, Florida Statutes).

The Florida State Legislature created the LRD in 1971 as an independent, multi-county special district with a mission to protect public health and preserve the Loxahatchee River watershed through wastewater solutions, scientific research, and environmental stewardship. A principal mechanism by which this mission is achieved is effective wastewater collection, treatment, and disposal. To improve surface and groundwater quality, LRD has worked to decommission septic systems within the urbanized portion of the Loxahatchee River watershed and convert homes to the regional sanitary sewer system. Presently, ~99 % of urban homes and businesses (i.e., east of Interstate 95) have been connected to the LRD sewer system.

2.2. Wastewater treatment plant

The LRD owns and operates the regional wastewater treatment facility for northeastern Palm Beach County and southeastern Martin County, Florida, USA. From 1976 to 1984, LRD provided advanced wastewater treatment and discharged treated effluent to a pond that flowed into the Northwest Fork of the Loxahatchee River. In 1984, LRD modified the treatment process to provide secondary treatment and began recycling treated effluent—also known as reclaimed water, reuse water, and irrigation quality water, among many other names (Ellis et al., 2019)—to meet landscape irrigation needs at local golf courses. In 1987, LRD discontinued surface water discharges to the Loxahatchee River when LRD began operating a deep injection well for the disposal of excess treated wastewater. In 1998, LRD began providing reclaimed water to a 1036-ha, master-planned, mixed-use community named Abacoa whose development conditions require 100 % of landscape irrigation needs within the community to be met with reclaimed water. In 2011, to keep up with the growing demand for reclaimed water, LRD reclaimed water supply was increased by blending up to 11,356 m^3d^{-1} (3.0 MGD) of nanofiltration concentrate (NF-concentrate) from the Town of Jupiter's drinking water plant with LRD reclaimed water as it enters onsite reclaimed water storage lakes (Stanley et al., 2009). Presently, the LRD wastewater treatment plant has a permitted treatment capacity of 41,640 m^3d^{-1} (11.0 million gallons per day, MGD), and provides secondary treatment including mechanical filtration, flow equalization, diffused aeration, secondary clarification, filtration, and high-level disinfection by chlorination. The treated effluent plus NF-concentrate meets Florida's public-access land application reclaimed water requirements (Fla. Admin. Code R. 62–610, Part III). Reclaimed water (treated effluent plus NF-concentrate) is recycled to meet landscape irrigation needs and offset groundwater withdrawals in the region. During wet weather periods, when reclaimed water storage features are full, excess reclaimed water is disposed of by deep well injection into the boulder zone. Pugsley (2020) provides a summary of the LRD wastewater treatment plant objectives, process systems, and the chronology of process improvements.

2.3. Reclaimed water storage and distribution

After treatment, LRD reclaimed water flows out of the wastewater treatment plant (Fig. 1, Supplementary Fig. 1), from the chlorine contact chamber, into two parallel, elevated lakes (where NF-concentrate is blended), and then sequentially through a series of four interconnected lakes (Supplementary Fig. 2). These onsite lakes have a cumulative total volume of 744,530 m^3 with a mean residence time of 30 days. These onsite lakes were designed as an "artificial lentic environment" with a high shoreline-to-volume ratio to promote natural biogeochemical water treatment and an underlying sandy-clay layer that limits groundwater seepage (Dent, 1975). These lakes support extensive littoral zones that function as constructed wetlands and are dominated by maidencane (*Panicum hemitomon*), alligator weed (*Alternanthera philoxeroides*), pennywort (*Hydrocotyle* spp.), and lake hygrophila (*Hygrophila costata*) with isolated, seasonal patches of water meal (*Wolffia columbiana*), small duckweed (*Lemna valdiviana*), and American water fern (*Azolla filiculoides*). Every 2–5 years, excess littoral vegetation is mechanically harvested and sent to a facility that processes vegetative waste into mulch or soil amendment. Onsite lakes also support an array of wading birds, reptiles, and fish, and serve as a public wildlife viewing area. Two onsite reclaimed water pump stations are used to distribute reclaimed water to customers through a network of 56,710 m of underground reclaimed water distribution pipes.

Approximately 64 % of LRD's reclaimed water is allocated to meet landscape irrigation needs at twelve local golf courses and the remaining 36 % is allocated to meet public-access landscape irrigation demands in Abacoa (Fig. 1; Table 1)—a mixed-use residential area that includes a university campus, professional and training baseball fields, public schools and parks, a community vegetable garden, common area lawns, and residential lawns. Each reclaimed water customer has a contract that stipulates maximum daily reclaimed water allocation, reclaimed water storage requirements, and reclaimed water cost structure. In general, offsite reclaimed water storage lakes (Supplementary Fig. 3) are required to hold a minimum volume equivalent to 3 days of peak irrigation demand; the total volume of offsite lakes is 547,087 m^3, the median area is 0.9 ha, and the mean residence time is 20 days (Table 1). Cumulatively, including onsite and offsite lakes, LRD reclaimed water is held in storage lakes for an average of 50 days before being used for irrigation. Groundwater quality in 27 shallow wells (10 background wells and 17 compliance wells) across 10 LRD reclaimed water customers (i.e., golf courses) from 1984 to 2006 was assessed and found no long-term or system-wide negative effects on groundwater quality after 22 years of operation (Arrington and Dent, 2008). All golf courses manage their reclaimed water irrigation systems, whereas in Abacoa LRD maintains a single pump station and major irrigation trunk lines that serve reclaimed water to neighborhood property owner associations. Throughout this study, LRD continuously metered all reclaimed water flows: from the treatment plant to the onsite lakes, NF-concentrate flows to onsite lakes, from onsite lakes to each offsite lake, from each offsite lake to the local irrigation systems (Supplementary Fig. 4). Downstream canals are the predominant lotic surface water bodies draining the area (Supplementary Fig. 5).

2.4. Nutrient sampling

Water samples were collected either monthly or quarterly from January 1, 2011 to December 31, 2022 for this study. NF-concentrate was sampled monthly, immediately before blending with the reclaimed water, and analyzed for total nitrogen and total phosphorus. Reclaimed water was sampled for total nitrogen, inorganic nitrogen, organic nitrogen, and total phosphorus from five sequential engineered systems (i.e., gray and green infrastructure; Supplementary Fig. 6): at the downstream end of the wastewater treatment plant (secondary treatment, gray infrastructure; $n = 1$), from the final onsite storage lake (onsite lake, green infrastructure; n = 1), from within offsite reclaimed water storage lakes (offsite lakes, green infrastructure; $n = 4$), as reclaimed water emerged from sprinklers within Abacoa (sprinklers, gray infrastructure; n = 4), and from the surface water drainage system downstream of the Abacoa community (downstream canals, green infrastructure; $n = 2$). For each sampling event, we collected and analyzed a single secondary treatment sample and a single onsite lake sample. The LRD reclaimed water is stored in thirteen offsite storage lakes but, for practical reasons, we selected and sampled four of these lakes throughout this study (i.e., Jupiter Hills, Loxahatchee Club, Admiral's Cove, and Abacoa). We sampled water from four sprinkler heads within the Abacoa community during each sampling event. Reclaimed water was collected as it emerged from sprinkler heads. Finally, we sampled water quality from two surface water canals located downstream of the Abacoa community (Fig. 1). These downstream canals provide stormwater drainage to the Abacoa community and any excess reclaimed water discharged within the community was assumed to impact water quality in these canals.

2.5. Laboratory analysis

Water samples were collected, preserved to a pH of ~2.0, transported on ice to the LRD WildPine Ecological Laboratory, refrigerated at 6 °C, and analyzed within 28 days of collection. The pH of all water samples was adjusted to 5.5–9.0 before analysis. All samples were processed following National Environmental Laboratory Accreditation Conference (NELAC) requirements. Detection limits were as follows: Total Kjeldahl nitrogen 0.2 mg L^{-1} (TKN; EPA 351.2), nitrate + nitrite 0.02 mg L^{-1} (NO_x; EPA 353.2), ammonia nitrogen 0.2 mg L^{-1} (NH_3^+; SM 4500-NH3 C), and total phosphorus 0.005 mg L^{-1} (SM 4500-P E). We calculated nitrogen fractions as total nitrogen = TKN + NO_x, organic nitrogen = TKN – NH_3^+, and inorganic nitrogen = NO_x + NH_3. See Stoner and Arrington (2017) for additional sampling and laboratory analysis details. Total nitrogen and total phosphorus values were compared to numeric nutrient criteria for Florida's peninsular freshwater canals as a conservative measure of eutrophic

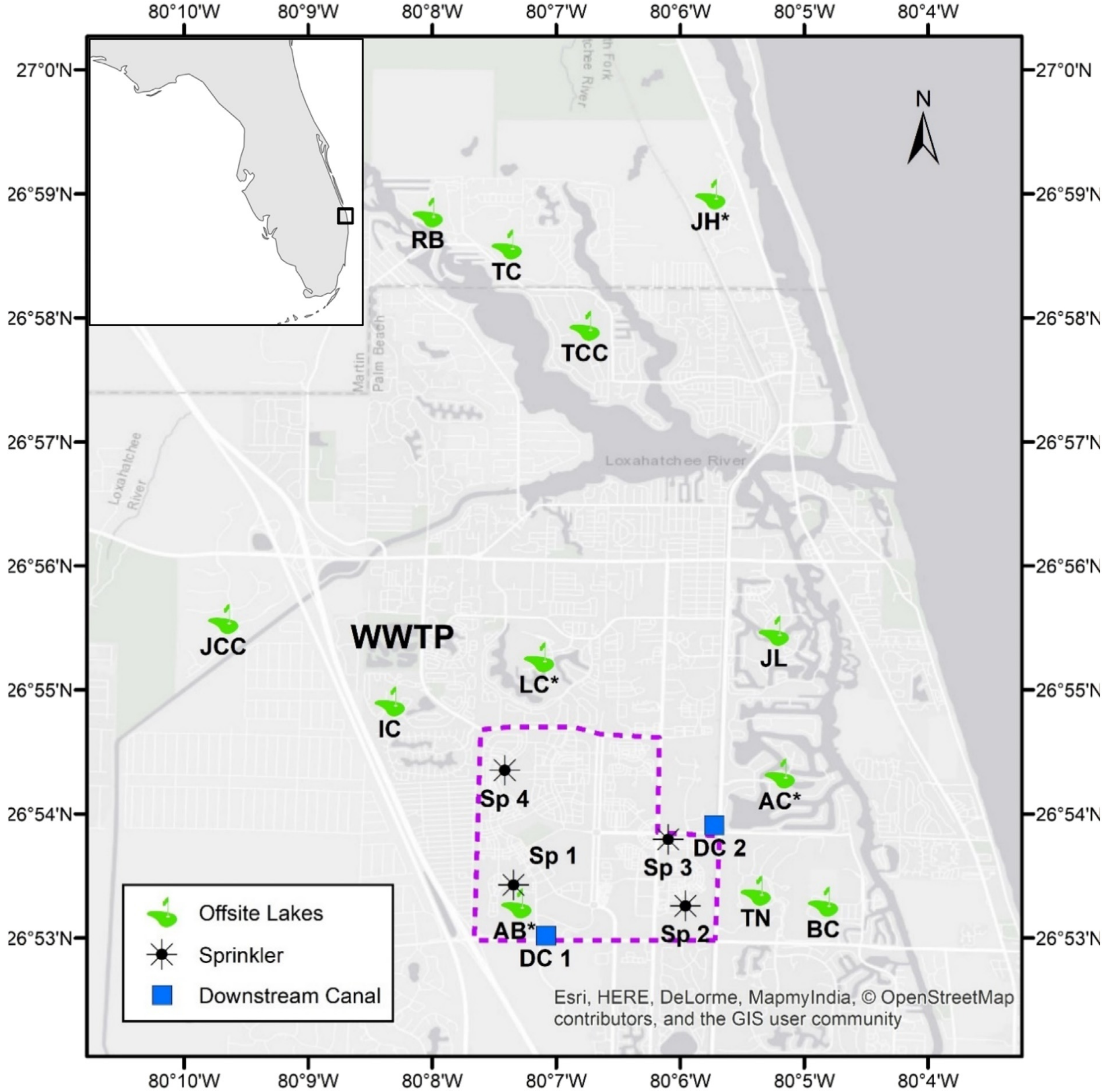


Fig. 1. Loxahatchee River District reclaimed water service area showing the wastewater treatment facility (WWTP), twelve golf courses irrigated with reclaimed water (green icons; Abacoa (AB), Admirals Cove (AC), Bears Club (BC), Indian Creek (IC), Jonathan's Landing (JL), Jupiter Country Club (JCC), Jupiter Hills (JH), Loxahatchee Club (LC), Riverbend (RB), Tequesta Country Club (TCC), Trump National (TN), Turtle Creek (TC)), and Abacoa 1036 ha mixed-use community entirely irrigated with reclaimed water (dashed purple polygon). Reclaimed water quality was monitored at (1) wastewater treatment plant site (WWTP), (2) four offsite (golf course) lakes (AB*, AC*, LC*, and JH*), (3) four reclaimed water sprinklers within Abacoa (SP1, SP2, SP3, and SP4), and (4) two stormwater canals downstream of Abacoa (DC1 and DC2). Nano-concentrate is blended with reclaimed water in onsite lakes at the WWTP. Reclaimed water is then distributed via underground pipes to all reclaimed water customers. Every golf course (plus the Abacoa community) has an on-site reclaimed water storage lake (see Table 1). Downstream canals provide offsite discharge of stormwater for the entire Abacoa community.

conditions (Florida Department of Environmental Protection, Numeric Nutrient Content Criteria).

2.6. Quantifying nutrient loading rates

Nitrogen and phosphorus loading rates were quantified using two approaches. Actual nutrient loading rates were calculated by multiplying the mean total nitrogen or total phosphorus concentration times the average reclaimed water daily hydraulic loading rate (i.e., actual nutrient loading rate) for the period of record (see Table 1, Fig. 3). Maximum potential nutrient loading rates were calculated by multiplying the mean total nitrogen or total phosphorus concentration times the contractual maximum reclaimed water daily hydraulic loading rate (i.e., the contractual daily allocation that cannot be exceeded) for the period of record (see Table 1, Fig. 3). The maximum potential nutrient loading rate is indicative of reclaimed water nutrient loading rates during drought conditions when customers are most likely to use their full daily allocation of reclaimed water.

2.7. Data analyses

Lognormal generalized linear mixed-effects models (GLMM) and planned contrasts between individual water infrastructure systems were used to characterize nutrient concentrations in reclaimed water as it

Table 1
Characterization of LRD reclaimed water customers for the period Jan. 1, 2011 to Dec. 31, 2022. Minimum lake residence times based on lake volume as a function of contractual maximum irrigation rates. Average lake residence times were based on observed irrigation rates. The total irrigated area was 1098 ha. Maximum reclaimed water hydraulic loading rates were defined contractually and established using agronomic rates and site-specific conditions. Average hydraulic loading rates were based on observed reclaimed water irrigation rates.

Reclaimed water customer	Land use	Minimum Offsite Lake Residence Time (days)	Average Offsite Lake Residence Time (days)	Irrigated area (ha)	Average reclaimed water hydraulic loading rate (m^3 ha^{-1} day^{-1})	Maximum reclaimed water hydraulic loading rate (m^3 ha^{-1} day^{-1})
Loxahatchee Club	Golf Course	13	21	82	18.2	30.0
Jupiter CC	Golf Course	18	45	105	12.6	32.4
Bear's Club	Golf Course	14	35	57	13.1	33.2
Trump National	Golf Course	6	7	53	29.9	36.0
Tequesta CC	Golf Course	10	13	51	28.0	37.4
Jonathan's Landing	Golf Course	7	10	49	25.3	37.4
Turtle Creek	Golf Course	25	41	56	23.2	37.3
Admiral's Cove	Golf Course	11	19	142	21.3	37.4
Golf Club of Jupiter	Golf Course	2	5	34	14.4	37.4
Riverbend	Golf Course	3	4	40	27.9	37.4
Jupiter Hills	Golf Course	7	8	102	30.6	44.4
Abacoa	Mixed Use[a]	16	41	327	25.2	46.4
	Average =	11	20	92	22.8	37.2

[a] Mixed Use includes a golf course, professional baseball field, community vegetable garden, training fields, public schools, public parks, and residential irrigation.

moved through gray and green infrastructure (i.e., secondary treatment, onsite lakes, offsite lakes, sprinklers, and downstream canals). We built a GLMM for each response variable, which were the assessed nutrients (i.e., total nitrogen, inorganic nitrogen, organic nitrogen, and total phosphorus). Each of these models included gray and green infrastructure systems as fixed effects and individual site locations as random effects (random intercepts) to group data coming from non-independent locations and to explicitly account for the repeated sampling of these locations (Gomes, 2022). To explain temporal variation in the data we fit the day of the year (ordinal date) as a linear (accounting for day-to-day trends) and 2nd order polynomial (accounting for seasonal trends) fixed effect and we fit year as a random effect (random intercept) to account for year-to-year variation within the study (Gomes, 2022). We assessed each model fit by visualizing residual-fitted value relationships, homogeneity of variance, normality of residuals with quantile-quantile and density-residual plots, Variance Inflation Factors (VIF) to assess collinearity between fixed effects, and random effects quantile-quantile plots (see "ModelChecks" at https://doi.org/10.5281/zenodo.7596368). To assess differences in concentrations of total nitrogen, inorganic nitrogen, organic nitrogen, and total phosphorus between adjacent infrastructure systems (i.e., secondary treatment → onsite lakes → offsite lakes → sprinklers → downstream canals), we conducted the following independent contrasts of the estimated marginal least-squares means, secondary treatment vs onsite lakes, onsite lakes vs offsite lakes, offsite lakes vs sprinklers, sprinklers vs downstream canals, and finally secondary treatment vs sprinklers to assess changes within the entire system. Since we make these five contrasts, all *p* values were adjusted for multiple a priori planned comparisons using the False Discovery Rate (FDR) methods (Benjamini and Hochberg, 1995; Benjamini and Yekutieli, 2001). All of the above analytical methods were conducted in R v. 4.2.2 using the packages 'lme4' (Bates et al., 2015), `performance` (Lüdecke et al., 2021), and 'emmeans' (Lenth et al., 2019) for model building, model checking, and planned contrasts, respectively (to access raw data, code for statistical analyses, and results see https://doi.org/10.5281/zenodo.7596368).

Values throughout the manuscript, in Fig. 3, and Table 2 are reported as mean (of log transformed values, then exponentiated to original scale) ± 1 standard deviation. When assessing nutrient concentrations relative to numeric nutrient criteria, we report geometric mean ± 95 % confidence intervals to be consistent the state statutes. When estimating nutrient loading rates, we used arithmetic means (not transformed means) because the arithmetic means were more conservative (larger; see Table 2). Nutrient loading rates are presented based on average and maximum hydraulic loading rates (see Table 1).

3. Results and discussion

3.1. Reclaimed water production, distribution, and hydraulic loading rates

From January 1, 2011 to December 31, 2022 the LRD wastewater treatment plant received and treated 113,241,359 m^3 (29.9 billion gallons) of wastewater, at an average daily rate of 25,836 m^3d^{-1} (6.8 MGD). Over the same period, the LRD deep injection well was operated on 50 % of the days and used to dispose of 29 % (7401 m^3 d^{-1}) of treated effluent, which occurs when there is no available capacity in reclaimed water storage lakes. The remaining 71 % (18,436 m^3d^{-1}) was treated to reclaimed water standards, blended with NF-concentrate (5530 m^3d^{-1}), and stored in onsite lakes. Ultimately, 84,540,667 m^3 of reclaimed water was distributed to reclaimed water customers at an average daily rate of 19,288 m^3d^{-1} and a maximum daily rate of 42,657 m^3 d^{-1}. The total area irrigated with LRD reclaimed water was 1098 ha (2712 acres). Average and maximum daily reclaimed water hydraulic loading rates are provided in Table 1 for each of the LRD reclaimed water customers, which include 12 golf courses and the community of Abacoa (Fig. 1).

3.2. Rainfall and irrigation rates

From January 1, 2011 to December 31, 2022 average monthly rainfall at the LRD wastewater treatment plant ranged from 6.25 to 23.30 cm mo^{-1} (Fig. 2). Average wet season (May–October) monthly rainfall was 18.51 cm mo^{-1} and dry season (November–April) rainfall averaged 8.71 cm mo^{-1}. There was relatively little monthly or seasonal variation in reclaimed water irrigation rates, which averaged 6.39 cm mo^{-1} annually, 6.37 cm mo^{-1} in the wet season and 6.41 cm mo^{-1} in the dry season (Fig. 2).

3.3. Nutrient concentrations

Observed nutrient concentrations systematically declined as wastewater and reclaimed water moved through gray and green infrastructure from the wastewater treatment plant to onsite and offsite storage lakes, sprinkler heads, and ultimately downstream canals. Raw wastewater entering the wastewater treatment plant contained approximately 42 mg L^{-1} of total nitrogen and 6 mg L^{-1} of total phosphorus; consistent with medium-strength untreated domestic wastewater (Metcalf and Eddy, 2014). After secondary treatment, the mean total nitrogen concentration was 19.42 ± 4.51 (mean ± 1 standard deviation) mg L^{-1}, comprising 16.75 ± 4.01 mg L^{-1} inorganic nitrogen and 2.57 ± 1.59 mg L^{-1} organic nitrogen (Fig. 3a); mean total phosphorus concentration was 2.92 ± 0.55 mg L^{-1}

Table 2

Summary statistics for nitrogen and phosphorus across reclaimed water systems. We conducted a priori planned contrasts between each water system and the immediately downstream system using generalized linear mixed-effects model estimates. We provide sample size, arithmetic mean, and mean of the log transformed values exponentiated to the original scale (to facilitate interpretation) for total nitrogen, inorganic nitrogen, organic nitrogen, and total phosphorus. The percent reduction column shows nutrient reduction in reclaimed water between upstream and downstream systems based on Log-Scale Means. False Discovery Rate adjusted *p*-values reveal statistically significant differences between upstream and downstream systems (⁎). Period of study was Jan. 1, 2011 to Dec. 31, 2022.

Nutrient	Summary statistics					Planned contrasts			
	Reclaimed water system	n	Mean (mg L^{-1})	Log-Scale Mean (mg L^{-1})	SD	Downstream system	t-ratio	p-value	% reduction
Total Nitrogen	Secondary Treatment	266	19.91	19.42	4.51	On-site Lakes	−10.04	<0.001*	73 %
	On-site Lakes	142	6.02	5.26	3.15	Off-site Lakes	−2.95	0.024*	26 %
	Off-site Lakes	187	4.33	3.87	2.31	Sprinkler	0.97	0.346	15 %
	Sprinklers	320	3.66	3.27	1.76	Downstream Canal	−18.67	<0.001*	75 %
	Downstream Canals	92	0.87	0.83	0.29				
Inorganic Nitrogen	Secondary Treatment	144	17.25	16.75	4.01	On-site Lakes	−8.76	<0.001*	85 %
	On-site Lakes	142	3.46	2.47	2.68	Off-site Lakes	−3.08	0.018*	42 %
	Off-site Lakes	184	2.14	1.43	2.08	Sprinkler	1.03	0.318	22 %
	Sprinklers	316	1.62	1.12	1.45	Downstream Canal	−12.85	<0.001*	80 %
	Downstream Canals	92	0.23	0.22	0.04				
Organic Nitrogen	Secondary Treatment	142	3.03	2.57	1.59	On-site Lakes	−0.44	0.675	7 %
	On-site Lakes	142	2.56	2.38	0.99	Off-site Lakes	−0.89	0.615	10 %
	Off-site Lakes	184	2.21	2.14	0.54	Sprinkler	0.70	0.615	10 %
	Sprinklers	311	2.08	1.91	0.83	Downstream Canal	−12.48	<0.001*	73 %
	Downstream Canals	92	0.64	0.52	0.27				
Total Phosphorus	Secondary Treatment	281	3.02	2.92	0.55	On-site Lakes	−4.15	0.006*	39 %
	On-site Lakes	142	1.85	1.77	0.42	Off-site Lakes	−2.27	0.052	20 %
	Off-site Lakes	187	1.55	1.41	0.49	Sprinkler	3.29	0.006*	19 %
	Sprinklers	321	1.23	1.14	0.47	Downstream Canal	−43.06	<0.001*	97 %
	Downstream Canals	92	0.05	0.04	0.04				

(Fig. 3b). These nutrient concentrations are consistent with reclaimed water receiving secondary treatment in Florida (Badruzzaman et al., 2012; Schmidt et al., 2013), and are sufficiently high to cause eutrophication of natural systems. As the reclaimed water completed the secondary wastewater treatment process (i.e., emerged from the chlorine contact chamber) it was discharged into two elevated, lined lakes and blended with NF-concentrate. NF-concentrate contained 2.18 ± 1.70 mg L^{-1} TN and 0.42 ± 2.17 mg L^{-1} TP. We did not measure ammonia in the NF-concentrate, so we could not partition this nitrogen into inorganic and organic fractions. Throughout 12 years of study, NF-concentrate comprised 22.54 % of water discharged to the reclaimed water storage lakes. Therefore, a dilution equation blending 22.54 % NF-concentrate (2.18 mg L^{-1} TN and 0.42 mg L^{-1} TP) with 77.46 % reclaimed water (19.42 mg L^{-1} TN and 2.92 mg L^{-1} TP) yielded reclaimed water with 15.53 mg L^{-1} TN and 2.36 mg L^{-1} TP—a 20.0 % decline in TN and an 19.3 % decline in TP. Thus, a portion of the nitrogen and phosphorus decline observed between secondary treatment and onsite lakes (Fig. 3) was a dilution effect.

Total nitrogen concentrations declined significantly among reclaimed water systems (Secondary vs sprinkler contrast, $p < 0.001$) as reclaimed water flowed from the secondary treatment system (19.42 ± 4.51 mg L^{-1}) to onsite lakes (5.26 ± 3.15 mg L^{-1}), offsite lakes (3.87 ± 2.31 mg L^{-1}), sprinklers (3.27 ± 1.76 mg L^{-1}), and downstream canals (0.83 ± 0.29 mg L^{-1}) (Fig. 3a; Table 2). Total nitrogen declined by 73 % (from 19.42 to 5.26 mg L^{-1}) between the end of the secondary wastewater treatment and the onsite lakes, with 20 % of the removal driven by dilution with NF-concentrate and the remaining 53 % removal driven by processes occurring in the onsite reclaimed water storage lakes. Mean total nitrogen concentrations measured at sprinkler heads (3.27 mg L^{-1}) were comparable to total nitrogen concentrations of 3 mg L^{-1} achieved by advanced wastewater treatment facilities (Fan et al., 2014; Metcalf and Eddy, 2014). Thus, the combined gray and green infrastructure achieved total nitrogen concentrations similar to advanced wastewater treatment systems but with significantly lower energy use, lower greenhouse gas emissions, and a fraction of the cost.

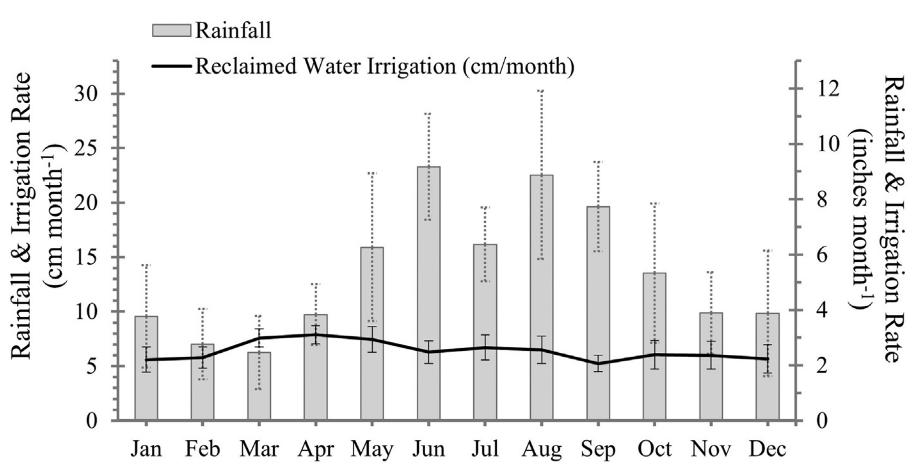


Fig. 2. Mean (± 95 % confidence intervals) monthly rainfall (gray bars) and reclaimed water irrigation (black line) rates for the period January 1, 2011, to December 31, 2022. The wet season (May to October) averaged 18.51 cm of rainfall per month while the dry season averaged 8.71 cm mo^{-1}. Mean monthly reclaimed water application rates exhibit some seasonality (peak in April and minimum in September), but far less than might be expected based on the seasonality of rainfall.

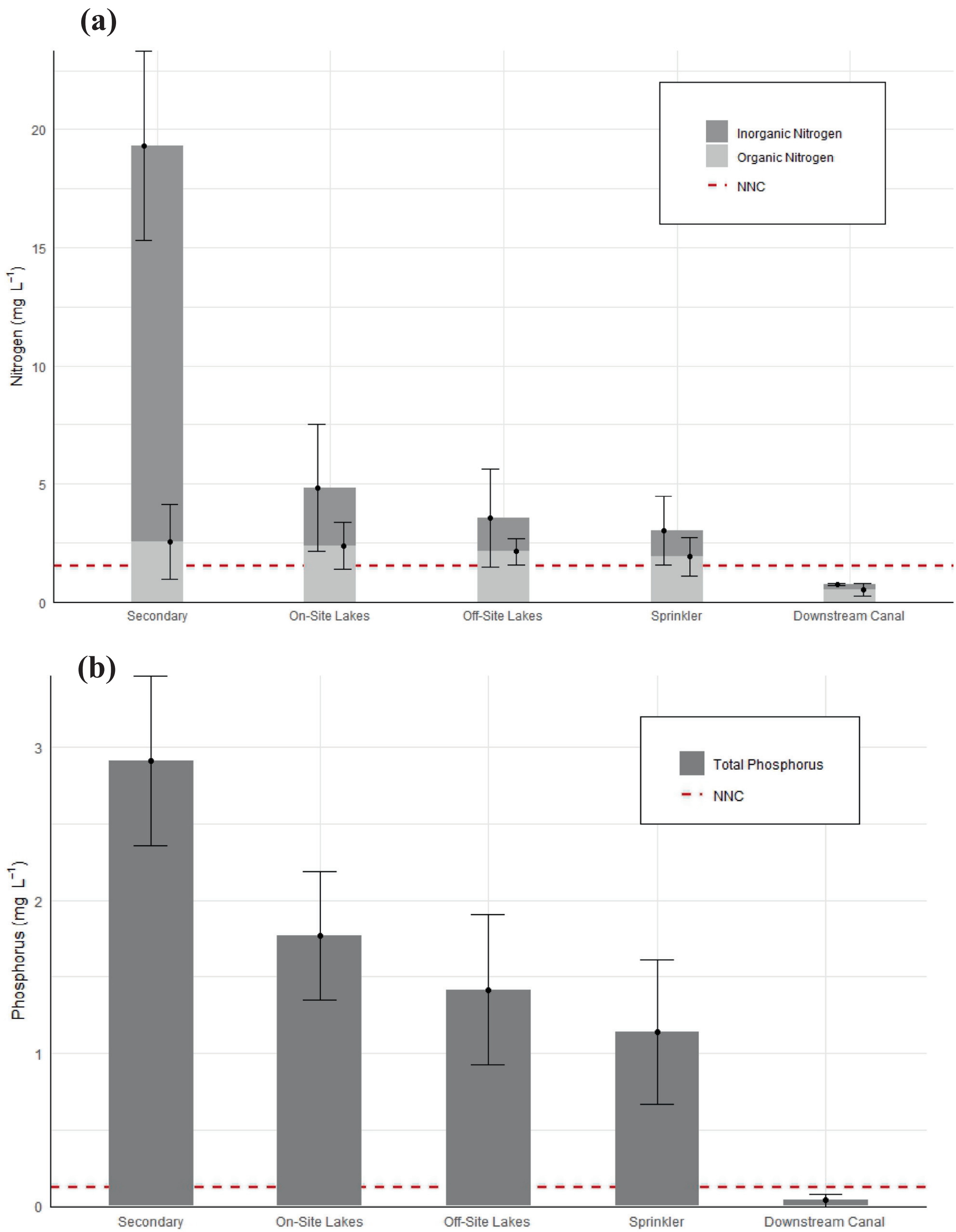


Fig. 3. Nutrient concentrations decreased as reclaimed water moved through the LRD-engineered systems. Mean (calculated on the logscale) (a) nitrogen and (b) phosphorus concentrations (± 1 standard deviation) for the period January 1, 2011, to December 31, 2022; summary statistics are provided in Table 2. The red dashed line depicts local numeric nutrient criteria (NNC) for peninsular freshwater streams (1.54 TN mg L^{-1} and 0.12 TP mg L^{-1}).

Inorganic nitrogen was the largest fraction of nitrogen in treated wastewater and declined significantly (Secondary vs sprinkler contrast, $p < 0.001$) among reclaimed water systems with the largest magnitude decline observed as reclaimed water moved from the secondary wastewater treatment system (16.75 ± 4.01 mg L^{-1}) to the onsite lakes (2.47 ± 2.68 mg L^{-1}), and smaller declines between subsequent systems, i.e., offsite lakes (1.43 ± 2.08 mg L^{-1}), sprinklers (1.12 ± 1.45 mg L^{-1}), and downstream canals (0.22 ± 0.04 mg L^{-1}) (Fig. 3a; Table 2). Inorganic nitrogen, i.e., nitrate + nitrite + ammonia, represented the most nitrogen that was lost—an 85 % decline in mean inorganic nitrogen concentrations occurred from secondary treatment to onsite lakes (Table 2; Fig. 3a). These decreased nitrogen concentrations were likely driven by physical and biological factors, including microbially-mediated ammonification-nitrification-denitrification (Lee et al., 2009; Rivers et al., 2018; Vymazal, 2007; Yazdi et al., 2021), assimilation by primary producers (Schwammberger et al., 2020), retention in sediments (Griffiths and Mitsch, 2020; Lusk and Chapman, 2021; Schroer et al., 2018), and biofilm uptake and transformation in reclaimed water transmission pipes (Rodríguez-Gómez et al., 2005).

Organic nitrogen concentrations did not differ significantly across all reclaimed water system (Secondary vs sprinkler contrast, $p = 0.211$), with concentrations declining consistently but not significantly as water moved from the secondary treatment plant (2.57 ± 1.59 mg L^{-1}) to onsite lakes (2.38 ± 0.99 mg L^{-1}) to offsite lakes (2.14 ± 0.54 mg L^{-1}) and sprinklers (1.91 ± 0.83 mg L^{-1}); however, there was a significant decrease in organic nitrogen concentrations between sprinklers and downstream canals (0.52 ± 0.27 mg L^{-1}; sprinkler vs canal contrast, $p < 0.001$; Table 2; Fig. 3a). Organic nitrogen increased, as a proportion of total nitrogen, from secondary treatment (13 %) to onsite lakes (45 %), offsite lakes (55 %), sprinklers (58 %), and downstream canals (63 %). Organic nitrogen concentrations were more persistent than inorganic nitrogen and are consistent with findings in stormwater systems, which identified few mechanisms other than burial in sediments that effectively removed organic nitrogen in wet detention systems analogous to our lakes (Harper and Baker, 2007; Vymazal, 2007).

Total phosphorus significantly declined among reclaimed water systems (Secondary vs sprinkler contrast, p < 0.001), from secondary treatment (2.92 ± 0.55 mg L^{-1}) to onsite lakes (1.77 ± 0.42 mg L^{-1}), offsite lakes (1.41 ± 0.49 mg L^{-1}, nearly significant at $p = 0.052$), sprinklers (1.14 ± 0.47 mg L^{-1}), and downstream canals (0.04 ± 0.04 mg L^{-1}) (Fig. 3b; Table 2). Total phosphorus declined by 39 % (from 2.92 to 1.77 mg L^{-1}) between secondary effluent and onsite lakes, with 49 % (0.56 mg L^{-1}) of this decline due to dilution with NF-concentrate and 51 % of the decline (0.59 mg L^{-1}) due to physical and biological processes in the onsite storage lakes. Phosphorus removal efficiency in the reclaimed water storage lakes was comparable to the median total phosphorus removal efficiency of 68 % (95 % confidence interval of 43–82 %) in Florida wetlands receiving secondarily treated domestic wastewater (Land et al., 2016). The primary processes removing phosphorus from the water column in these systems were sorption, precipitation, plant update, and soil accretion (Vymazal, 2007). Mean total phosphorus concentrations measured at sprinkler heads (1.14 mg L^{-1}) were only slightly higher than effluent produced by advanced wastewater treatment (1 mg L^{-1}; 403.086, Florida Statutes). The joint gray and green infrastructure produced effluent quality comparable to advanced wastewater treatment facilities (Fan et al., 2014; Metcalf and Eddy, 2014).

In stormwater canals downstream of a mixed-use community irrigated exclusively with reclaimed water, geometric means of total nitrogen and total phosphorus (0.83 and 0.04 mg L^{-1}, respectively) were below established numeric nutrient criteria for peninsular freshwater streams (1.54 and 0.12 mg L^{-1}; Florida Administrative Code R. 62–302.531). Mean chlorophyll *a* concentration corrected for phaeophytin at these same locations was 10.9 μg L^{-1}. Observed total nitrogen and total phosphorus geometric means from secondary treatment (19.40 and 2.92 mg L^{-1} TN and TP, respectively), onsite lakes (5.26 and 1.77 mg L^{-1}), offsite lakes (3.87 and 1.41 mg L^{-1}), and sprinklers (3.27 and 1.14 mg L^{-1}) all exceeded Florida's numeric nutrient criteria for peninsular freshwater streams (Fig. 3a). Nonetheless, the geometric means of total nitrogen and total phosphorus within downstream canals (0.83 and 0.04 mg L^{-1}) were 46 % and 70 % below the numeric nutrient criteria for peninsular freshwater streams even though monitored canal sites were located downstream of and receiving stormwater from the 1036 ha area that was entirely irrigated with reclaimed water. While others have documented eutrophication caused by landscape irrigation with treated reclaimed water (Toor et al., 2017), our results demonstrate that waterbodies receiving stormwater discharged from a large, mixed-use community irrigated entirely with reclaimed water were not eutrophic (i.e., nitrogen, phosphorus, and chlorophyll *a* water column concentrations were below numeric nutrient criteria; Fig. 3). Nutrient loading from landscape irrigation with reclaimed water did not impact surface water quality likely because landscape vegetation (predominantly turfgrass) assimilated and retained nutrients. Many of these nutrients were removed from the local system when excess vegetative matter was harvested and sent to mulching facilities. Further, the predominantly calcium carbonate soils immobilized nutrients (especially phosphorus) between sprinkler heads and downstream canals.

The reclaimed water distribution system, i.e., the underground pipe network, also appeared to contribute to declining nitrogen concentrations. Surface waters in reclaimed water storage lakes are generally aerobic and contained meaningful concentrations of nitrate and nitrite, but reclaimed water becomes anoxic as it flows through distribution pipes (Anwar et al., 2022; Li et al., 2019; Rodríguez-Gómez et al., 2005). In our study, sulfide odors and incidental dissolved oxygen measurements immediately before water emerged from sprinkler heads indicate the anoxic condition of the water as it traveled through the irrigation distribution system (56,710 m of underground pipes). This provides conditions for nitrification-denitrification in linked aerobic-anaerobic conditions.

3.4. Nutrient loading rates

In addition to assessing nutrient concentrations, we also quantified nutrient loading rates driven by reclaimed water landscape irrigation and contextualized these loading rates relative to agronomic requirements. We estimated nutrient loading rates that would have occurred if landscape irrigation had occurred with reclaimed water derived from each of the engineered steps in the system (i.e., from the end of secondary treatment, onsite lakes, offsite lakes, or sprinklers). Based on observed nutrient concentrations (i.e., actual mean values shown in Table 2) in water samples and the actual reclaimed water hydraulic loading rate (23 m^3 d^{-1} ha^{-1}), we computed the average total nitrogen (Fig. 4a) and phosphorus (Fig. 4b) loading rates. We observed a dramatic decline in average nitrogen loading from 164 kg ha^{-1} yr^{-1} after secondary treatment to 49 kg ha^{-1} yr^{-1} after spending an average of 30 days in onsite lakes (Fig. 4a). Projected nitrogen loading rates continued to decline as the source of reclaimed water moved from onsite lakes to offsite lakes 36 kg ha^{-1} yr^{-1} and sprinklers 30 kg ha^{-1} yr^{-1} (Fig. 4A). Average phosphorus loading rates exhibited a similar pattern with the potential phosphorus loading rate declining 25 kg ha^{-1} yr^{-1} in secondary treatment to 15 kg ha^{-1} yr^{-1} in onsite lakes, 13 kg ha^{-1} yr^{-1} in offsite lakes, and 10 kg ha^{-1} yr^{-1} in sprinklers (Fig. 4B). We also examined maximum potential nitrogen and phosphorus loading rates by using maximum reclaimed water hydraulic loading rate rather than the actual reclaimed water hydraulic loading rate (Fig. 4). If the reclaimed water customers took their maximum daily contractual allocation of reclaimed water, they, theoretically, could load the following amount of nitrogen to the landscape: 245 kg ha^{-1} yr^{-1} after secondary treatment, 74 kg ha^{-1} yr^{-1} after onsite lakes, 53 kg ha^{-1} yr^{-1} from offsite lakes, or 45 kg ha^{-1} yr^{-1} from sprinklers (Fig. 4A). Similarly, maximum phosphorus loading rates could have been 37 kg ha^{-1} yr^{-1} from secondary treatment, 23 kg ha^{-1} yr^{-1} from onsite lakes, 19 kg ha^{-1} yr^{-1} from offsite lakes, or 15 kg ha^{-1} yr^{-1} from sprinklers (Fig. 4B). The estimated loading rates measured from secondary treatment surpasses the proposed critical loading rate of nitrogen and phosphorus suggested for functional wetlands, 45 and 10 kg ha^{-1} yr^{-1}, respectively (Verhoeven et al., 2006).

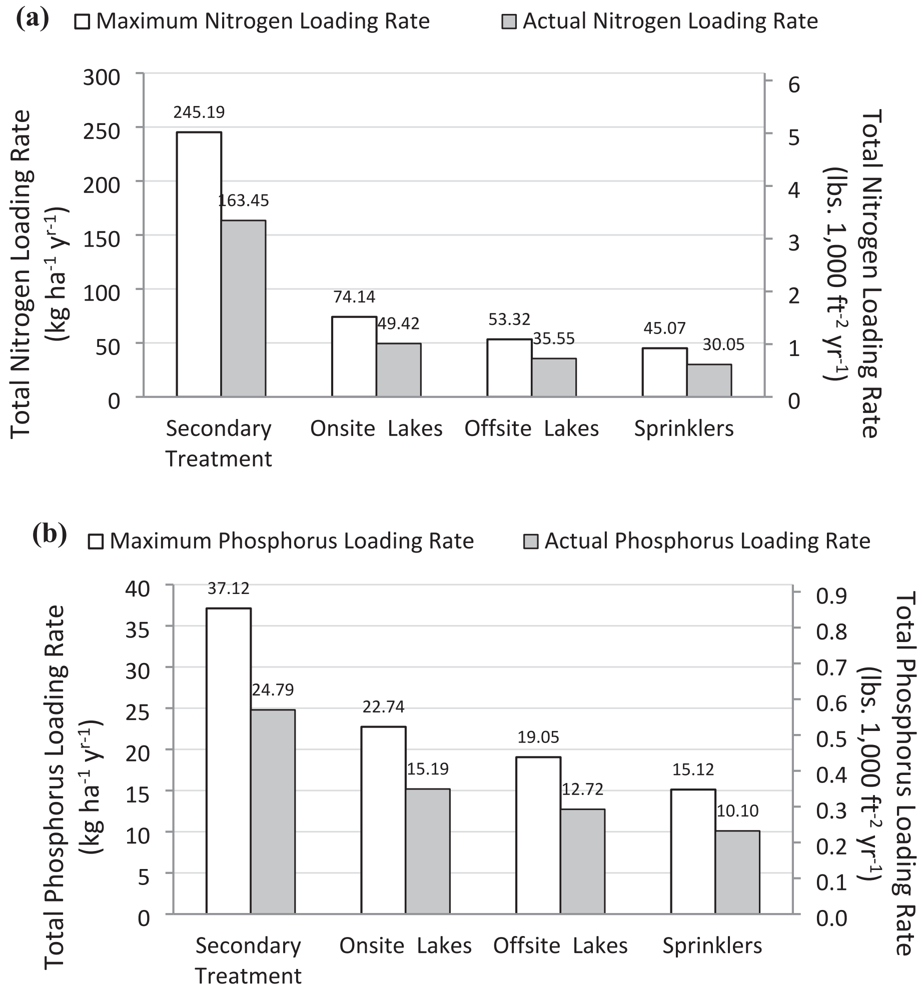


Fig. 4. Potential nutrient loading rates of (a) total nitrogen and (b) total phosphorus derived from landscape irrigation with reclaimed water calculated from mean nutrient values (Table 2) during the period January 1, 2011, to December 31, 2022. Nutrient loading was calculated based on measured mean (a) total nitrogen or (b) total phosphorus concentrations times the contractual maximum reclaimed water hydraulic loading rate (i.e., maximum loading rate) or the average reclaimed water hydraulic loading rate (i.e., actual loading rate) for the period of record, see Table 1. The most relevant nutrient loading rates are those shown for sprinklers—the source of reclaimed water applied to the landscape in the present study.

3.5. Nitrogen needs met with reclaimed water

In Fig. 5, we plot nitrogen loading rates as a percentage of agronomic nitrogen requirements for local turfgrasses. We did not assess phosphorus using this approach, because phosphorus demands in Florida are site-specific based on soils (Yang and Toor, 2017). Values for optimum growth were determined for local south Florida turfgrass species and derived from the University of Florida Institute of Food and Agricultural Sciences: St. Augustine grass (*Stenotaphrum secundatum*) low 195 kg ha^{-1} yr^{-1} (4 lbs. 1000 $ft.^{-2}$ yr^{-1}), St. Augustine grass high 293 kg ha^{-1} yr^{-1} (6 lbs. 1000 $ft.^{-2}$ yr^{-1}), Bahia grass (*Cynodon* spp.) low 98 kg ha^{-1} yr^{-1} (2 lbs. 1000 $ft.^{-2}$ yr^{-1}), Bahia grass high 195.3 kg ha^{-1} yr^{-1} (4 lbs. 1000 $ft.^{-2}$ yr^{-1}), Bermuda grass (*Cynodon dactylon*) low 214 kg ha^{-1} yr^{-1} (5 lbs. 1000 $ft.^{-2}$ yr^{-1}), Bermuda grass high 342 kg ha^{-1} yr^{-1} (7 lbs. 1000 $ft.^{-2}$ yr^{-1}), and established landscape plants ranging from zero to 293 kg ha^{-1} yr^{-1} (6 lbs. 1000 $ft.^{-2}$ yr^{-1}) (Martinez et al., 2014; Trenholm et al., 2002). Based on this, we included 98 kg ha^{-1} yr^{-1} (2 lbs. 1000 $ft.^{-2}$ yr^{-1}), 195 kg ha^{-1} yr^{-1} (4 lbs. 1000 $ft.^{-2}$ yr^{-1}), and 293 kg ha^{-1} yr^{-1} (6 lbs. 1000 $ft.^{-2}$ yr^{-1}) to provide a range of realistic values for local landscaping needs.

We assumed landscape irrigation with reclaimed water that yielded nitrogen loads >100 % of landscape nitrogen needs would contribute to the eutrophication of downstream waters (Trenholm et al., 2002). Based on the nitrogen requirements for plants in south Florida, on average, excess nutrients and potential eutrophication would only occur if irrigation had occurred with reclaimed water collected directly after secondary wastewater treatment and this was limited to low (98 kg ha^{-1} yr^{-1}) and mid-level (195 kg ha^{-1} yr^{-1}) nutrient requirement conditions (over 100 %, red line, Fig. 5). Landscape irrigation with reclaimed water provided an average of 10–31 % of nitrogen needs of turfgrasses and actual nitrogen loading rates never exceeded turfgrass nitrogen demand (Fig. 5).

Total nitrogen derived from reclaimed water emerging from sprinkler heads only provided 10–18 % of recommended fertilization rate for St. Augustine grass, the dominant local turfgrass. This is consistent with previous work that found irrigation with effluent from advanced treated wastewater (averaging 3 mg L^{-1} total nitrogen) alone was insufficient to support maximum St. Augustine grass growth (Fan et al., 2014). Additionally, an unpublished report that assessed multiple plots of St. Augustine grass irrigated with reclaimed water within Abacoa (see Fig. 1), including varying amounts of supplemental fertilization (0, 50 %, 75 %, 100 % of suggested agronomic fertilization rates), recommended fertilization should occur at 75 % of the recommended nitrogen application rate (Weinberg, 2015). These findings were based on quantitative and qualitative assessment of turfgrass plots within Abacoa over a year and support our findings that nutrients in the reclaimed water provide ~25 % of the nitrogen needed to

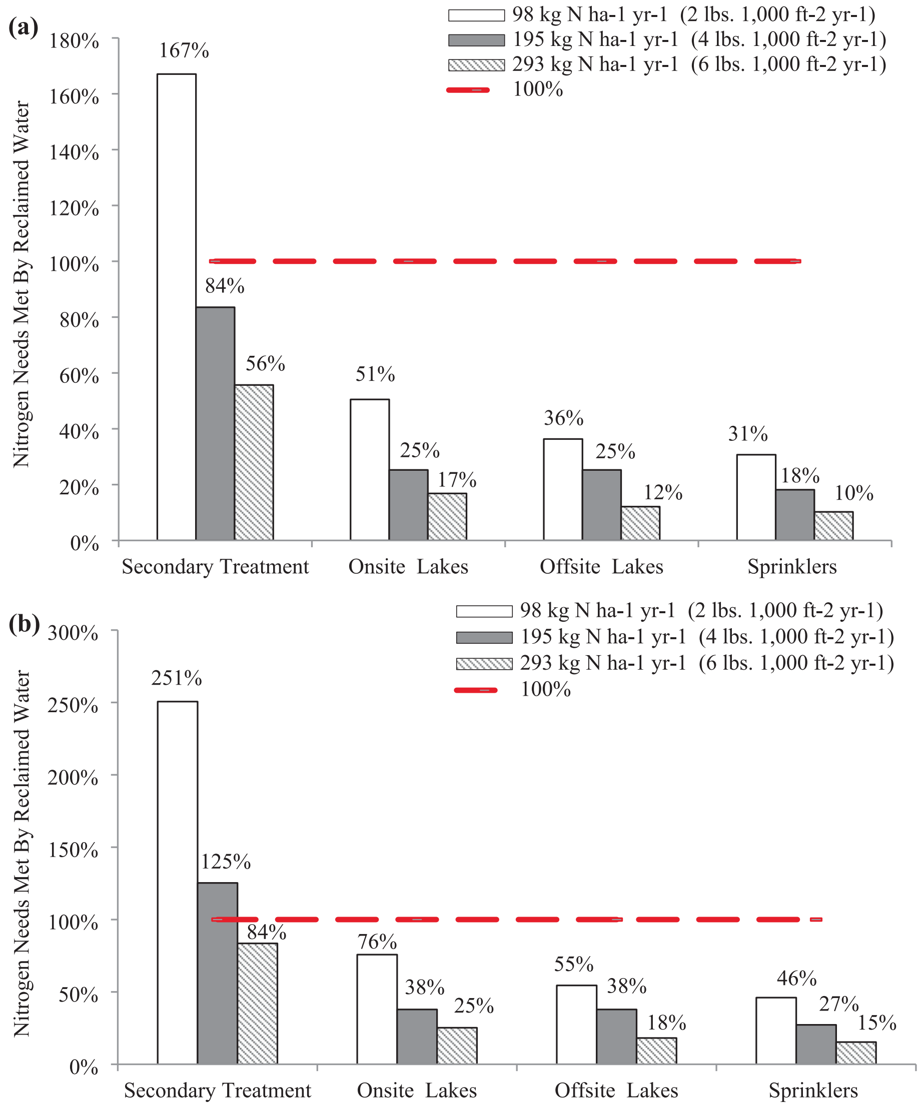


Fig. 5. Percent of turfgrass agronomic nitrogen requirements i.e., nitrogen needs, met by landscape irrigation with reclaimed water as it moved through the LRD-engineered systems for (a) average nitrogen loading rate and (b) maximum nitrogen loading rate (see Fig. 4) derived from mean nutrient values (Table 2) from the period January 1, 2011, to December 31, 2022. Percent values for optimum plant growth based on 98 kg ha^{-1} yr^{-1} (white bar), 195 kg ha^{-1} yr^{-1} (gray bar), and 293 kg ha^{-1} yr^{-1} (lined bar). The dashed red line is estimated plant assimilation based on optimum plant growth. Values <100 % suggest full plant assimilation and > 100 % assimilation indicates potential eutrophication downstream.

support lush turfgrass. Thus, it appears that irrigation with reclaimed water lessens the need for additional fertilizer, further addressing green goals by obviating the need for mining fertilizer—an energy-intensive, ecosystem-damaging activity. We did not calculate the percent of phosphorus needs met with reclaimed water; nevertheless, low phosphorus and chlorophyll *a* concentrations in surface waters of downstream canals indicate eutrophication is not occurring and suggests the phosphorus in the reclaimed water was assimilated into the landscape.

3.6. Other considerations

We acknowledge that this study lacks causal mechanisms underlying the declining nutrient concentrations observed through these infrastructure systems; yet, regardless of mechanisms, evidence that water quality was significantly improved through the passive use of green infrastructure has important management implications. A logical next step to optimize green infrastructure development is to quantify system-specific factors affecting nutrient removal in storage lakes. Much emphasis has been placed on algal and microbial communities in systems receiving reclaimed water (Chen et al., 2017; Liu et al., 2021; Luo and Li, 2018; Yang et al., 2022), and that warrants attention in the design of any system. Potential by-products of the system, e.g., trace gas emissions (Kyung et al., 2020; Kyung et al., 2015; Mannina et al., 2016), need to be quantified at scale. Other aspects of reclaimed water need to be considered, such as residuals from pharmaceutical and personal care products (Lyu et al., 2019) or various microbiological parameters (Deviller et al., 2020). Factors besides nutrient concentrations may affect irrigated plants, e.g., water salinity (Ahmad et al., 2010; Liu et al., 2023; Parsons et al., 2010) or via effects on soil properties (Zalacain et al., 2019). Future studies should assess preferential uptake of nitrogen and phosphorus from reclaimed water irrigation vs fertilizers and quantify the nutrient subsidy of plants by nutrients in reclaimed water. Rigorous economic cost-benefit analyses of the infrastructure (e.g., reduced greenhouse emissions and cost efficiency) may provide additional, quantifiable justifications to sway customers and policymakers to conceptually accept, permit, and fund green infrastructure systems. That is, translating abstract scientific values into understandable currencies, e.g., carbon emissions or dollars, could better highlight the positive attributes of joint gray and green infrastructure.

4. Conclusions

Our findings show gray infrastructure designed for secondary treatment of wastewater, integrated with green infrastructure, achieved lower nutrient concentrations nearly equivalent to advanced wastewater treatment systems. This occurred while consuming substantially less energy and producing fewer greenhouse gas emissions than traditional gray infrastructure—at lower cost and higher efficiency. Using reclaimed water to meet landscape irrigation needs provides a drought-proof, alternative source of water, allowing natural water to remain in natural systems such as wetlands, surface waters, and underground aquifers. Nutrients supplied to landscapes via irrigation with effectively treated and rationed reclaimed water should be quantified and fertilizer application rates reduced accordingly.

This LRD reclaimed water system has been in operation for 39 years for which we report data for 12 years—there is no evidence that landscape irrigation with reclaimed water is driving eutrophication of surface waters. Nutrient concentrations within downstream canals were relatively low because biological (e.g., turfgrasses, biofilms) and physical (e.g., adsorption) factors contributed to nutrient uptake. We encourage other utilities and regulators to consider the economic, societal, and environmental benefits derived from implementing joint gray and green infrastructure when designing reclaimed water systems. As long as the public desires lush landscapes, using reclaimed water to meet landscape irrigation demands at lawns, golf courses, and public parks is a value-added approach. This demonstrates a circular economy design and takes steps toward desired sustainable development goals.

CRediT authorship contribution statement

D. Albrey Arrington: Conceptualization, Investigation, Methodology, Project administration, Writing - Original Draft.

Rachel Joy Harris: Resources, Investigation, Visualization, Writing - Original Draft.

Craig A. Layman: Investigation, Writing - Review & Editing.

Dylan G. E. Gomes: Formal analysis, Visualization, Writing – Reviewing & Editing.

Data availability

Our raw data, statistical code, model checks, and results have been posted at https://doi.org/10.5281/zenodo.7596368

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We wish to acknowledge Rick Dent for his technical understanding and foresight in the conceptualization and implementation of the irrigation water quality program. We also recognize S. Noel, T. Ryan, D. Kehr, H. Johnson, D. Porter, J. Metz, A. Loptatosky, D. Tomasello, and B. Howard for their assistance with field sampling and lab analyses. Thank you to Courtney Marshall for drafting the flow schematic of our system. Finally, we extend our gratitude to three anonymous reviewers whose comments improved the quality of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162232.

References

Ahmad, M., Bajahlan, A.S., Al-Hajery, K.A., 2010. Potential impacts of industrial reclaimed water on landscape irrigation. Int. J. Agric. Biol. 12, 707–712.

Almuktar, S.A.A.A.N., Abed, S.N., Scholz, M., 2018. Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review. Environ. Sci. Pollut. Res. 25, 23595–23623.

Amann, A., Weber, N., Krampe, J., Rechberger, H., Peer, S., Zessner, M., et al., 2022. Systematic data-driven exploration of austrian wastewater and sludge treatment-implications for phosphorus governance, costs and environment. Sci. Total Environ. 846.

Ament, M.R., Roy, E.D., Yuan, Y.P., Hurley, S.E., 2022. Phosphorus removal, metals dynamics, and hydraulics in stormwater bioretention systems amended with drinking water treatment residuals. <sb:contribution><sb:title>J. Sustain. Water </sb:title></sb:contribution><sb:host><sb:issue><sb:series><sb:title>Built Environ.</sb:title></sb:series></sb:issue></sb:host> 8.

Angelakis, A.N., Asano, T., Bahri, A., Jimenez, B.E., Tchobanoglous, G., 2018. Water reuse: from ancient to modern times and the future. Front.Environ.Sci. 6, 26.

Anwar, A., Liu, X.M., Zhang, L.H., 2022. Biogenic corrosion of cementitious composite in wastewater sewerage system-a review. Process Saf. Environ. Prot. 165, 545–585.

Arrington, D.A., Dent, R.C., 2008. Maintenance of groundwater quality throughout twenty years of reuse. Water Pract. 2, 1–10.

Badruzzaman, M., Pinzon, J., Oppenheimer, J., Jacangelo, J.G., 2012. Sources of nutrients impacting surface waters in Florida: a review. J. Environ. Manag. 30, 80–92.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking Landscapes and Communities. Island Press, Washington DC.

Benjamini, Y., Hochberg, Y., 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. Ser. B Methodol. 57 (1), 289–300.

Benjamini, Y., Yekutieli, D., 2001. The control of the false discovery rate in multiple testing under dependency. Ann. Stat. 1165–1188.

Chen, R., Ao, D., Ji, J.Y., Wang, X.C.C., Li, Y.Y., Huang, Y., et al., 2017. Insight into the risk of replenishing urban landscape ponds with reclaimed wastewater. J. Hazard. Mater. 324, 573–582.

Dent, R.C., 1975. Water Resources Management in the Loxahatchee River Basin: Optimum Design and Management of Artificial Lentic Environments for Total Water Reclamation From Treated Wastewater. Loxahatchee River Environmental Control District, Jupiter, FL.

Deviller, G., Lundy, L., Fatta-Kassinos, D., 2020. Recommendations to derive quality standards for chemical pollutants in reclaimed water intended for reuse in agricultural irrigation. Chemosphere 240.

Ellis, S.F., Savchenko, O.M., Messer, K.D., 2019. What's in a name? Branding reclaimed water. Environ. Res. 172, 384–393.

Estevez, S., Gonzalez-Garcia, S., Feijoo, G., Moreira, M.T., 2022. How decentralized treatment can contribute to the symbiosis between environmental protection and resource recovery. Sci. Total Environ. 812.

Fan, J., Hochmuth, G., Kruse, J., Sartain, J., 2014. Effects of reclaimed water irrigation on growth and nitrogen uptake of turfgrass. HortTechnology 24, 565–574.

Gomes, D.G., 2022. Should I use fixed effects or random effects when I have fewer than five levels of a grouping factor in a mixed-effects model? PeerJ 10, e12794.

Griffiths, L.N., Mitsch, J., 2020. Nutrient retention via sedimentation in a created urban stormwater treatment wetland. Sci. Total Environ. 727, 138337.

Harper, H.H., Baker, D.M., 2007. Evaluation of Current Stormwater Design Criteria Within the State of Florida.

Janke, B.D., Finlay, J.C., Taguchi, V.J., Gulliver, J.S., 2022. Hydrologic processes regulate nutrient retention in stormwater detention ponds. Sci. Total Environ. 823.

Jayasooriya, V.M., Ng, A.W.M., Muthukumaran, S., Perera, B.J.C., 2017. Green infrastructure practices for improvement of urban air quality. Urban For. Urban Green. 21, 34–47.

Kyung, D., Kim, M., Chang, J., Lee, W., 2015. Estimation of greenhouse gas emissions from a hybrid wastewater treatment plant. J. Clean. Prod. 95, 117–123.

Kyung, D., Jung, D.Y., Lim, S.R., 2020. Estimation of greenhouse gas emissions from an underground wastewater treatment plant. Membr.Water Treat. 11, 173–177.

Land, M., Granéli, W., Grimvall, A., Hoffmann, C.C., Mitsch, W.J., Tonderski, K.S., et al., 2016. How effective are created or restored freshwater wetlands for nitrogen and phosphorus removal? A systematic review. Environ.Evid. 5.

Lee, P., Smyth, C., Boutin, S., 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. J. Environ. Manag. 70, 165–180.

Lee, C., Fletcher, T.D., Sun, G., 2009. Nitrogen removal in constructed wetland systems. Eng. Life Sci. 9, 11–22.

Lenth, R., Singmann, H., Love, J., Buerkner, P., Herve, M., 2019. R package 'emmeans'.

Li, W.K., Zheng, T.L., Ma, Y.Q., Liu, J.X., 2019. Current status and future prospects of sewer biofilms: their structure, influencing factors, and substance transformations. Sci. Total Environ. 695.

Liu, W., Xu, Z.Q., Long, Y.J., Feng, M.Q., 2021. Replenishment of urban landscape ponds with reclaimed water: spatiotemporal variations of water quality and mechanism of algal inhibition with alum sludge. Sci.Total Environ. 790.

Liu, X., Shang, L., Yang, F., Zhou, W., 2023. Determining reclaimed water quality thresholds and farming practices to improve food crop yield: a meta-analysis combined with random forest model. Sci.Total Environ. 862, 160774.

Lüdecke, D., Ben-Shachar, M.S., Patil, I., Waggoner, P., Makowski, D., 2021. Performance: an R package for assessment, comparison and testing of statistical models. J.Open Source Softw. 6 (60).

Luo, X., Li, X.Y., 2018. Using the EFDC model to evaluate the risks of eutrophication in an urban constructed pond from different water supply strategies. Ecol. Model. 372, 1–11.

Lusk, M.G., Chapman, K., 2021. Chemical fractionation of sediment phosphorus in residential urban stormwater ponds in Florida, USA. UrbanSci. 5.

Lyu, S.D., Chen, W.P., Qian, J.P., Wen, X.F., Xu, J., 2019. Prioritizing environmental risks of pharmaceuticals and personal care products in reclaimed water on urban green space in Beijing. Sci. Total Environ. 697.

Maniam, G., Zakaria, N.A., Leo, C.P., Vassilev, V., Blay, K.B., Behzadian, K., et al., 2022. An assessment of technological development and applications of decentralized water reuse: a critical review and conceptual framework. Wiley Interdiscip.Rev.-Water 9.

Mannina, G., Cosenza, A., Gori, R., Garrido-Baserbac, M., Sobhani, R., Rosso, D., 2016. Greenhouse gas emissions from wastewater treatment plants on a plantwide scale: sensitivity and uncertainty analysis. J. Environ. Eng. 142.

Martinez, C.J., Clark, M.W., Toor, G.S., Hochmuth, G.J., Parsons, L.R., 2014. Accounting for the Nutrients in Reclaimed Water for Landscape Irrigation AE479. University of Florida Institute for Food and Agricultural Sciences.

Metcalf & Eddy, 2014. Wastewater Engineering: Treatment and Reuse. McGraw-Hill Education, New York, NY.

Narain-Ford, D.M., Bartholomeus, R.P., Raterman, B.W., van Zaanen, I., Ter Laak, T.T., van Wezel, A.P., et al., 2021. Shifting the imbalance: intentional reuse of Dutch sewage effluent in sub-surface irrigation. Sci. Total Environ. 752.

Palmer, M.A., Liu, J., Matthews, J.H., Mumba, M., D'Odorico, P., 2015. Manage water in a green way. Science 349, 584–585.

Parsons, L.R., Sheikh, B., Holden, R., York, D.W., 2010. Reclaimed water as an alternative water source for crop irrigation. Hortscience 45, 1626–1629.

Partyka, M.L., Bond, R.F., 2022. Wastewater reuse for irrigation of produce: a review of research, regulations, and risks. Sci. Total Environ. 828.

Pugsley, J.A., 2020. Wastewater Treatment Facility. 2020. . https://loxahatcheeriver.org/about-us/wastewater-treatment-system/.

Rao, A.P., Patel, J., Pradhan, A.K., 2022. Application of alternative sources of water in agricultural food production-current trends and future prospects. <sb:contribution><sb:title>Curr. Opin. Food</sb:title></sb:contribution><sb:host><sb:issue><sb:series><sb:title>Sci.</sb:title></sb:series></sb:issue></sb:host> 47.

Rivers, E.N., McMillan, S.K., Bell, C.D., Clinton, S.M., 2018. Effects of urban stormwater control measures on denitrification in receiving streams. Water 10.

Rodríguez-Gómez, L., Delgado, S., Álvarez, M., Elmaleh, S., 2005. Inhibition of sulfide generation in a reclaimed wastewater pipe by nitrate dosage and denitrification kinetics. Water Environ.Res. 77, 193–198.

Ryan, P., Wanielista, M., Chang, N.B., 2010. Nutrient reduction in stormwater pond discharge using a chamber upflow filter and skimmer (CUFS). Water Air Soil Pollut. 208, 385–399.

Schmidt, H., Waller, P., Oppenheimer, J., Badruzzaman, M., Pinzon, J., Jacangelo, J., 2013. No sweetener in your stormwater, but what about your reclaimed water? Fla. Water Resour.J. 2, 35–47.

Schroer, W.F., Benitez-Nelson, C.R., Smith, E.M., Ziolkowski, L.A., 2018. Drivers of sediment accumulation and nutrient burial in coastal stormwater detention ponds, South Carolina, USA. Ecosystems 21, 1118–1138.

Schwammberger, P.F., Yule, C.M., Tindale, N.W., 2020. Rapid plant responses following relocation of a constructed floating wetland from a construction site into an urban stormwater retention pond. Sci. Total Environ. 699.

Sinclair, J.S., Reisinger, A.J., Bean, E., Adams, C.R., Reisinger, L.S., Iannone, B.V., 2020. Stormwater ponds: an overlooked but plentiful urban designer ecosystem provides invasive plant habitat in a subtropical region (Florida, USA). Sci. Total Environ. 711.

Song, K.Y., Lu, Y., Dao, G.H., Chen, Z., Wu, Y.H., Wang, S.N., et al., 2022. Reclaimed water for landscape water replenishment: threshold nitrogen and phosphorus concentrations values for bloom control. Algal Res.-Biomass Biofuels Bioprod. 62.

Stanford, B.D., Arrington, D.A., Raseman, W.J., Becker, W.C., 2021. Improved operational reliability and contaminant removal in water reuse through filter upgrades. AWWA Water Sci. 3 (5), e1253.

Stanley, E., Arrington, D.A., Dent, R.C., Burden, D.G., Taylor, R.B., 2009. Preserving the environment by increasing reuse supplies blending nanofiltration concentrate and treated effluent. Fla. Water Resour.J. 52–59.

Stoner, E.W., Arrington, D.A., 2017. Nutrient inputs from an urbanized landscape may drive water quality degradation. Sustain.Water Qual.Ecol. 9, 136–150.

Sturiale, L., Scuderi, A., 2019. The role of green infrastructures in urban planning for climate change adaptation. Climate 7.

Sun, D.Y., Lin, X.H., Lu, Z.B., Huang, J.W., Li, G.M., Xu, J.C., 2022. Process evaluation of urban river replenished with reclaimed water from a wastewater treatment plant based on the risk of algal bloom and comprehensive acute toxicity. Water Reuse 12, 1–10.

Taguchi, V.J., Weiss, P.T., Gulliver, J.S., Klein, M.R., Hozalski, R.M., Baker, L.A., et al., 2020. It is not easy being green: recognizing unintended consequences of green stormwater infrastructure. Water 12.

Toor, G.S., Occhipinti, M.L., Yang, Y.Y., Majcherek, T., Haver, D., Oki, L., 2017. Managing urban runoff in residential neighborhoods: nitrogen and phosphorus in lawn irrigation driven runoff. PLoS One 12, e0179151.

Trenholm, L.E., Gilman, E.F., Denny, G., Unruh, J., 2002. Fertilization and Irrigation Needs for Florida Lawns and Landscapes. Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences. University of Florida UF/IFAS Extension (Rev. 2009).

Troitsky, B., Zhu, D.Z., Loewen, M., van Duin, B., Mahmood, K., 2019. Nutrient processes and modeling in urban stormwater ponds and constructed wetlands. Can.Water Resour.J. 44, 230–247.

VanArman, J., Graves, G.A., Fike, D., 2005. Loxahatchee watershed conceptual ecological model. Wetlands 25, 926–942.

Verhoeven, J.T.A., Arheimer, B., Yin, C., Hefting, M.M., 2006. Regional and global concerns over wetlands and water quality. Trends Ecol. Evol. 21, 96–103.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Sci. Total Environ. 380, 48–65.

Wang, J., Liu, J.H., Wang, H., Mei, C., 2020. Approaches to multi-objective optimization and assessment of green infrastructure and their multi-functional effectiveness: a review. Water 12.

Weinberg, E., 2015. TECHNICAL MEMORANDUM Abacoa Reclaimed Water Fertilization Study-Fertilization Guidelines Prepared for: Abacoa POA.

Yang, Y.Y., Toor, G.S., 2017. Stormwater runoff driven phosphorus transport in an urban residential catchment: implications for protecting water quality in urban watersheds. Sci. Rep. 8, 11681.

Yang, L., Wei, J., Qi, J., Zhang, M., 2022. Effect of sewage treatment plant effluent on water quality of Zhangze Reservoir based on EFDC model. Front. Environ. Sci. 10.

Yazdi, M.N., Scott, D., Sample, D.J., Wang, X.X., 2021. Efficacy of a retention pond in treating stormwater nutrients and sediment. J. Clean. Prod. 290.

Zalacain, D., Bienes, R., Sastre-Merlin, A., Martinez-Perez, S., Garcia-Diaz, A., 2019. Influence of reclaimed water irrigation in soil physical properties of urban parks: a case study in Madrid (Spain). Catena 180, 333–340.

Zhang, Q., Smith, K., Zhao, X., Jin, X.K., Wang, S.Y., Shen, J.J., et al., 2021. Greenhouse gas emissions associated with urban water infrastructure: what we have learnt from China's practice. Wiley Interdiscip.Rev.-Water 8.

Zhu, Z.F., Dou, J., 2018. Current status of reclaimed water in China: an overview. J.Water Reuse Desalin. 8, 293–307.

Zurita, F., White, J.R., 2014. Comparative study of three two-stage hybrid ecological wastewater treatment systems for producing high nutrient, reclaimed water for irrigation reuse in developing countries. Water 6, 213–228.