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Lake Trafford Nutrients Budget and Influxes After Organic Sediment Dredging (South Florida, USA)

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Abstract: Lake Trafford, a 600-ha subtropical lake in southwestern Florida, has suffered from over 50 years of cultural eutrophication, resulting in the invasion of *Hydrilla verticillata* and organic sediment accumulation due to herbicide treatments. This study aimed to assess the effects of dredging on nutrient dynamics. A pre-dredging nutrient budget, developed using land use models and climatic data, estimated nutrient loads of 190 kg d^{-1} for total nitrogen (TN) and 18.6 kg d^{-1} for total phosphorus (TP), with total maximum daily loads (TMDLs) of 70.4 kg d^{-1} for TN and 4.15 kg d^{-1} for TP. Post-dredging analysis, using detailed spatiotemporal data, showed higher nutrient loads of 274.3 kg d^{-1} for TN and 24.2 kg d^{-1} for TP. While dredging reduced legacy nutrient accumulation, it led to increased nutrient influx from groundwater, caused by the exposure of organic sediment, as evidenced by increased lake water electrical conductivity. These findings demonstrate the importance of conducting thorough pre-dredging assessments to mitigate unintended consequences, offering practical insights for managing nutrient loads and improving restoration strategies in eutrophic lakes.

Keywords: Lake Trafford; eutrophication; nutrient budget; sediment dredging; groundwater nutrient loading; legacy nutrient loading

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1. Introduction

1.1. Historical Background

Lake Trafford is a small subtropical lake spanning approximately 600 hectares located in southwestern Florida within a 180 km^2 drainage basin. The lake is hydraulically connected to the underlying unconfined aquifer system [1]. When the lake stage reaches an altitude of 6.4 m NAVD'88, water from the lake sheet flows down-gradient into Corkscrew Swamp and to the south into the Fakahatchee Strand, ultimately reaching the coast through the 10,000 islands [2,3]. Historically, Lake Trafford was known as a premier freshwater boating and fishing location [3]. It had a sandy bottom and a diverse, expansive coverage of both submerged and emergent aquatic vegetation. Beginning in the 1960s, urbanization near the City of Immokalee and expansion of local agricultural land use introduced excessive quantities of nutrients into the lake. Over several decades, the influx of nutrients spurred the proliferation of the macrophyte *Hydrilla verticillata*, an invasive plant native to Asia that was accidentally introduced into the lake in 1969.

Although Hydrilla can have positive effects on aquatic ecosystems, such as improving water clarity by stabilizing sediments and reducing particulates and absorbing nutrients like nitrogen and phosphorus, it is a very problematic aquatic plant in southern Florida. With optimal conditions of light, temperature, and nutrients, this plant can grow up to 2.5 cm day^{-1} and a single tuber can produce more than 6000 new tubers per m^2 [4]. *Hydrilla* beds can smother native vegetation (e.g., *Vallisneria americana* and *Potamogeton illinoensis*) and reduce the habitat and suitability of fish populations at elevated densities [5]. *Hydrilla* can grow in dark, turbid waters, requiring only 0.75% of incoming solar radiation to grow [6]. It can grow in a wide variety of conditions and has been known to double its water body coverage in as little as six weeks [5]. Visitors to the lake reported issues such as boat propeller fouling and diminished fishing areas caused by *Hydrilla* covering the entire lake from bottom to surface.

The infestation of *Hydrilla* was remediated using herbicides between 1970 and 1990. The decay of the aquatic plant debris caused the accumulation of thick deposits of organic sediment on the lake bottom. The increased internal and external nutrient loading and organic sediment deposition caused the perpetual disturbance of the bottom sediment due to the lack of anchored vegetation, which led to decreasing water clarity [7].

As a result, Lake Trafford experienced an ecological regime shift from a clear water state to a turbid, phytoplankton-dominated state with no submerged aquatic vegetation to compete for nutrients or stabilize organic sediment once the *Hydrilla* was eradicated (i.e., the turbid state of the alternative stable states as described in Scheffer et al. [8] and summarized in Scheffer et al. [9]).

1.2. Pre-Dredging Nutrient Loading and Sediment Accumulation

The large amounts of organic sediment that had accumulated from the decaying *Hydrilla* created an average 0.74 m thick organic sediment and up to 2 m in some areas [10]. The sediment deposition resulted in reducing lake water volume, increasing the biochemical oxygen demand and causing recurrent (harmful at times) algae blooms that caused massive fish kills (e.g., 50,000 fishes in 1996 [3]). Consequently, Lake Trafford was then added to the State of Florida 303(d) list of impaired waterbodies in 2002 due to chronic hypoxia and elevated concentrations of unionized ammonia typical of dystrophic lakes [11]. The decline of recreation in and around Lake Trafford as well as increasing public outcry from residents spurred the start of a restoration effort beginning in 1996.

In 2000, a collation of governmental groups, including the U.S. Army Corps of Engineers, the Big Cypress Basin of the South Florida Water Management District, the Florida Fish and Wildlife Conservation Commission, and the Collier County Tourist Development Council, provided funding (USD 21 million) to begin remedial measures to improve lake water quality. The funded activities included the dredging of organic sediment from the lake, creation of a storage location for the dredged sediment more than 1.65 km from the lake, restoration of native fish populations, and to reduce the nutrient load into the lake that caused eutrophication.

Removal of organic sediments has been commonly used in lake restoration efforts in many global locations and lake types [12–19]. Commonly, sediment dredging can produce short-term improvements that may not last in time [20,21]. Also, this remedial activity can sometimes cause some unexpected, negative impacts [2,22,23].

Between 2006 and 2010, 4.8×10^6 m^3 of organic sediment was removed from Lake Trafford as part of a remediation plan to restore the lake ecosystem. The mud thickness in the lake before and after removal is shown in Figure 1. Prior to removal of the organic sediment from the lake, the nutrient loading into the lake was modeled based on land use as part of a legally mandated assessment of TMDL for the lake.

The TMDL modeled water and nutrient loading into Lake Trafford using the Hydrologic Simulation Program–Fortran (HSPF), and applied local land use data, topography, and local groundwater well data to model surface flow, baseflow, interflow, and direct precipitation [11]. The model estimated that the lake received an average of 32% of its incoming water from baseflow, 24% from interflow, 23% from direct precipitation, and 21% from runoff during the modeling period between 1998 and 2007 [11]. Estimation of nutrient concentrations were also applied based on land use data to estimate the annual load of nitrogen and phosphorus to the lake. Overall, the model estimated loading at 190 kg d^{-1} of TN and 18.6 kg d^{-1} of TP during the model simulation period. Runoff was estimated to be the largest contributor of TN at 92 kg d^{-1} while subsurface deliveries (baseflow and interflow) contributed 83.5 kg d^{-1}. Conversely, TP loading was estimated to be higher among subsurface deliveries (12.2 kg d^{-1}) and lower from surface runoff (5.6 kg d^{-1}). Per the TMDL report, final load limits were set at a daily maximum load of 70.4 kg d^{-1} for TN and 4.15 kg d^{-1} for TP.

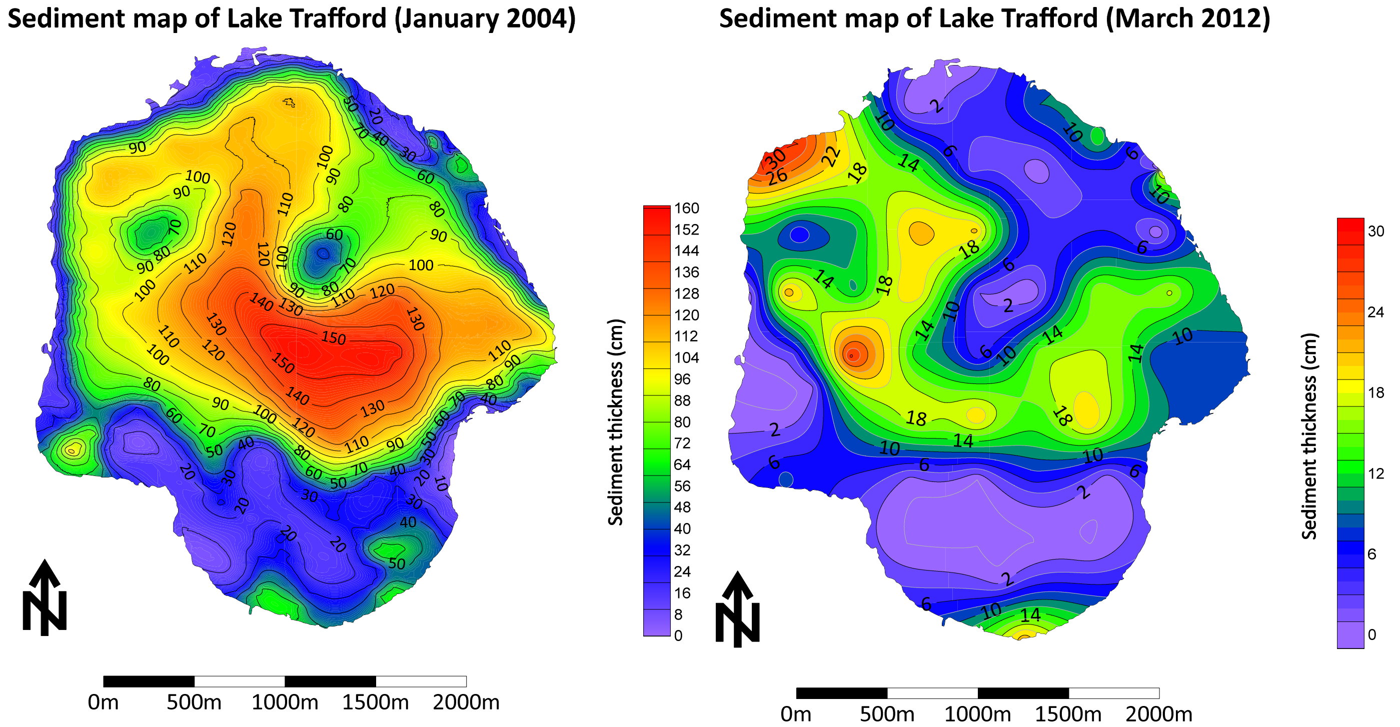

Figure 1. Sediment accumulation pre- (2004 map) and post- (2012 map) dredging of Lake Trafford. Note the 5 time discrepancies between the scales (from Thomas et al. [1]).

1.3. Objectives and Research Hypothesis

Lake nutrient budgets are critical for understanding the impact of nutrient inputs on lake water quality and particularly for managing eutrophication. Excessive nutrient overloading, from especially nitrogen (N) and phosphorus (P), leads to algal blooms, oxygen depletion, and overall threatens aquatic ecosystems. Hence, managing these nutrient inputs is essential for maintaining lake health, and nutrient budgets provide a systematic way to assess sources, sinks, and the overall impact on water quality. In lakes like Lake Trafford, it is essential to accurately account for nutrient inputs from groundwater and runoff since these can be substantial within the subtropical regions.

A post-dredging water budget for Lake Trafford was measured in great detail and is reported by Thomas et al. [1]. Because of the very large quantity of data collected during the one-year study, the post-dredging nutrient balance for the restoration project is reported in this paper. Both the water and nutrient budgets were measured from 2015 to 2016, covering a full year.

A key aspect of this investigation was an assessment of the nutrient input from groundwater which could be carrying higher concentrations of inorganic nutrients than previously estimated and may also be interacting with the surface water of Lake Trafford in unexpected ways. Groundwater nutrient pollution is becoming increasingly problematic and its delivery to lakes and coastal systems can be significant across large temporal and spatial scales [24]. Many studies have shown that nutrient concentrations in groundwater (specifically phosphorus) can be high enough to cause lake eutrophication [25,26]. Nitrogen and phosphorus concentrations in groundwater typically become elevated due to anthropogenic activity, including fertilizer applications for agriculture [27] and the use and poor maintenance of subterranean septic tanks. Both septic tanks and agricultural activity are thought to elevate nutrient concentrations in the surficial aquifer system surrounding Lake Trafford [11].

Post-dredging groundwater seepage may be higher than pre-dredging seepage, as the Lake Trafford average bottom-sediment conductivity has increased post-dredging, potentially indicating increased groundwater discharge [28]. Genereux and Bandopadhyay [29] found that increased sediment thickness and density with lower hydraulic conductivities were very influential on spatial seepage patterns, and often caused increased groundwater discharge farther from shore, even with uniform sediment coverage.

The data reported herein will allow for an evaluation to be made on the impacts of the organic sediment removal on the water quality state within the lake and effects on the eutrophic condition, including regrowth of problem aquatic vegetation, namely *Hydrilla*. It was demonstrated that the groundwater influx into the lake was impacted (probably increased as it is the case in other studies, e.g., [18]) by the organic sediment removal based on an increase in the measured specific conduction of the lake in the post dredging condition (Figure 2). The purpose of the final budget was to determine the most significant sources of nutrients to the lake, the most problematic areas or times for nutrient loading, and to help identify potential areas for remediation. Additionally, the water and nutrient budgets are ideal for comparison to the Lake Trafford-adopted TMDL, which estimated water and nutrient loading into Lake Trafford via land use-based runoff modeling. Increasing the knowledge of the Lake Trafford hydrology and nutrient dynamics is important to guiding its restoration and its hopeful return to a clear water state and is important for comparison to other, less studied subtropical lakes occurring in other regions.

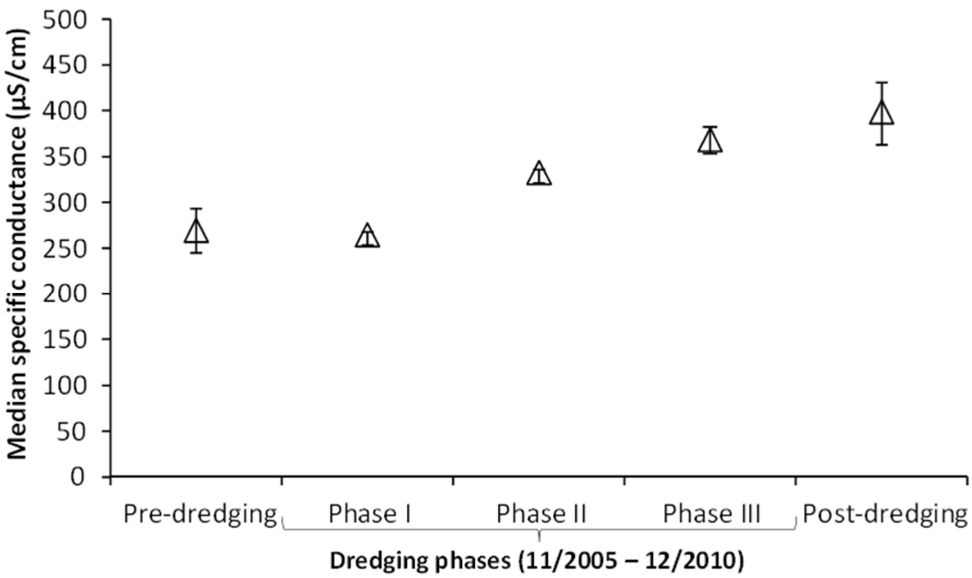

Figure 2. Median specific conductance of Lake Trafford for the various dredging periods: pre-dredging from 1 January 2004, phase I dredging operations from 4 November 2005 to 25 April 2006, phase II dredging operations from 1 December 2006 to 25 April 2006, phase III dredging operations from 1 June 2009 to 28 December 2010 and post-dredging from 1 January 2010 to 31 December 2012. Post-dredging median specific conductance is significantly higher than pre-dredging (p-value < 0.001). Error bars represent the interquartile range (25th–75th percentiles).

This study hypothesizes that while dredging can improve water quality by removing organic sediments, it may also expose groundwater nutrient influxes that were previously capped, potentially offsetting the benefits of dredging. Therefore, the post-dredging nutrient budget will likely show increased contributions from groundwater, requiring further management strategies to mitigate nutrient loading.

2. Material and Methods

2.1. Site Description

Lake Trafford (26.42729° N, 81.48956° W) is a shallow, subtropical, dissolution lake located west of the City of Immokalee in northern Collier County, Florida ([11]; Figure 3).

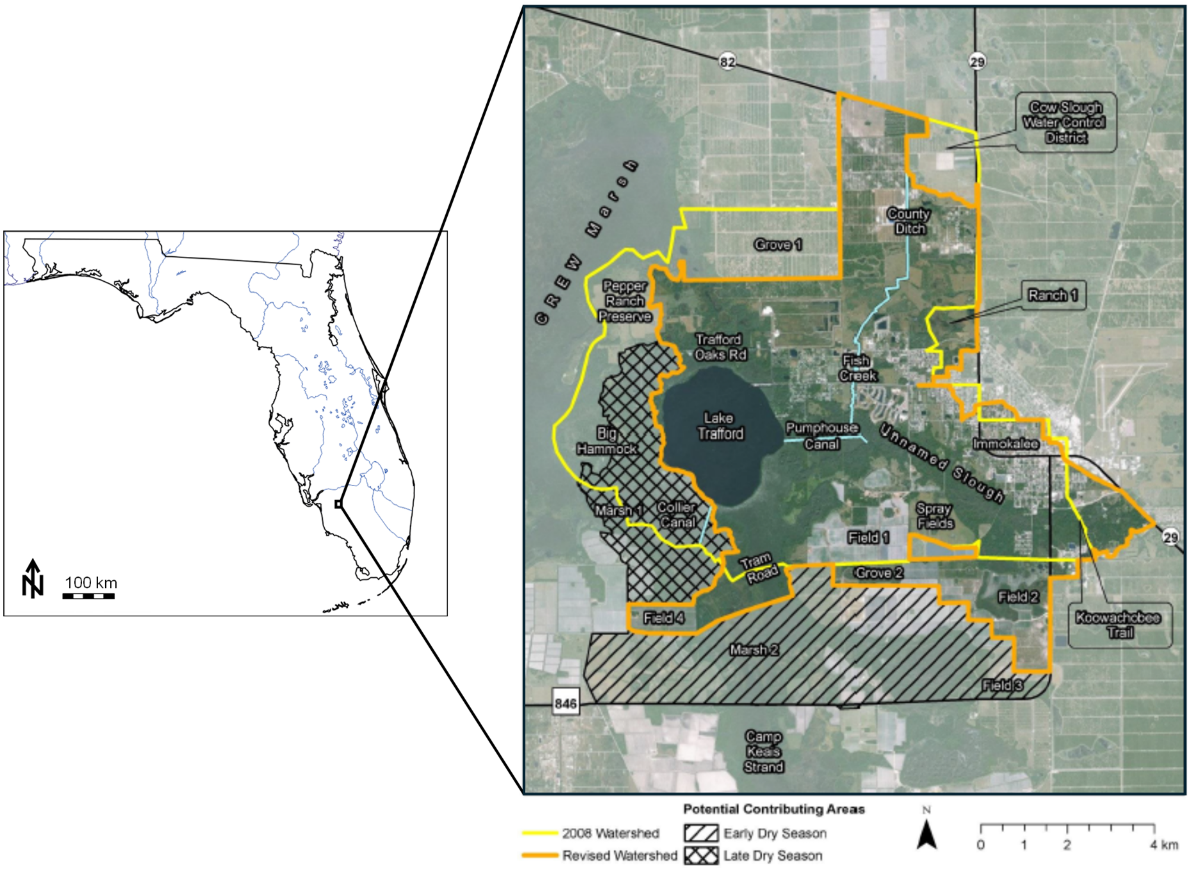

Figure 3. Trafford watershed boundary delineated for the 2008 TMDL report [11] and was revised by Wallace in 2017 [30]. The map includes the location of the Lake Trafford watershed (**right**) within the state of Florida ((**left**) map). State Road 82 (SR 82), State Road 29 (SR 29), and County Road 846 (CR 846) are depicted on the map.

The lake is mostly round with a surface area of approximately 600 ha and an average depth of 1.6 m when the lake stage is at 5.53 m NAVD'88, yielding a maximum depth of about 2.6 m [1]. Due to its circular shape and long multi-directional fetch (2.5–3.15 km depending on wind direction), Lake Trafford is polymictic and prone to high wave activity in times of high winds [2,3].

While Lake Trafford is a seepage lake with no defined tributaries in or out, it is bordered by low-lying wetlands to the south and west that have been known to receive lake water overflow when water levels approach 6.0 m NAVD'88 [11]. The City of Immokalee is situated directly east of Lake Trafford, with extensive agricultural land to the north and south. Its first official drainage basin delineation is found in the 2008 TMDL report [11] and it was reevaluated in 2017 [30] using water level sensors, current, and LIDAR (Figure 3).

2.2. Water Budget

A very detailed one-year investigation of the water budget was made to allow for quantitative analysis of the nutrient budget for Lake Trafford. A diagram of the water budget components is given in Figure 4. The detailed results of this investigation are given in Thomas et al. [1]. Additional information on each component that impacts the nutrient budget is given in the results.

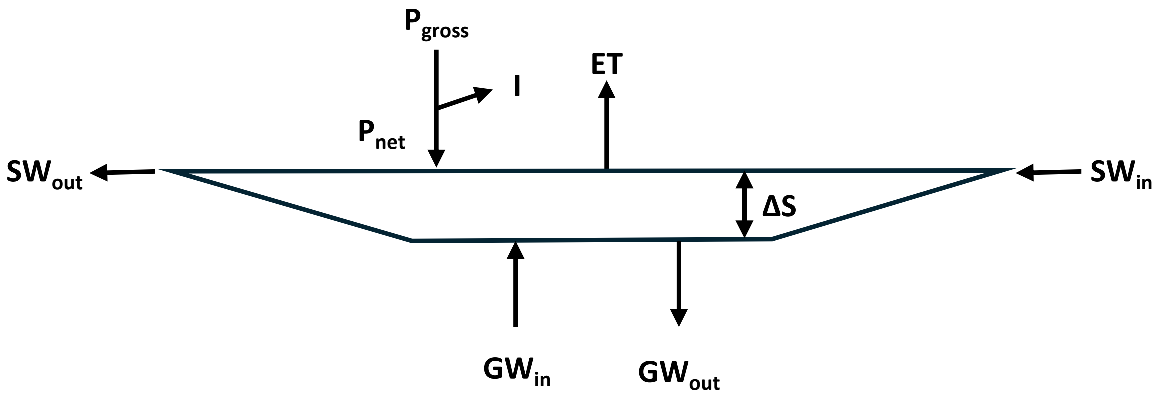

Figure 4. Diagram depicting typical inputs and outputs for aquatic systems. SW_{out} is surface water outflow; SW_{in} is surface water inflow; GW_{in} is groundwater discharge; GW_{out} is groundwater recharge; ET is evapotranspiration; P_{gross} is precipitation; I is interception of precipitation; P_{net} is the net precipitation; ΔS is change in storage [1,31].

2.3. Nutrient Budget

2.3.1. Nutrient Budget Computation

To create the nutrient budget, nutrient mass loading was determined for each component of the water budget (Figure 4). Average mass loads over two-week periods were determined using Equation (1):

$$L = \frac{\sum_{j=1}^{14} A_j C_j Q_j}{\sum_{j=1}^{14} A_j} \tag{1}$$

where L is the mean load, A is either 1 or 0 depending on whether data are available on day j, C_j is the concentration on day j, and Q_j is the flow rate on day j [32]. Loads were expressed as kg per unit time for each budget component. The structure of the nutrient budget model mirrors that of the water budget model [1] with two exceptions: (i) direct surface water runoff was determined through deduction and no water samples were taken to determine nutrient concentration and (ii) dry deposition of particulate nutrients has no corresponding water flux. Data collection occurred from October 2015 to October 2016 and was performed every other week where data could be easily qualified based on sampling event numbers ranging from 1 through 28. Additionally, several composite sampling systems were used that collected samples for extended periods of time (canal and atmospheric nutrient loading). Nutrient data from these systems were applied as the average for each biweekly event. Water samples were taken from each component of the water budget to determine mass nutrient loads and to create a corresponding nutrient budget.

2.3.2. Lake Trafford Groundwater

Groundwater influxes and outfluxes were measured using 20 seepage meters including 5 duplicate meters as described in Thomas et al. ([1], Figure 5).

Sampling water for nutrient analysis directly from a seepage meter collection bag is not recommended, as Belanger and Mikutel [33] found that the residence time of the water in the meters is too long and allows for the anoxic conditions to change the chemistry of incoming groundwater. A shallow groundwater well was thus positioned adjacent to each seepage meter either protruding about 30 cm above the lakebed at locations 1–14 or 30 cm below the lakebed (Figure 6). Between sampling events, the shallow wells were fitted with a press-fitted vented PVC cap at their apex while the deeper wells had their valve closed between sampling events. Each well was dug with a manual post digger so that the resulting borehole was 60 cm deep and was half filled with ASTM silica quartz 20/30 (diam. 841–595 µm) on the bottom and bentonite clay above it (Figure 6).

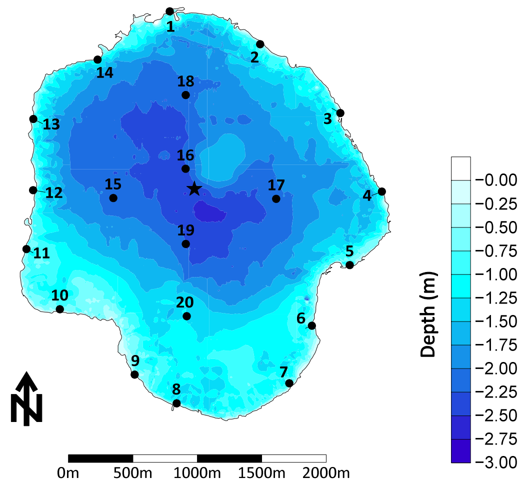

Figure 5. Location of the seepage meters (closed dots) within Lake Trafford. Meters 3, 5, 10, and 13 were used to estimate seepage variation for a given location. Meters 1–14 are situated in the littoral zone, while meters 15–20 are situated in open, deeper water. The black star in the central portion of the lake refers to the station used to sample the lake water column.

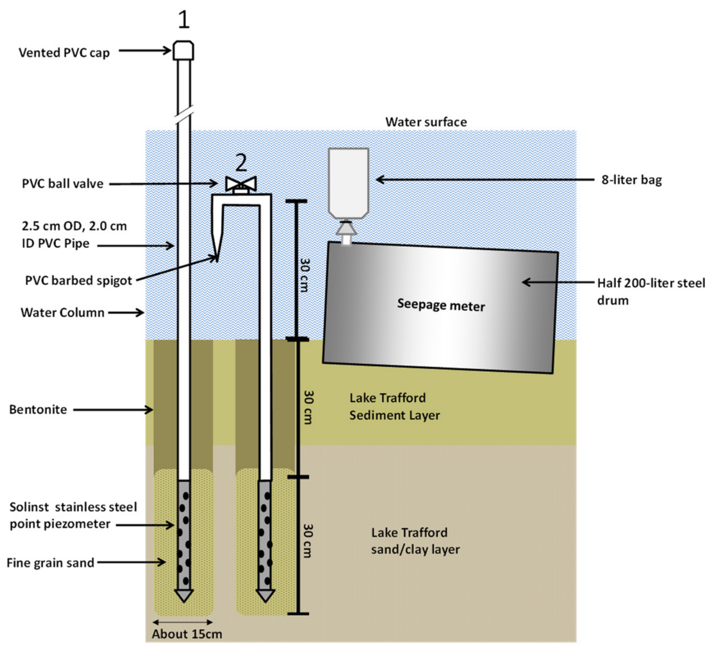

Figure 6. Seepage meter and groundwater wells: well design "1" was used for the shallow seepage meter locations 1 through 14 and well design "2" with a ball valve at the apex was used for the deeper seepage meter locations. The deeper wells were sampled via SCUBA (cf. text for more details).

Deeper groundwater wells were installed using SCUBA gear. Groundwater sampling consisted of coupling a high-pressure braided clear flexible PVC tubing to either the apex of the wells next to the shoreline or to the ribbed spigot with the ball valve in the open position for the deeper wells. The access to the deeper wells was performed via SCUBA. If a seepage meter site measured positive groundwater flux (i.e., >1.25% increase in seepage bag volume of 4 L), groundwater was sampled from the adjacent well and collected at a low flow rate using a Solinst 410 peristaltic pump (www.solinst.com) operated from the boat. The well was first purged two times its standing volume (determined by the current water depth, known depth of the well in the sediment, diameter, and length of the tubing used) before samples were taken. Once collected, samples were preserved with sulfuric acid (pH < 2) and chilled <6 °C, except for one 120 mL sample intended for orthophosphate

(SRP) analysis, which received no acid. Samples were sent to the Florida Department of Environmental Protection (FDEP) laboratory in Tallahassee via overnight shipping for next day analysis. Turbidity, pH, temperature, and conductivity were all recorded in the field using a Hach HQ40d connected to an IntelliCAL™ CDC401 and a PHC101 probe as well as a Hach 2100Q portable turbidity meter (www.hach.com). When conductivity or turbidity levels were found to be abnormally high (turbidity) or low (conductivity), a well evaluation was performed and replaced if needed. Wells 3, 5, 8, 10, and 16 were all replaced during the study. It is believed that loss in performance in these wells was caused by incidental contact with them (boat contact). Well 16 was accidentally broken by the researcher boat anchor during a windy day.

For positive groundwater discharge, groundwater mass loading was calculated using the flow rate and the nutrients concentration of the sampled well groundwater. Conversely, in the event of groundwater recharge, the ambient water column concentration was used to calculate the negative mass load of nutrients.

2.3.3. Lake Trafford Water

Every other week, an integrated water sample was collected from the center of the lake (Latitude North 26.4240°, Longitude West 81.4935°, Figure 5) using a homemade water column bailer. This bailer consisted of a 3.7 m long schedule 40 PVC pipe (6.0 cm OD, 5.2 cm ID) equipped with a one-way check valve at the bottom.

2.3.4. Water from the Five Canals Leading to Lake Trafford

Surface water discharge from each of the five canals connected to the lake was measured with a Sontek IQ or IQ+ flow velocimeter (www.ysi.com/sontek). The locations of the installed velocimeter and water sampler for each canal are described in Thomas et al. [1]. Each flow meter was connected to a WaterLOG storm3 data logger (www.ysi.com), itself connected to an ISCO 3700 automatic sampler (www.teledyneisco.com) so that discharge-weighed water samples, each of 100 mL, could be composited into the same water vessel (a 20 L polyethylene bladder) nested inside the ISCO sampler. The water vessel included 750 mL of 0.5 N sulfuric acid used as a preservative at the beginning of each composite two-week-long sampling event. Positive flow thresholds were changed monthly for each canal depending on anticipated rainfall and discharge. Since the acid preservative prevented the determination of orthophosphate due to acid hydrolysis, a grab sample from each canal was taken during each sampling trip to estimate the loading of soluble reactive phosphorus by determining the typical TP:SRP ratio for each canal.

2.3.5. Dry and Wet Deposition

Dry and wet deposition were measured experimentally at the study site using a homemade dry and wet deposition sampler. The unit was composed of a wooden platform supporting two 19 L HDPE buckets (www.leaktite.com), with the top of the buckets reaching the standard 1.5 m height for dry deposition collection [34]. A railing system was devised, featuring a sliding lid connected to an IP67 rated 30.5 cm linear actuator powered by a deep cycle 12 V battery. The actuator was engineered to either push or retract, sliding the lid along tracks to alternately cover one bucket or the other. During deployment at Lake Trafford, the two buckets would each collect a form of deposition: one bucket for wet and one bucket for dry. The lid was used to cover the dry deposition bucket during rain events (thus exposing the wet deposition bucket) and to cover the wet deposition bucket during dry periods (thus exposing the dry deposition bucket). This was accomplished by wiring the linear actuator to an Arduino Uno open-source coding board, a bread board, a 4 channel 5 V relay board, and a rain drop sensor mounted on top of the unit. A simple code was written using Arduino language that would move the linear actuator one way while precipitation was detected and move the other way when the rain stopped. The program allowed the sensitivity of the rain drop sensor to be adjusted and was always kept at a high sensitivity to prevent light precipitation from entering the dry deposition bucket.

Each bucket was prefilled with an acid solution. The dry deposition collection bucket received 3.78 L of DI water with 150 mL of 0.5 N sulfuric acid and the wet deposition collection bucket received 150 mL of 0.5 N sulfuric acid only. A volume of 19 L is the standard volume for dry deposition measurements and is preferred when compared with the method using empty buckets because it is known to underestimate nitrogen loading [35]. Both buckets received acid as a sample preservative and enough acid was used to maintain pH < 2, even in the event of large amounts of rainfall. Additionally, beginning in February 2016, the buckets' openings were fitted with a stainless-steel screen (3.35 mm × 3.35 mm pore size) to prevent the accumulation of insects and occasionally small reptiles (e.g., anoles, tree frogs) from tainting the samples.

The sampler operated continuously for a fourteen-day period after which the buckets were removed and measured volumetrically. The screens were rinsed with sample water to clean off any dust that had adhered to the screen itself. The samples were then homogenized and subsampled. The buckets were cleaned with a mild sulfuric acid solution and replaced with new water and acid solutions. When samples were collected, a 12 V battery was also swapped with a fully charged battery. Like the ISCO composite samples, orthophosphate could not be analyzed because the samples remained in the field for two weeks and were acidified during this time [36].

Dry and wet deposition rates in the composite sampling containers were applied to the entire lake surface area. The size of the container opening was extrapolated over the planar surface area of Lake Trafford to calculate nutrient deposition loads.

2.3.6. Nutrients Analyses

Samples were analyzed by the Florida Department of Health (DOH), meeting the requirements of the National Environmental Laboratory Accreditation Program (NELAP) accredited by the Florida Department of Environmental Protection (FDEP) Laboratory in Tallahassee for total phosphorus (TP, EPA method 365.1), soluble reactive phosphorus (SRP, EPA method 365.1), total Kjeldahl nitrogen (TKN, EPA method 351.2 Rev. 2.0), ammonia nitrogen (NH_4^+, EPA method 350.1), and nitrate-nitrite nitrogen (NO_x, EPA method 353.2). All samples were handled and preserved according to applicable FDEP standard operating procedures (SOPs) before being shipped overnight to the FDEP laboratory for analysis. Temperature and pH were measured for all samples in the field and laboratory to determine the ratio of ionized (NH_4^+) and unionized (NH_3) forms of ammonia [37], the latter of which is partly responsible for the Lake Trafford official impairment designation [11]. Samples were taken every other fourteen days or composited over these two-week periods (Table 1). Quality control blanks were taken for all sampling equipment and field duplicates were taken for approximately 20% of all groundwater and surface water samples.

Table 1. Sampling type and nutrient species analyzed for each budget component. While six nutrient species were analyzed, only TP and TN (TKN + NO_x) were used for this budget. Check marks "x" in the table indicate the analyte that was sampled.

Budget Component	Sample Type	TP	SRP	TKN	NO_x	NH_4	TOC
Groundwater	Grab (well)	x	x	x	x	x	x
Canal (flow weighed)	Composite	x		x	x		x
Canal (grab)	Grab	x	x	x	x	x	x
Rainfall	Composite	x		x	x		
Dry deposition	Composite	x		x	x		
Lake water	Integrated water column	x	x	x	x	x	

2.3.7. Nutrient Budget Modeling

The nutrient budget model utilized sheet flow values determined from the water budget model to complete the nutrient budget [1]. The nutrient concentrations for sheet flow entering Lake Trafford were estimated using the average composite sample concentration for the five canal locations during each event, with the assumption that the water in the canals has similar chemistry to the direct incoming sheet flow [1]. The final nutrient budget model is represented in Equation (2) as follows:

$$TruTN_{t+1} = TruTN_t + GWLin_t - GWLout_t + CL_t + ADL_t + SFLnet_t + ILnet_t \quad (2)$$

where $TruTN_{t+1}$ is the total kilograms of nutrient (nitrogen or phosphorus) in the lake water; $GWLin_t$ is nutrient loading via groundwater discharge; $GWLout_t$ is nutrient loss via groundwater recharge; CL_t is nutrient loading via canal discharge; ADL_t is nutrient loading via atmospheric deposition; $SFLnet_t$ is net nutrient loading via sheet flow; $ILnet_t$ is the net internal nutrient loading or nutrient retention (via biological uptake or sedimentation), which will be henceforth be referred to as "in-lake processes".

$ILnet_t$ was determined much like sheet flow. Using the nutrient concentrations in the lake and the calculated lake volume, the total kilograms of nitrogen and phosphorus could be calculated. This was then used to determine the difference between the model nutrient mass and the true nutrient mass. This can be represented using Equation (3) as follows:

$$ILnet_t = truTN_t - ModTN_t \quad (3)$$

ModTN in Equation (3) is equal to the value as defined in Equation (4).

$$ModTN = GWLin_t - GWLout_t + CL_t + ADL_t + SFLnet_t \quad (4)$$

Many water samples collected for nutrient analysis were composited over two-week time periods. Thus, the nutrient mass budget could only be run with a biweekly time step (Table 2).

Table 2. Daily rates of groundwater nutrient loading in and out, categorized by sampling event. Mean daily values and standard deviations are reported.

Event	Date Bracket	TN Load in ($kg\ d^{-1}$)	TN Load out ($kg\ d^{-1}$)	TP Load in ($kg\ d^{-1}$)	TP Load out ($kg\ d^{-1}$)
1	1 October 2015–14 October 2015	274.44	−0.10	14.91	−0.01
2	15 October 2015–26 October 2015	261.59	−0.07	12.58	−0.04
3	26 October 2015–11 November 2015	169.49	−0.07	8.53	0.00
4	12 November 2015–23 November 2015	88.97	−2.93	4.33	−0.18
5	23 November 2015–7 December 2015	74.33	−0.35	5.50	−0.02
6	8 December 2015–21 December 2015	82.33	−0.14	5.86	0.00
7	22 December 2015–4 January 2016	13.95	−7.00	2.28	−0.56
8	5 January 2016–18 January 2016	13.74	−2.42	0.53	−0.08
9	19 January 2016–1 February 2016	36.91	−0.43	3.47	−0.02
10	2 February 2016–16 February 2016	108.51	−0.06	6.17	−0.25
11	17 February 2016–1 March 2016	28.13	−1.74	1.40	−0.14
12	2 March 2016–14 March 2016	89.31	−0.10	5.77	0.00
13	15 March 2016–28 March 2016	139.27	−0.07	10.75	−0.01
14	29 March 2016–11 April 2016	103.05	−1.41	6.94	−0.11
15	12 April 2016–26 April 2016	132.50	−0.08	8.14	0.00
16	27 April 2016–9 May 2016	60.10	−0.16	4.06	−0.01
17	10 May 2016–23 May 2016	187.85	−0.17	9.58	−0.01
18	24 May 2016–11 June 2016	127.51	0.00	6.59	0.00

Table 2. *Cont.*

Event	Date Bracket	TN Load in (kg d^{-1})	TN Load out (kg d^{-1})	TP Load in (kg d^{-1})	TP Load out (kg d^{-1})
19	12 June 2016–22 June 2016	158.28	−0.06	11.22	0.00
20	23 June 2016–6 July 2016	42.68	−1.69	1.63	−0.06
21	7 July 2016–19 July 2016	53.62	−0.58	4.54	−0.03
22	20 July 2016–2 August 2016	35.48	−0.64	2.84	−0.55
23	2 August 2016–16 August 2016	104.11	−0.33	8.17	−0.06
24	17 August 2016–29 August 2016	127.46	−3.49	10.71	−0.13
25	30 August 2016–12 September 2016	461.50	−4.23	22.76	−0.12
26	13 September 2016–26 September 2016	179.56	−1.26	11.28	−0.06
27	27 September 2016–10 October 2016	115.78	−0.07	6.43	−0.01
28	11 October 2016–25 October 2016	23.06	−0.77	2.38	−0.03
	Mean	117.63	−1.09	7.12	−0.30
	SD	95.75	1.63	4.80	1.16

2.3.8. Data Handling and Statistics

Data were logged and stored in Microsoft Excel 2016 (www.microsoft.com) and statistical analysis performed using IBM SPSS version 28 statistical software (www.ibm.com). The spatial and temporal variability of the flow rates and nutrient loading were analyzed and extrapolated for the entire lake using Surfer 28 contour mapping software (www.goldensoftware.com). Surfer 28 was also used to determine the total volume of water discharged as well as the total mass of groundwater nutrient loading.

3. Results

3.1. Water Budget Results

The key factors enabling the quantification of the surface water and groundwater components of the water budget are illustrated in Figure 7. The most substantial contribution to the inflow comes from the canals or 61% of the total. The other two input factors include direct rainfall and groundwater, contributing 27% and 12%, respectively. Outflows are predominantly through sheet flow (69%) and evapotranspiration (30.5%), with groundwater outflow representing a minimal 0.5%. For a comprehensive analysis of the water budget specific to Lake Trafford in South Florida, refer to the detailed study by Thomas et al. [1].

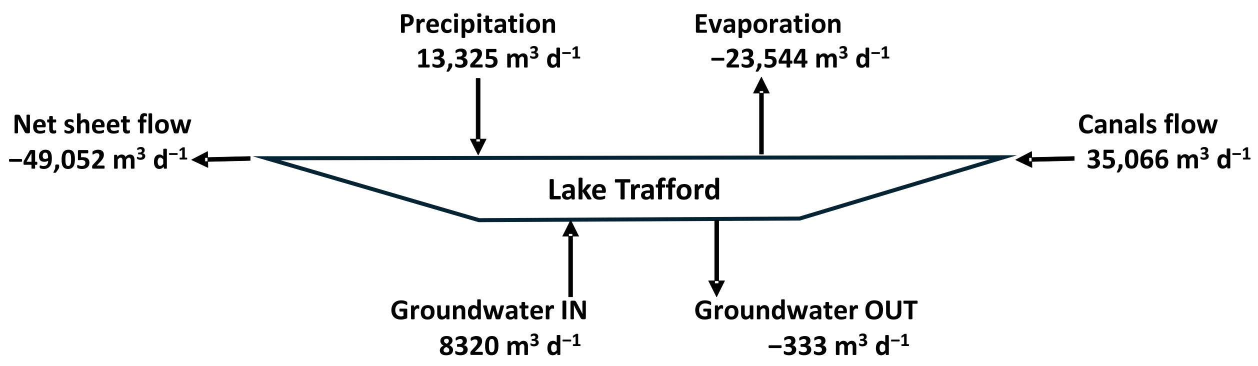

Figure 7. Water budget of Lake Trafford (from Thomas et al. [1]).

3.2. Nutrient Concentrations Measured in Groundwater

Figure 8 shows the nutrient concentrations for each sampling event using box and whisker plots, which graphically depict the statistical distribution of total nitrogen (TN) and total phosphorus (TP) across groundwater sampling stations in Lake Trafford. Each plot illustrates the median, quartiles, and potential outliers for TN and TP concentrations, thereby providing a clear visual representation of the variability and spread of data over the study period. The box plots reveal a marked elevation in TN levels at central lake sampling stations, where concentrations frequently exceed 30 mg L^{-1}. This is significantly higher than those observed at stations along the littoral zones, indicating distinct spatial differences in nutrient concentrations within the lake. In terms of TP, the plots show a less pronounced but still noticeable variation between different sampling locations, with the highest recorded concentrations also centered around the middle of the lake.

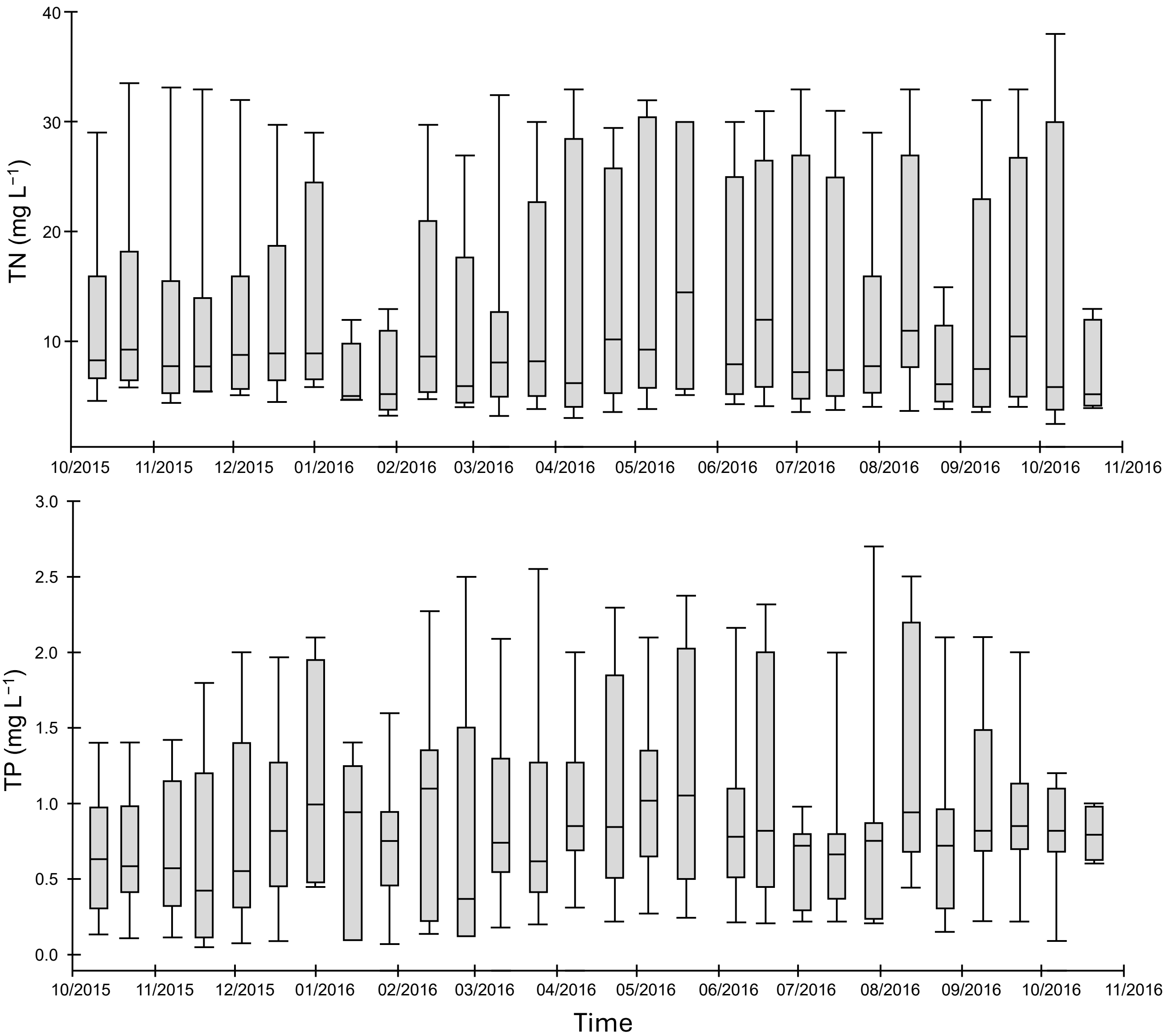

Figure 8. Box and whisker plots of well sample concentrations for TN (**top**) and TP (**bottom**) from October 2015 to October 2016. It is important to note that not all wells were sampled during each event.

The average TN concentration in the groundwater, calculated from these data points, was recorded at 12.68 ± 9.79 mg L^{-1}, dominated by ammonia-N species, which comprised

84.6% of the nitrogen content. Similarly, the average TP concentration was 0.89 ± 0.63 mg L^{-1}, with the majority being orthophosphate-P, making up 83.2% of the measured phosphorus. These groundwater concentrations are considerably higher than the average surface water TP concentration in Lake Trafford during the same period, which was 0.13 ± 0.04 mg L^{-1}. These figures illustrate the broader trends observed in the detailed box and whisker plots, highlighting the areas of the lake most affected by elevated nutrient levels.

The average TN and TP mass loading rates over the twenty-eight sampling events is shown in Figure 9. Nutrient loading results from both flow (Q) and nutrient concentration in the ground water, leading to loading maps that closely align with flow patterns and nutrient concentrations. This relationship is particularly evident with total nitrogen (TN) loading in the lake center, where concentrations are significantly elevated compared to surrounding areas.

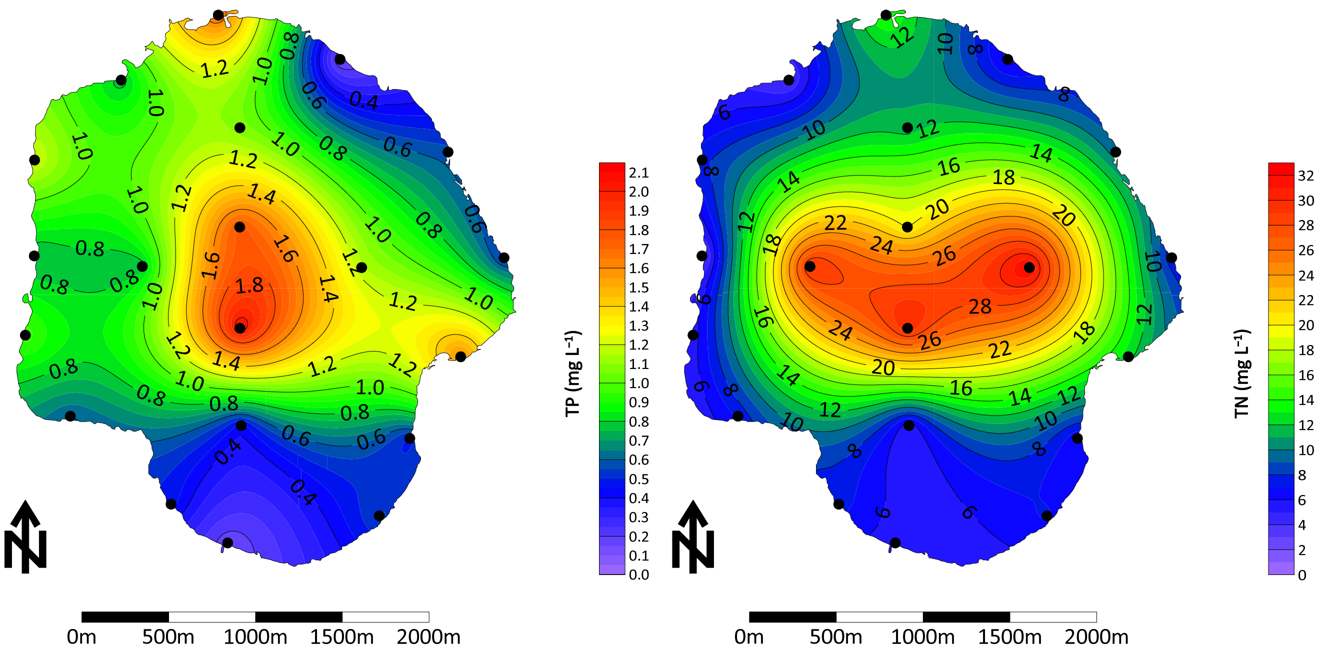

Figure 9. Spatial variation in average total phosphorus (**left**) and nitrogen (**right**) concentrations (mg L^{-1}) of groundwater samples taken at the twenty groundwater seepage locations. Higher concentrations are found in the center samplings stations of the lake. Meters are shown on the map (closed black dots).

Using the interpolated maps, the total daily mass loading rate of TN and TP through groundwater influx and efflux were quantified based on the water budget [1]. Table 2 and Figure 10 present the results of this analysis for each of the twenty-eight sampling events, as well as the overall average. The mean groundwater discharge into Lake Trafford of 8075 ± 4775 m^3 d^{-1} represents roughly 0.07% of the mean lake volume, while the mean recharge of −347 ± 509 m^3 d^{-1} represents 0.003%. Overall, there was greater groundwater discharge (inflow) than groundwater recharge (outflow) in all sampling events, except for sampling event 7 (4th and 5th of January 2016; 1487 L m^{-2} d^{-1} discharge, −2649 L m^{-2} d^{-1} recharge).

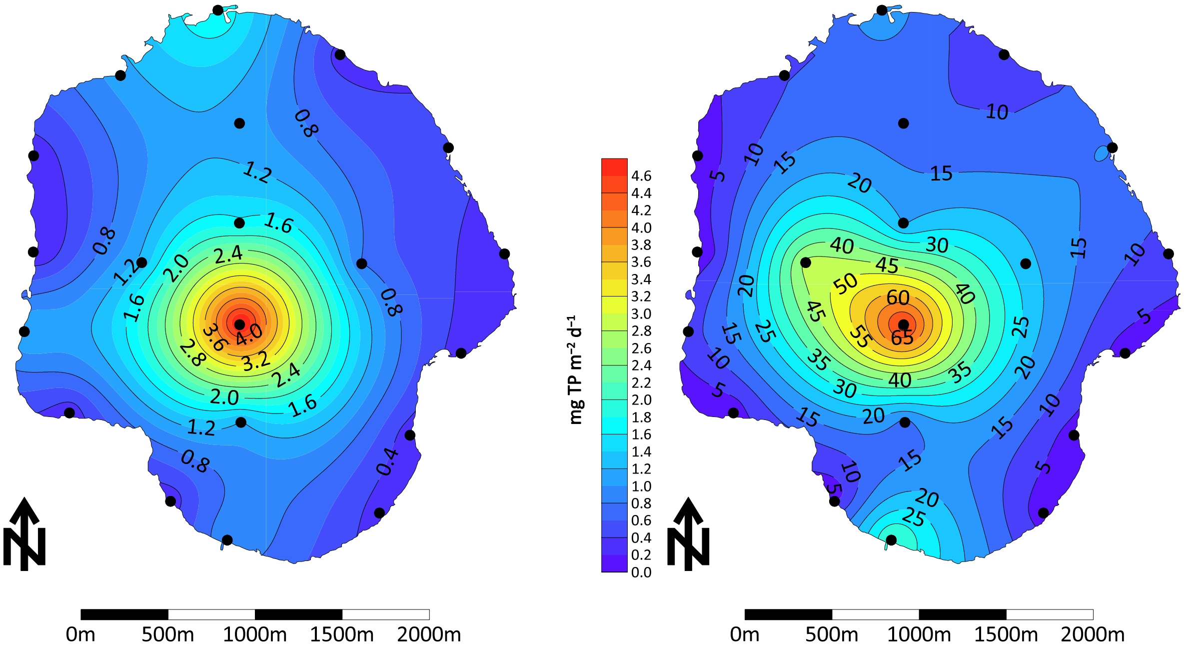

Figure 10. Interpolated Surfer maps of the average loading of TN (**left**) and TP (**right**) in mg m^{-2} d^{-1} for the 28 sampling events. Elevated flow and nutrient concentrations in the center locations are particularly evident, especially for Meter 19. Meter numbers are shown on the map next to their location (closed black dots).

Mean daily nitrogen and phosphorus additions via groundwater discharge averaged 117.63 ± 95.75 kg TN d^{-1} and 7.12 ± 4.80 kg TP d^{-1}, representing 0.007% and 0.0002% of the average total nutrient mass in the lake, respectively (Table 2). The mean N:P mass ratio of the groundwater discharge was 14.1 ± 2.97:1. The lowest ratio observed was 9.4:1, which occurred during sampling event 28 (24th and 25th of October 2016).

3.3. Nutrients Measured in Surface Water Inflow

Nutrient concentrations from canal discharge varied both in magnitude and relative abundance between nutrient species (Table 3; Figure 11). Canal 1 had both the highest average TP concentration (0.28 mg L^{-1}) and the lowest nitrogen to phosphorus mass ratio (7.28:1). This is significant because phosphorus is the limiting nutrient in Lake Trafford.

Table 3. Mean values for TP and TN concentrations in canal samples, as well as mean daily discharge values for each canal; 10.32 and 81.31 kg d^{-1} for TP and TN, respectively. Mass N:P ratios are also presented.

Canal	TP (mg L^{-1})	TP Daily Load (kg)	TN (mg L^{-1})	TN Daily Load (kg)	N:P Ratio
1	0.28	8.92	2.07	57.06	7.3:1
2	0.19	0.40	2.82	5.13	15.1:1
3	0.13	−0.01	2.23	−0.23	15.1:1
4	0.14	0.56	2.47	10.35	17.7:1
5	0.09	0.45	2.05	8.99	21.9:1
Total		10.32		81.31	7.9:1

The TN and TP loading from each canal for the 28 biweekly events is shown in Figure 11. Because mass loading is a product of Q, the loading is much higher during periods of rainfall and higher groundwater level when Q was also higher. Mean daily loads from all canals were averaged at 81.3 ± 75.1 kg d^{-1} and 10.3 ± 13.9 kg d^{-1} for TN and TP, respectively. The cumulative total nitrogen (TN) load from the combined canal discharge amounted to 31,709 kg TN over the study period, representing 108% of the average TN mass within the entire lake volume during that time. The total TP load from the collective canal discharge was 4026 kg TP over the course of the study, equating to 259% of the average mass of TP in the entire lake volume during that time. This discrepancy between TN and TP is caused by the much lower N:P mass ratio of the discharge from Canal 1, which accounted for most of the canal discharge (Table 3).

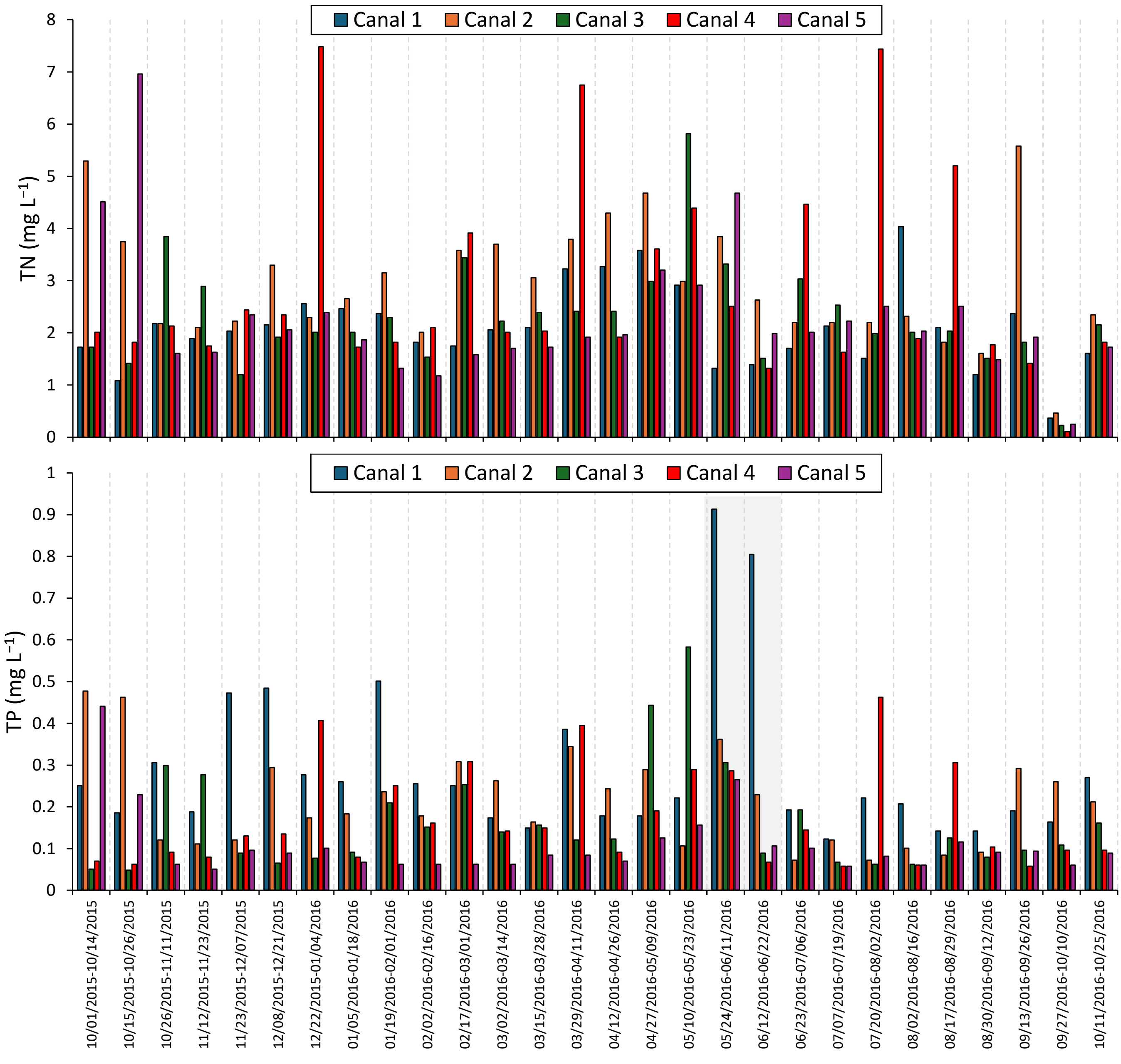

Figure 11. Composite sample concentrations for TN (**top**) and TP (**bottom**) for each canal during the study period. The highlighted portion of the graph in gray (bottom) may be evidence of a first flush for Canal 1 after the first heavy rains of the wet season occurred.

SRP/TP ratios varied and ranged from less than 0.1 to higher than 0.8 and increased for all canals during event 8 and then began to taper off for the rest of the dry season. Canal 1 consistently had the highest ratio (Figure 12).

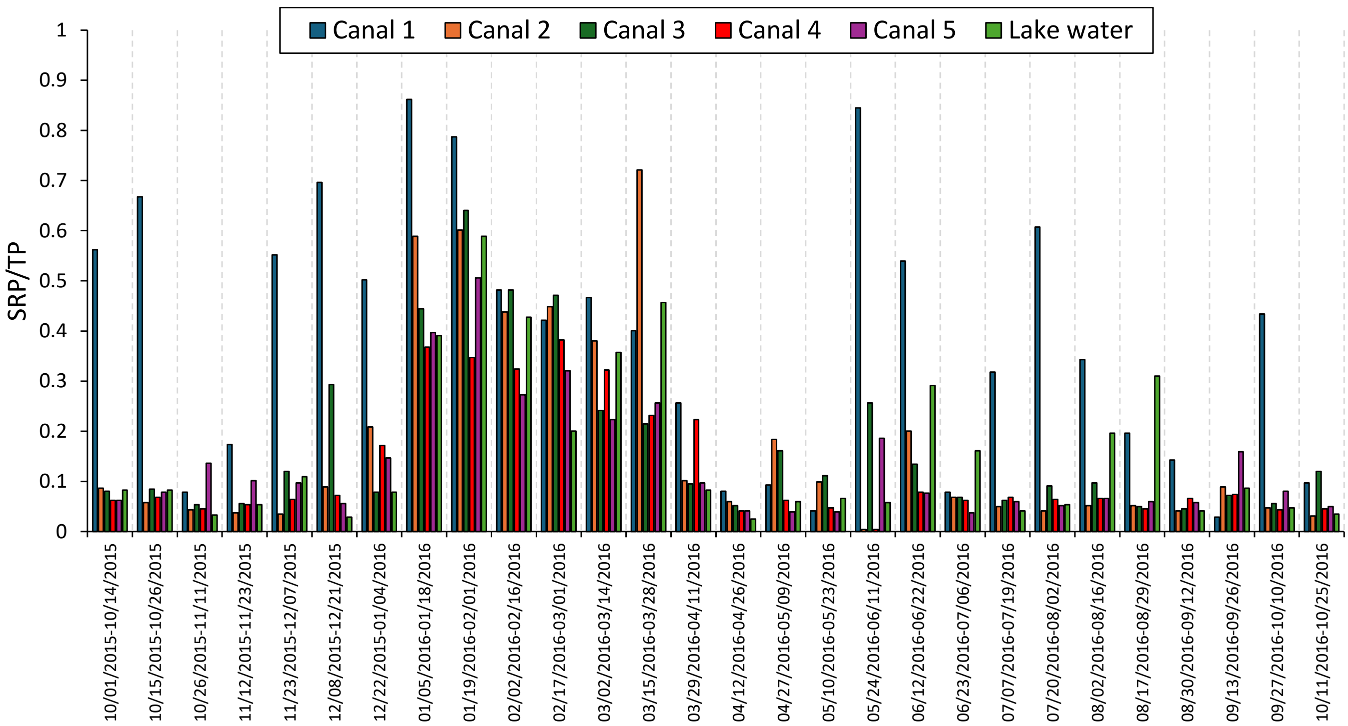

Figure 12. SRP/TP ratios for Lake Trafford's five drainage canals and center-lake grab samples. Grab samples in the canals were used to estimate SRP concentrations in composite samples.

3.4. Nutrients Measured in Dry and Wet Deposition

Figure 13 displays the biweekly loading rates of TN and TP into Lake Trafford, categorizing the contributions by dry and wet deposition. The top chart for TN shows a notable fluctuation in loading rates, with dry deposition providing a steady input of nitrogen and the presence of wet deposition, marked by white bars, dependent on rainfall events. The absence of wet deposition on certain dates indicates a lack of rainfall and, consequently, no wet deposition. The TP chart details the TP loading rates and exhibits a pattern of fluctuations that are less variable than TN, indicating a somewhat consistent phosphorus input from the surrounding environment. As with TN, the wet deposition of TP is also variable, with its contributions generally being lower compared to dry deposition.

The data reflect the complex interplay of environmental factors affecting nutrient loading, with dry deposition acting as a continuous source and wet deposition providing episodic contributions tied to precipitation events. Dry deposition was typically higher than wet deposition, except for events with large rain events during a portion of the wet season (23 June 2016 to 12 September 2016). The mean daily load over the course of the study was 24.40 ± 18.06 kg d^{-1} and 2.47 ± 1.86 kg d^{-1} for TN and TP, respectively. The mean daily wet deposition load over the course of the study was 17.45 ± 21.16 kg d^{-1} and 1.40 ± 1.65 kg d^{-1} for TN and TP, respectively. High standard deviations are the result of some events having no rainfall, and thus zero mass loading via wet deposition.

In Figure 14, the relative contribution of mean daily atmospheric deposition to the nutrient content of Lake Trafford is displayed for TN (top graph) and TP (bottom graph), distinguishing between wet and dry deposition. For both TN and TP, dry deposition consistently contributes to the lake nutrient content. Wet deposition, although varying significantly from month to month, added a notable amount to the overall nutrient deposition at times, in varying degrees, depicted by the extent of the gray sections above the black bars. Dry deposition accounted for an average of 69.4% of the total atmospheric deposition over the course of data collection, with wet deposition accounting for an average of 30.6%.

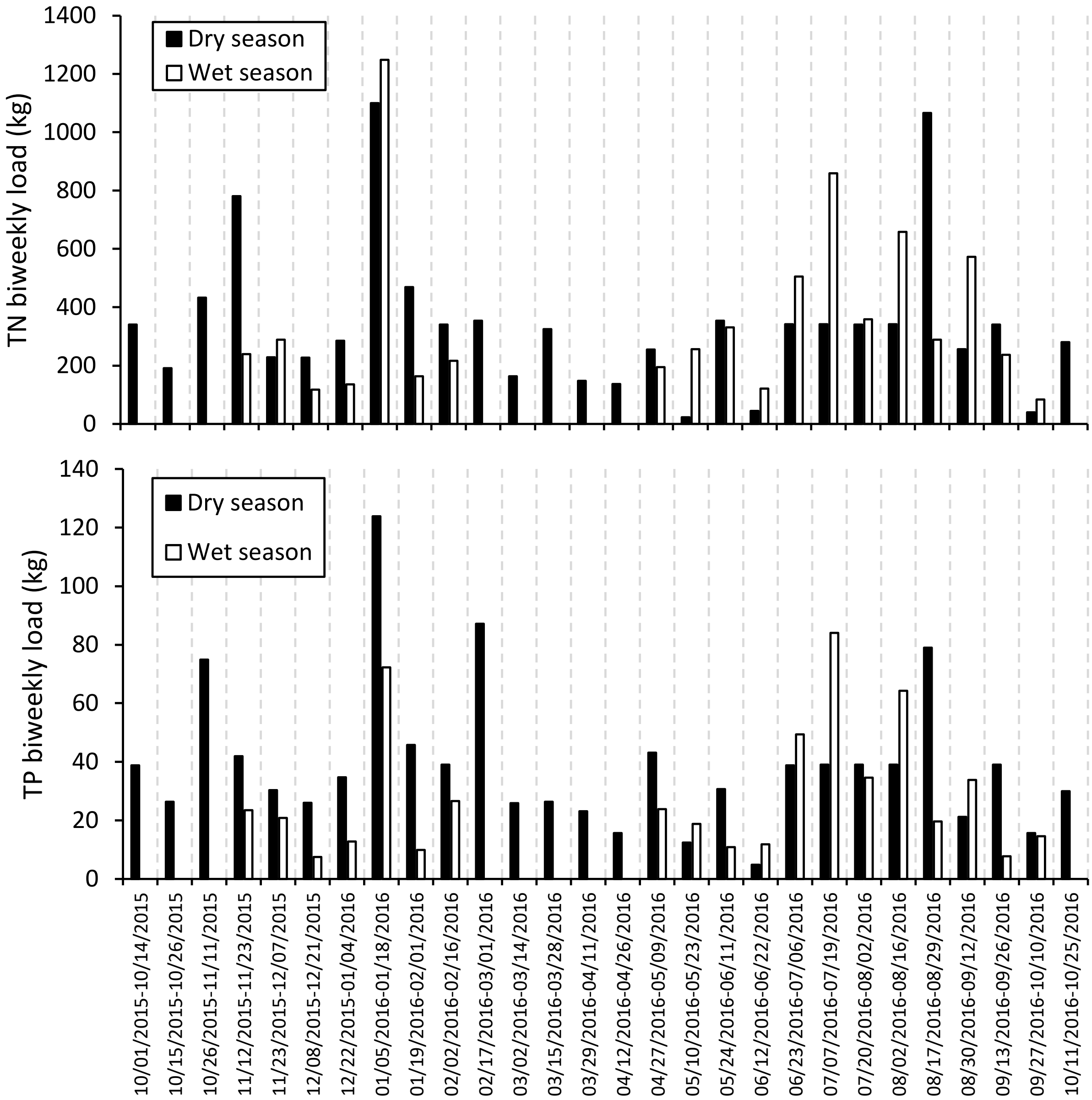

Figure 13. Biweekly loading rates of TN (**top**) and TP (**bottom**) for dry (black bars) and wet (white bars) deposition. Bars are absent for wet deposition loading when rainfall did not occur during a given sampling event.

Total atmospheric deposition for Lake Trafford averaged 41.85 ± 34.10 kg TN d^{-1} and 4.07 ± 2.82 kg TP d^{-1}. These figures correspond to 0.14% and 0.26% (on a daily basis) or 51% and 95% (on an annual basis) of the mean TN and TP mass, respectively, within Lake Trafford.

For total nitrogen (TN), the annual dry deposition rate is 1854.2 mg m^{-2} $year^{-1}$, and the wet deposition rate is 1326.9 mg m^{-2} $year^{-1}$. This indicates that dry deposition contributes slightly more to the total nitrogen load in Lake Trafford compared to wet deposition. For total phosphorus (TP), the annual dry deposition rate in Lake Trafford is 187.8 mg m^{-2} $year^{-1}$, while the wet deposition rate is 106.5 mg m^{-2} $year^{-1}$. Like TN, dry deposition is the predominant source of phosphorus deposition in Lake Trafford, contributing a larger portion when compared to wet deposition.

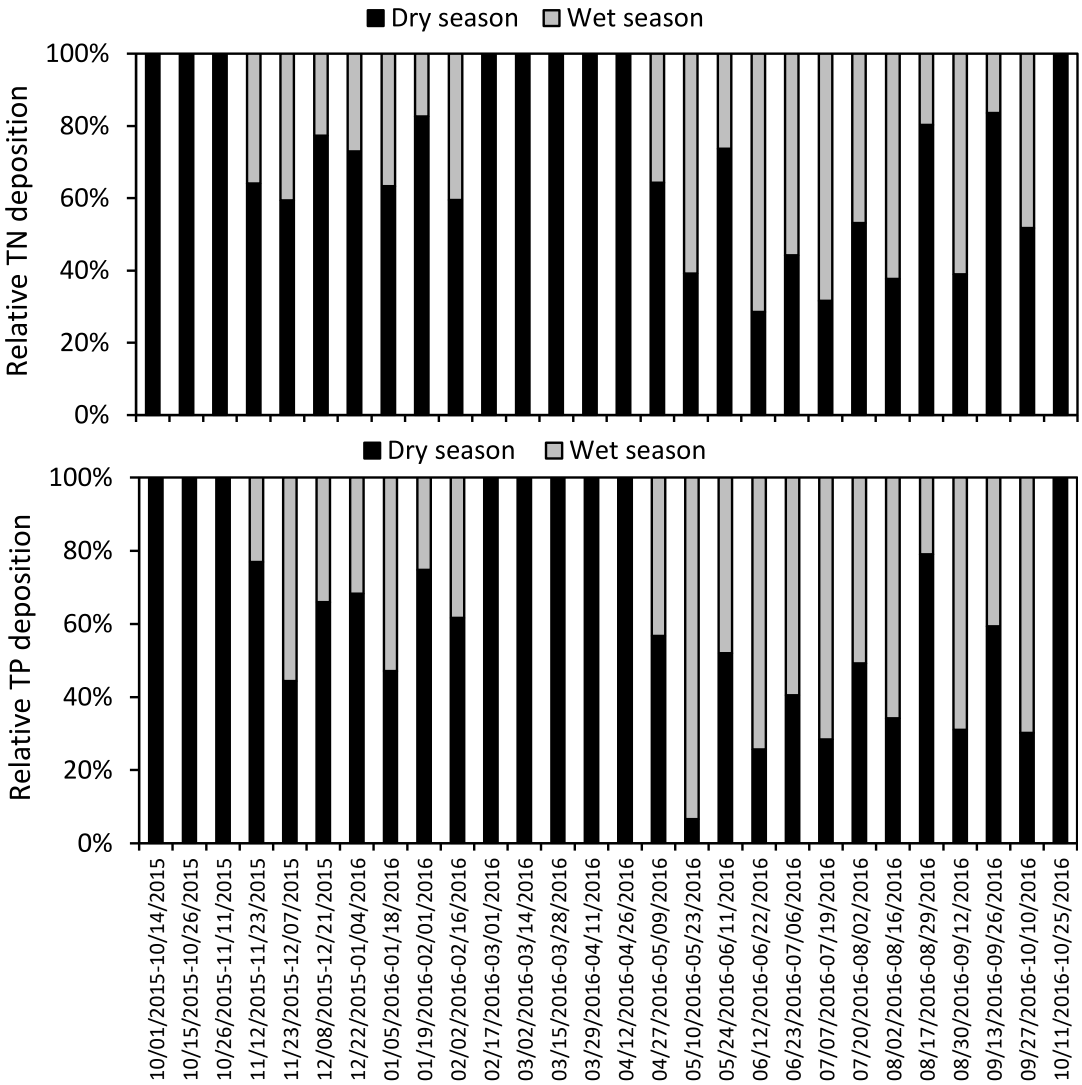

Figure 14. Relative percentage of mean daily atmospheric deposition accounted for by wet (stacked gray bar) and dry (stacked black bar) deposition for nitrogen (**top graph**) and phosphorus (**bottom graph**).

3.5. Water Quality in Lake Trafford—TN, TP, Total Organic Carbon (TOC), pH, Conductivity and Temperature

Figure 15 depicts time series plots of nutrients (TN and TP), TOC, and other water quality data (pH, conductivity, and temperature) for samples taken from the center of Lake Trafford during the study period (October 2015–October 2016). TN levels show notable fluctuations throughout the year with peaks occasionally exceeding 3 mg L^{-1}, which may be indicative of higher nitrogen inputs. The fluctuations correlate with seasonal changes; notably, TN concentrations tend to be higher during the dry season, which is an eight-month period from October through May in southwest Florida.

TP concentrations display less variability but do experience some spikes. These sporadic increases could be linked to specific events or the seasonal dynamics of the lake. Similarly to TN, TP concentrations are typically higher in the dry season and lower during the wet season due to greater rainfall diluting nutrient concentrations from June to September in Florida. This seasonal pattern suggests that water quality management strategies should account for the dry and wet cycles of the region, particularly when considering nutrient load mitigation efforts to prevent potential eutrophication and algal blooms.

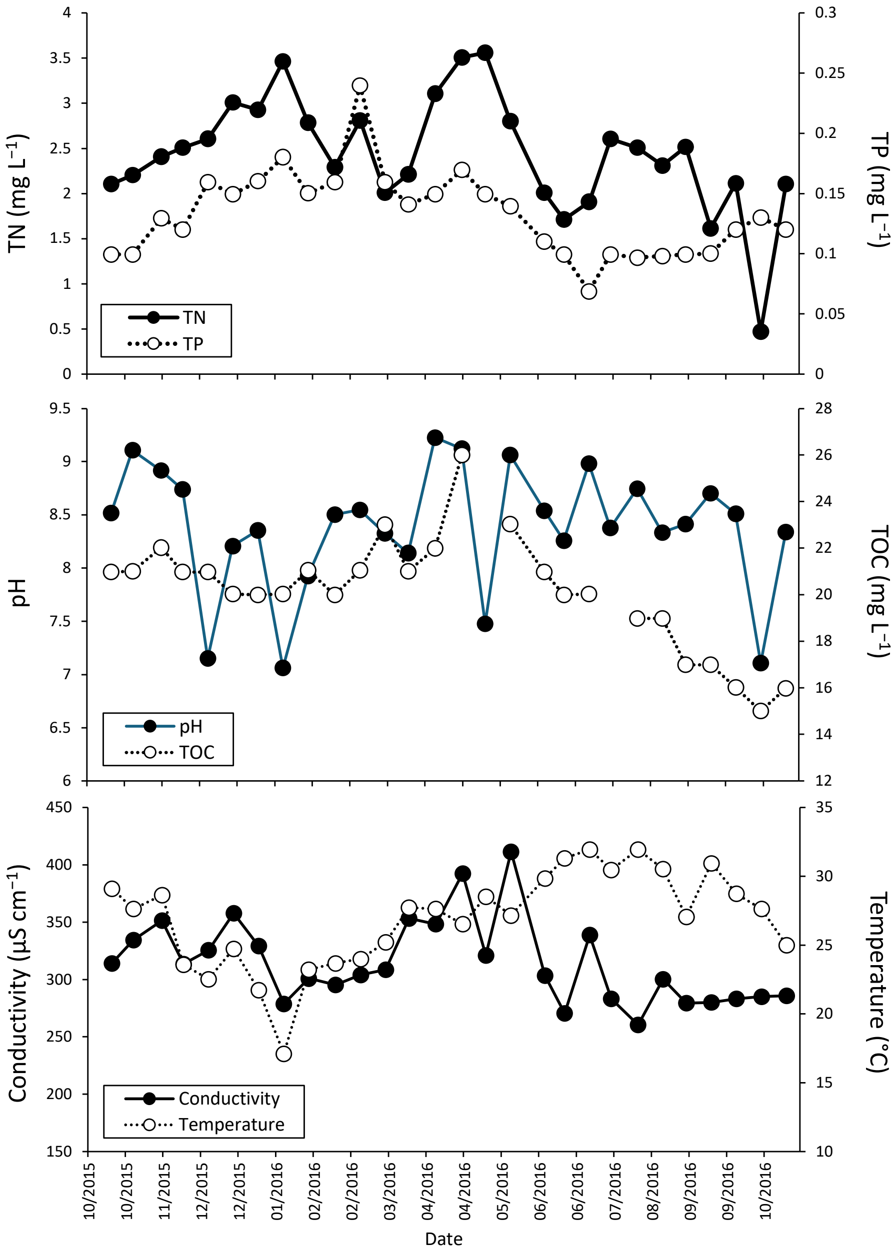

Figure 15. Time series plots of lake water quality—TN and TP (**top**), pH and TOC (**center**), and conductivity and temperature (**bottom**) for samples taken from the center of Lake Trafford during the study period (October 2015–October 2016).

Water pH values fluctuate between approximately 7 and 9, indicating that the water is generally alkaline. This is typical for many freshwater bodies in Florida. TOC varies significantly, ranging from 12 to nearly 28 mg L^{-1}. These variations suggest changes in organic matter input and decomposition, which could be influenced by biological activity, runoff, and temperature. The conductivity in Lake Trafford displays a general increasing trend over time with fluctuations, which peaks towards the end of the dry season. This pattern is likely due to higher evaporation rates during the dry months, leading to increased concentrations of ions as the water volume decreases. Starting with the wet season, there is a rapid decrease in conductivity, which can be attributed to dilution effects from increased rainfall that introduces more water volume, thus reducing ion concentrations. Water temperature is relatively stable with seasonal fluctuations, peaking in the warmer months.

3.6. Nutrient Budget for Lake Trafford

A comprehensive overview of the final daily nutrient budget for all measured loadings into Lake Trafford over the course of the study period is shown in Figure 16. The figure includes contributions from various sources, including groundwater, canals, atmospheric deposition, and sheet flow. This detailed nutrient budget is crucial for understanding the dynamics of nutrient influxes and their impact on the lake ecosystem.

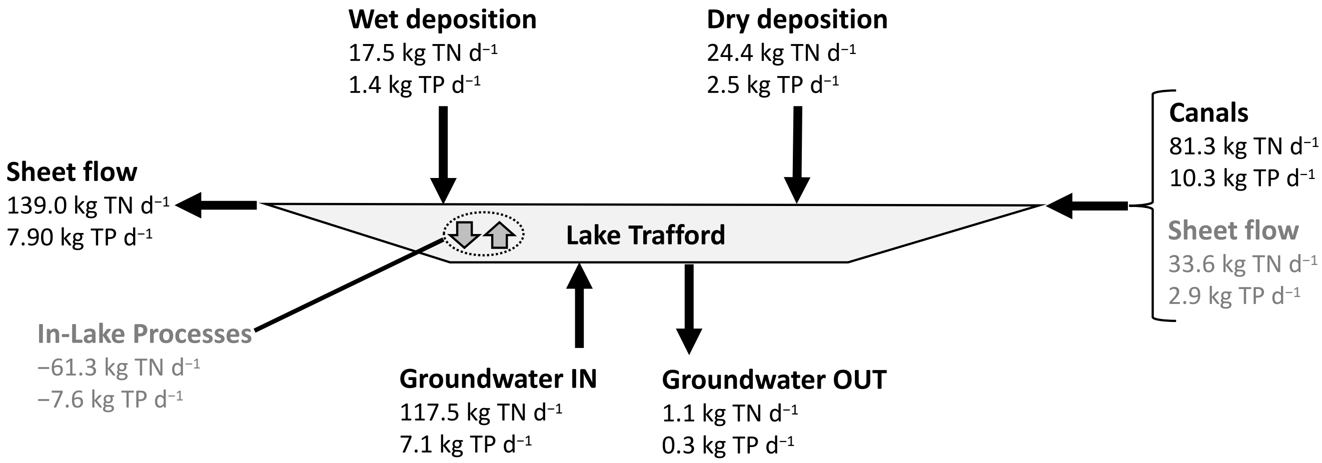

Figure 16. The final daily nutrient budget of all measured loadings for Lake Trafford over the course of the study period. The circled thick gray arrows within the lake represent various physical, chemical, and biological in-lake processes.

The nutrient budget is based on water fluxes measured in situ or derived from the water budget, such as sheet flow. Loads were calculated by multiplying the measured or estimated nutrient concentrations by each flow rate, summarized in Figure 16 and Table 4. The final daily load for Lake Trafford was determined to be 274.3 $\pm$ 87.2 kg for total nitrogen (TN) and 24.2 $\pm$ 21.7 kg for total phosphorus (TP).

As sheet flow could only be determined as a net value, estimations were required for both inflow and outflow volumes. This entailed averaging all net positive and net negative flows, subsequently utilizing these averages to compute loads. Consequently, the reliability of loading results for sheet flow is comparatively diminished in contrast to those derived from other fluxes.

In-lake processes, represented as net values, include internal loading (positive values) and biological uptake or sedimentation (negative values). These were excluded from the final total nutrient load calculation for Lake Trafford to focus on external nutrient sources. On average, net in-lake processes exhibited negative values (-61.3 kg TN day^{-1} and -7.6 kg TP day^{-1}), indicating that biological uptake or sedimentation had a more significant influence than internal loading. This finding highlights that internal update through in-lake processes (biological, photochemical, and physical) had a significant influence on the overall nutrient budget.

Figure 17 illustrates the relative contributions of different sources to the nutrient loading of TN and TP into Lake Trafford. It reveals that groundwater was found to be the largest source of TN to the lake, contributing 43% of the total TN load. For TP, groundwater accounted for 29% of the total load. This significant contribution from groundwater underscores the importance of subsurface water flows in influencing the nutrient levels in Lake Trafford.

Table 4. Summary statistics for all facets of nitrogen (N) and phosphorus (P) budgets including in-lake processes. GW in is groundwater discharge, and GW out is groundwater recharge.

N	Lake TN Conc. (mg L^{-1})	GW in (kg d^{-1})	GW out (kg d^{-1})	Canals TN (kg d^{-1})	Atmospheric Deposition (kg d^{-1})	Sheet Flow (kg d^{-1})	In-Lake Processes (kg d^{-1})
Mean	2.43	117.5	−1.1	81.3	41.4	−105.4	−61.26
Std	0.64	93.7	1.6	75.1	33.4	199.9	73.5
Min	0.46	13.7	−7.0	−45.4	8.4	−661.6	−279.1
Max	3.56	461.5	0.0	426.3	167.4	1010.6	84.2
P	**Lake TP Conc. (mg L^{-1})**	**GW in (kg d^{-1})**	**GW out (kg d^{-1})**	**Canals TN (kg d^{-1})**	**Atmospheric Deposition (kg d^{-1})**	**Sheet Flow (kg d^{-1})**	**In-Lake Processes (kg d^{-1})**
Mean	0.13	7.1	−0.3	10.3	4.1	−4.9	−7.6
Std	0.03	4.7	1.2	14.0	2.8	16.3	9.8
Min	0.07	0.5	−6.2	−14.3	1.1	−35.0	−48.2
Max	0.24	22.8	0.0	122.4	14.0	136.7	0.4

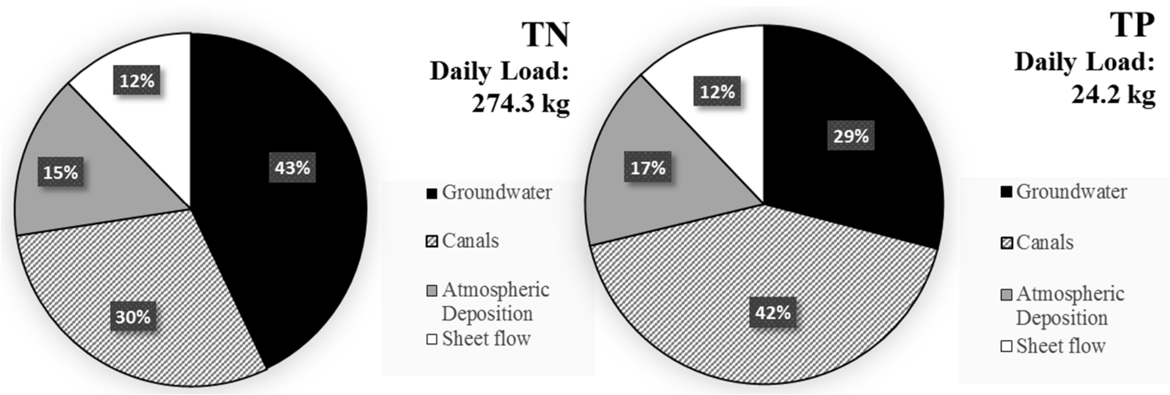

Figure 17. Relative percentages of each source of nutrient loading into Lake Trafford for total nitrogen and total phosphorus. Sheet flow was estimated by averaging all positive net sheet flow, and all negative net sheet flow.

The discharge from the five canals was identified as the largest contributor to the TP load, delivering 42% of the total TP load to the lake. Canals also contributed 30% of the TN load. The high nutrient load from canals suggests that managed waterways are primary pathways for nutrients entering the lake, likely reflecting the influence of agricultural and urban runoff. Atmospheric deposition accounted for 15% of the TN load and 17% of the TP load. This includes both wet and dry deposition from the atmosphere, introducing nutrients into the lake system. Although atmospheric deposition is a smaller contributor compared to groundwater and canals, it still plays a significant role in the overall nutrient budget. Sheet flow, representing overland water movement, contributed 12% to the loading of both TN and TP. This indicates the impact of surface runoff from the surrounding landscape on the lake's nutrient budget.

Overall, the presented nutrient budgets underscore the significance of both groundwater and canals as dominant pathways for nutrient inflow into Lake Trafford. The differences in their relative contributions to TN and TP suggest variations in the sources and behaviors of these nutrients in the environment, which are critical for developing effective water quality management and nutrient mitigation strategies for the lake.

4. Discussion

4.1. Nutrients in Groundwater Inflow

The nutrient concentrations in groundwater exhibited a notable dichotomy, with deeper sites consistently displaying higher concentrations compared to shallower sites. Particularly for total nitrogen, some samples recorded concentrations exceeding 30 mg L^{-1}. The mean TN concentration for all groundwater samples from Lake Trafford of 12.68 $\pm$ 9.80 mg L^{-1} is nearly three times higher than results from Lake Tohopekaliga (4.6 mg L^{-1}; [38]), three times higher than results from Lake Jesup (4.2 mg L^{-1}; [39]), and almost five times higher than samples from a wet detention pond on the Fort Myers campus of Florida Gulf Coast University (FGCU) (2.7 mg L^{-1}; [40]).

It is unknown what is driving the elevated nutrient levels at the central seepage sites, and further studies are imperative to ascertain the causes and develop targeted mitigation strategies. Furthermore, coupled with the regular groundwater discharge in these areas, nitrogen loading from groundwater discharge is much higher than anticipated because of the high nitrogen concentrations in the pore water from the center lake sites. Recent studies have indicated that anthropogenic activities, including agricultural runoff and septic system leakage, are significant contributors to elevated nitrogen levels in groundwater [41]. These findings underscore the need for integrated watershed management approaches to address both surface and subsurface nutrient sources.

Average phosphorus concentrations (0.90 $\pm$ 0.62 mg L^{-1}) were also elevated above surface water concentrations and concentrations from groundwater seepage from other Florida lakes. TP concentrations in Lake Trafford were approximately 3.5 times the concentrations of seepage into Lake Tohopekaliga (0.25 mg L^{-1}; [38]), 2.5 times the concentrations for Lake Jesup (0.33 mg L^{-1}; [39]), and over 3.5 times the concentrations for the FGCU pond (0.27 mg L^{-1}; [40]). This makes phosphorus loading via groundwater discharge higher into Lake Trafford than other studied systems, even with its normal rates of seepage. The elevated phosphorus levels in Lake Trafford groundwater inflow may also be influenced by local geology and soil phosphorus content, which can contribute to higher baseline concentrations [25]. Moreover, recent environmental changes, such as increased rainfall and rising water tables, have been linked to higher rates of nutrient leaching into groundwater [42].

The findings highlight significant implications for nutrient management strategies for similar types of water bodies and emphasize the potential for substantial nutrient input loading through groundwater seepage. This is especially pertinent in regions like Florida, where the unique hydrology, characterized by flat topography and proximity to the groundwater table and ocean, can amplify nutrient transport mechanisms. These insights call for enhanced monitoring and adaptive management strategies that can dynamically respond to changes in groundwater nutrient dynamics, ensuring sustainable water quality management for Lake Trafford and similar ecosystems.

4.2. Nutrients in Canal Discharge into the Lake

Canal discharge was, as expected, dependent on rainfall, with flows mostly stagnant during extended dry periods. Most of the discharge occurred from Canal 1, which also had the highest concentrations of nitrogen and phosphorus, making it a substantial source of water and nutrients into Lake Trafford.

It is hypothesized that Canal 1 experiences much more flow because of its connection with the Immokalee Slough, a wetland area that extends east from Lake Trafford, meandering its way between farmland to the south and the City of Immokalee to the north. This area is clearly within the Lake Trafford drainage basin and is likely the reason for the higher Q and nutrient concentrations in Canal 1. Increased impervious surface area in the City of Immokalee and agricultural runoff from the lands to the south are potentially the source of the excessive nutrients, especially stormwater runoff, which is likely channeled into the slough.

Phosphorus (P) is more often the limiting nutrient in freshwater environments, while nitrogen (N) is typically considered the limiting nutrient in marine (ocean) ecosystems. The data show that Canal 1 not only has the highest flow among all monitored canals in this study, but also has the highest SRP/P ratio. It is a significant finding in that when assessing the potential for algal bloom development in a waterbody, soluble reactive phosphorus (SRP) is generally considered a more effective indicator than total phosphorus (TP). That is because SRP represents the portion of P that is readily available for algae and other aquatic plants to utilize for growth and reproduction. In contrast, TP encompasses both dissolved and particulate forms of phosphorus. While TP measures the overall phosphorus content in the water, not all of it is immediately accessible to algae. Particulate phosphorus may require decomposition or sedimentation processes to release phosphorus in a form that algae can use. Monitoring SRP levels provides direct insights into P availability for algal growth and can serve as an early warning signal for potential algal blooms. High concentrations of SRP often correlate more closely with algal bloom occurrences compared to TP concentrations alone. Considering that Canal 1 serves as the primary pathway for soluble reactive phosphorus (SRP) transported by surface water flow into the lake, effective management and monitoring of the sub-watershed contributing to Canal 1 could aid in identifying opportunities for watershed management. By focusing on this sub-watershed, efforts can be directed towards minimizing SRP input into the lake via surface water flow.

Recent studies have emphasized the importance of managing agricultural runoff and urban stormwater to control nutrient inputs into water bodies [43,44]. Implementing best management practices (BMPs) such as buffer strips, retention ponds, and controlled drainage systems can significantly reduce nutrient loads entering canals [45]. Additionally, enhanced monitoring programs that track SRP levels in real-time can help identify critical periods of nutrient influx and allow for timely interventions to prevent algal blooms [42].

4.3. Nutrients in Dry and Wet Deposition

The average dry deposition rates observed in this study appeared somewhat elevated, aligning with rates documented in both the Ohio Valley and the Northeastern US for total nitrogen deposition [46]. Notably, values calculated for Tampa Bay were approximately 50% lower than those recorded in this study [47]. While uncertainties persist, the relatively remote location of the lake, distanced from major industrial areas, suggests that the recorded values may be attributable to the prolonged period of composite sample collection. Measured TP concentrations exhibited similarity to those documented in a study conducted at the Emergent Technologies Institute, located approximately 8 km north of FGCU in Lee County [48]. This suggests that other factors beyond geographical proximity to industrial zones might contribute to the observed deposition rates. One such factor could be higher deposition rates resulting from pre-harvest sugar cane burning in the nearby Everglades Agricultural Area (EAA), situated approximately 35 miles west-northwest of Lake Trafford. The complexities surrounding the observed deposition rates underscore the necessity for rigorous scientific inquiry to resolve this issue conclusively.

Dry and wet deposition collection and analysis were effectively carried out using the custom-designed deposition collection sampler. However, two notable challenges were encountered during the process: (i) contamination by insects, small reptiles, and amphibians in several samples, and (ii) suboptimal placement of the land-based location, potentially influenced by nearby trees, which may have affected deposition patterns. To address the issue of contamination, a small stainless-steel screen was integrated into the collection buckets, proving successful in mitigating insect and reptile fouling. Nevertheless, it is important to note that this measure could have impacted deposition rates, as the selected screen size represented a compromise between preventing fouling and the potential blockage of dry deposition. Moving forward, optimizing site selection and refining sampling methodologies should be considered to enhance the accuracy and reliability of deposition data in future studies.

A recent study has indicated that local agricultural practices, particularly pre-harvest sugar cane burning, can significantly contribute to elevated nutrient deposition rates in nearby water bodies. These practices release particulate matter and associated nutrients into the atmosphere, which can then be deposited in both dry and wet forms [49]. The proximity of the Everglades Agricultural Area (EAA) to Lake Trafford likely exacerbates this effect, highlighting the need for targeted mitigation strategies in agricultural management.

The role of atmospheric deposition as a nutrient source is increasingly recognized, especially in regions with extensive agricultural activity. For instance, Chen et al. [50] found similar patterns of nutrient deposition in areas adjacent to agricultural fields, underscoring the widespread impact of such practices. These findings align with observations from Lake Trafford, suggesting that both dry and wet deposition are influenced by regional agricultural emissions.

Advancements in deposition collection technologies, such as the custom-designed deposition collection sampler used in this study, have improved the accuracy of nutrient deposition measurements. However, challenges such as contamination and suboptimal site placement remain significant hurdles. Future studies should focus on optimizing these methodologies to ensure more reliable data collection.

4.4. Nutrient Loading Compared to the TMDL Study

The nutrient concentrations observed in the current study notably exceed those modeled in the TMDL report for Lake Trafford [11]. Specifically, the TMDL report estimated surface runoff TP concentrations at approximately 0.040 mg L^{-1}, depending on annual variations. However, surface discharge measurements from canals in this study averaged 0.166 mg TP L^{-1}, revealing a fourfold increase over TMDL projections. Furthermore, groundwater concentrations of TN showed an even greater disparity. The TMDL report that TN concentration estimates ranged from 0.04 to 0.78 mg L^{-1}, yet in situ measurements from this study averaged over 12 mg L^{-1}, underscoring a substantial underestimation. These findings are consistent with other recent studies that have identified groundwater as a major nutrient source often underestimated in traditional surface water nutrient models [51].

The average total daily loads (TDL) for TN and TP calculated in the TMDL report were 190.5 kg day^{-1} and 18.6 kg day^{-1}, respectively. In contrast, the findings of the current study present higher daily loads, at 274.3 kg day^{-1} for TN and 24.2 kg day^{-1} for TP. These figures suggest discrepancies of 31% for TN and 23% for TP when compared to the TMDL report. It is important to note that the TMDL's modeled total loads for wetter years, such as in 2005, were estimated at 335 kg day^{-1} for TN and 37.6 kg day^{-1} for TP, which aligns more closely with the higher nutrient loads observed in this study.

The significant differences between the TMDL estimations and the current study measurements are likely caused by a variety of factors, including changes in land use, increased nutrient inputs, or climatic variations that were not accounted for in the TMDL model. These findings underscore the need for more updated and comprehensive nutrient modeling that accurately reflects the current conditions of Lake Trafford. A revised approach to nutrient management and mitigation strategies may also be necessary to ensure the health and sustainability of the lake's ecosystem.

4.5. In-Lake Processes and the Impact of Dredging of Organic Sediment

Utilizing the nutrient budget established in this investigation, net values for "in-lake processes" encompassing both positive loads like internal loading and negative loads such as biological uptake and sedimentation could be estimated. Historically, Lake Trafford grappled with legacy loading stemming from a thick organic sediment layer prone to re-suspension during windy conditions. Sediment dredging served as the remedy for this legacy load, and data from this study suggest that it achieved its intended objective. On average, net in-lake processes exhibited negative values (-133.7 kg TN day^{-1} and -16.3 kg TP day^{-1}), indicating that biological uptake or sedimentation exerted a more significant influence than internal loading. These values tended to become less negative during the fall and winter months, only to increase negatively as warmer conditions returned in the spring. This pattern likely reflects a decreased primary production of macrophytes and phytoplankton during colder conditions and lower light levels in winter, underscoring the role of biological uptake as a pivotal driver of the lake's internal nutrient dynamics. While internal loading may persist, particularly in areas untouched by dredging, it no longer appears to be as problematic as in the past.

Despite the positive impact of organic sediment dredging on in-lake processes, it may have also affected the lake interaction with regional groundwater flow. The average conductivity of lake water has been on the rise, suggesting increased groundwater influx, especially in the central part of the lake. Since groundwater carries nutrients, any rise in influx rate adversely impacts the lake's nutrient balance. As observed by numerous researchers, sediment dredging yields positive short-term benefits, but these benefits may diminish over time [14,20,21,52,53]. The growing groundwater influence presents a new challenge and merits further exploration.

4.6. Future Remedial Work Required to Improve Water Quality in Lake Trafford

The TMDL report from 2008 indicated that the total maximum daily loads for Lake Trafford should be limited to 70.4 kg d^{-1} and 4.2 kg d^{-1} for TN and TP, respectively. This equates to reductions of 60% for TN and 77% for TP. The results of this study are indicative of how far from these targets we are in terms of reducing nutrient loading into Lake Trafford. Load reductions will be necessary to prevent Lake Trafford from becoming more eutrophied. The FDEP has not adopted a Basin Management Action Plan (BMAP) for Lake Trafford. Data from multiple studies, including this one, should likely influence future policy decisions.

The data from this study indicate several areas where load reductions could be targeted, but there is one area that would be the most effective from a policy or project standpoint. Elevated concentrations of nitrogen and phosphorus in the groundwater are problematic, but the source of these nutrients is likely derived from the entire watershed, and perhaps even outside of it. Spot targeting reductions for groundwater nutrient leaching would be difficult, but fertilizer and perhaps septic tank policy changes may have a positive impact. The most effective place for nutrient reduction is likely Canal 1, which delivers most of the phosphorus from the five canals and a significant portion of the overall phosphorus load to Lake Trafford. This makes it a prime candidate for a remediation project. The fact that it is also a surface water delivery with sources that are probably evident upon inspection also makes it ideal.

4.7. Future Research

This project has identified several areas of potential study that could yield valuable insights. Given the ambiguous and densely vegetated boundaries of Lake Trafford, conducting a piezometer study with sites extending beyond the lake boundary into the surrounding wetlands may offer a more comprehensive approach to monitoring groundwater discharge and recharge compared to relying solely on seepage meters. Ion and radio isotope research on the groundwater entering Lake Trafford could also be valuable for determining the sources of inflowing groundwater and potentially point to sources of groundwater pollution. Additionally, studying the hydrogeology beneath Lake Trafford may explain the unusual flow patterns. Further study is also needed involving the Immokalee Slough, particularly where and when nutrient loads are moving into it. It is unknown whether MS4 outfall drainage is present or if it is being used as drainage for crop land. However, its large deliveries of water and nutrients to Lake Trafford make it worth further investigation. Finally, this was the first attempt at the direct measurement of dry deposition falling on to Lake Trafford. Continual measurements would be useful for determining the average value and whether it is truly elevated over background values for one reason or another.

Considering potential remedial actions, depositing bentonite into some or all the deepest parts of the lake could be explored. This intervention has been implemented with positive results in other locations [54]. Bentonite has been shown to bind soluble phosphorus effectively, thereby reducing internal nutrient input from sediments into the water. Also, it can reduce groundwater influx carrying heavy nutrient loads, thereby mitigating nutrient enrichment in Lake Trafford. These proposed areas of study and remedial actions have the potential to enhance understanding of Lake Trafford ecosystem dynamics and inform effective management strategies for its conservation and restoration.

5. Conclusions

Based on the extensive nutrient budgeting efforts, it has become clear that despite remedial actions such as removal of organic sediments, nutrient loads in Lake Trafford remain high, and do not meet the target loads set by the total maximum daily load (TMDL) for the lake. Groundwater loading was notably high due to elevated nutrient concentrations observed in pore water beneath the lake, with the driving causes of this issue yet to be discerned. Additionally, surface water inflow was richer in nutrients than anticipated, while dry deposition loading exceeded expectations, resembling levels seen in more industrialized areas. There is a necessity for further study to confirm these observations and to understand if any overestimation has occurred.

Overall, daily nutrient loading was comparable to upper TMDL estimates from previous rainy years, surpassing average daily load values calculated in the TMDL, suggesting increased loading due to more rainfall during the study period. The positive aspect of this study is that internal loading appears reduced post-dredging, with sedimentation and biological uptake likely mitigating ongoing internal loading. This is a promising result of the dredging efforts, as pointed out in other studies [21,53,55], although denitrification in the sediments could be limited after dredging, therefore possibly outweighing the benefits of the ammonification reduction [53,56].

Future efforts should focus on reducing the overall nutrient load entering Lake Trafford to restore its original water quality and clarity. Continuation of this project could enhance understanding of Lake Trafford's hydrology and nutrient loading under varying hydrological conditions (e.g., wet versus dry years). However, reducing sampling frequency to once a month may be more cost-effective while still providing adequate temporal resolution, especially given the continuous or automated nature of most sampling methods. Furthermore, increasing the time for bag deployments on the seepage meters to 48, 72, or even 96 h may serve as a balance between increased temporal resolution, and preservation of the delicate seepage bags.

As Jing et al. outlined in their paper [21], many restoration projects involving dredging failed to be successful as they are not associated with ecological lake restoration projects. In the management of Lake Trafford, the main objective should be reducing nutrient loads, but other complementary actions like promoting native submerged aquatic vegetation (SAV) plantings are also vital. Both decreased loading and increased SAV coverage will be needed to return Lake Trafford to a clear water state. Although it is controversial, because of its prolific growth, *Hydrilla* could be used as a management tool to control sediment re-suspension and uptake nutrients out of the water column until the lake switches to a clearer water state, which would allow for the rapid return of rooted submerged aquatic vegetation (SAV). The use of the adequate amount of grass carps could then selectively graze upon *Hydrilla*, thus allowing the native SAV to proliferate. However, to date, this biocontrol approach does not seem to have been successful, even though grass carps were parsimoniously added over time to prevent overgrazing of the more desirable SAV like tape grass (*Vallisneria americana*). Despite SAV planting of this aquatic plant especially, Lake Trafford is currently mostly devoid of SAV for reasons that should be investigated further.

A noted potential drawback of the sediment dredging has been the enhancement of the groundwater connection to the lake, especially the central area. The high nutrient load entering the lake is from groundwater, which will continue until the connectivity of the lake bottom with groundwater flow lessens with time, as caused by natural sedimentation. Experimental deployment of bentonite on the lakebed, especially within its deepest region, could be explored to mitigate groundwater influx and reduce nutrient loading over time.

In conclusion, while the sediment dredging has brought forth some positive changes, the heightened nutrient levels call for ongoing management and research. Future studies should assess the specifics of groundwater interactions, the causes of high nutrient levels, and explore the practicality and effectiveness of various remedial actions, such as the use of bentonite, to ensure the long-term health and ecological balance of Lake Trafford.

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References

1. Thomas, S.; Lucius, M.A.; Kim, J.-Y.; Everham, E.M.; Dettmar, D.L.; Missimer, T.M. Water Budget for Lake Trafford, a Natural Subtropical Lake in South Florida: An Example of Enhanced Groundwater Influx in a Subtropical Lake Subsequent to Organic Sediment Dredging. *Water* **2024**, *16*, 1188. [CrossRef]
2. Ferlita, J.A. JA Ecological Indicators of Restoration Success: Zooplankton as Indicators of Lake Change in a Dredged Southwest Florida Lake. Master's Thesis, Florida Gulf Coast University, Fort Myers, FL, USA, 2014.
3. Ceilley, D.W.; Thomas, S.; Everham, E.M. *Lake Trafford Management Action Plan. Lake Trafford Management Action Team*; South Florida Water Management District (SFWMD): West Palm Beach, FL, USA, 2013.
4. Sutton, D.L.; Portier, K.M. Density of tubers and turions of hydrilla in South Florida. *J. Aquat. Plant Manag.* **1985**, *23*, 64–67.
5. Haller, W.T.; Sutton, D.L. Community structure and competition between Hydrilla and Vallisneria. *Hyacinth Control. J.* **1975**, *13*, 48–50.
6. Canfield, D.; Langeland, K.A.; Linda, S.B.; Haller, W.T. Relations between water transparency and maximum depth of macrophyte colonization in lakes. *J. Aquat. Plant Manag.* **1985**, *23*, 25–28.
7. Søndergaard, M.; Jensen, J.P.; Jeppesen, E. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* **2003**, *506*, 135–145. [CrossRef]
8. Scheffer, M.; Hosper, S.H.; Meijer, M.L.; Moss, B.; Jeppesen, E. Alternative equilibria in shallow lakes. *Trends Ecol. Evol.* **1993**, *8*, 275–279. [CrossRef]
9. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591–596. [CrossRef]
10. ART Engineering. *Lake Trafford Critical Restoration Project—Aquascan Radar Survey Report*; ART Engineering: Tampa, FL, USA, 2004; Available online: https://www.art-engineering.com/Projects/Lake-Trafford-Report.pdf (accessed on 5 November 2024).
11. Kang, W.J.; Gilbert, D. *TMDL Report: Nutrient, Un-Ionized Ammonia, and DO TMDLs for Lake Trafford (WBID 3259W)*; Florida Department of Environmental Protection: Tallahassee, FL, USA, 2008.
12. Peterson, S.A. *Sediment Removal as a Lake Restoration Technique*; Office of Water Regulations and Standards, U.S. Environmental Protection Agency: Corvallis, OR, USA, 1981. Available online: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000I8NB.TXT (accessed on 5 November 2024).

13. Moss, B.; Balls, H.; Irvine, K.; Stansfield, J. Restoration of Two Lowland Lakes by Isolation from Nutrient-Rich Water Sources With and Without Removal of Sediment. *J. Appl. Ecol.* **1986**, *23*, 391–414. [CrossRef]
14. Kleeberg, A.; Kohl, J.-G. Assessment of the long-term effectiveness of sediment dredging to reduce benthic phosphorus release in shallow Lake Müggelsee (Germany). *Hydrobiologia* **1999**, *394*, 153–161. [CrossRef]
15. Wu, Z.; Yu, Z.; Sheng, H.; Xu, J.; Han, Y.; Xu, Y.; Feng, N.; Yao, J. Ecological effects of the dredging in the West Lake, Hangzhou. *J. Lake Sci.* **2008**, *20*, 277–284. [CrossRef]
16. Björk, S.; Pokorný, J.; Hauser, V. Restoration of Lakes Through Sediment Removal, with Case Studies from Lakes Trummen, Sweden and Vajgar, Czech Republic. In *Restoration of Lakes, Streams, Floodplains, and Bogs in Europe: Principles and Case Studies*; Eiseltová, M., Ed.; Springer: Dordrecht, The Netherlands, 2010; pp. 101–122. ISBN 978-90-481-9265-6.
17. Dement'ev, V.A. Removal of organic sediments from reservoirs and lakes and their processing. *Power Technol. Eng.* **2010**, *44*, 289–292. [CrossRef]
18. Zhang, S.; Zhou, Q.; Xu, D.; Lin, J.; Cheng, S.; Wu, Z. Effects of sediment dredging on water quality and zooplankton community structure in a shallow of eutrophic lake. *J. Environ. Sci.* **2010**, *22*, 218–224. [CrossRef] [PubMed]
19. Liu, C.; Zhong, J.; Wang, J.; Zhang, L.; Fan, C. Fifteen-year study of environmental dredging effect on variation of nitrogen and phosphorus exchange across the sediment-water interface of an urban lake. *Environ. Pollut.* **2016**, *219*, 639–648. [CrossRef]
20. Fan, C.; Zhang, L.; Wang, J.; Zheng, C.; Gao, G.; Wang, S. Processes and mechanism of effects of sludge dredging on internal source release in lakes. *Chin. Sci. Bull.* **2004**, *49*, 1853–1859. [CrossRef]
21. Jing, L.; Bai, S.; Li, Y.; Peng, Y.; Wu, C.; Liu, J.; Liu, G.; Xie, Z.; Yu, G. Dredging project caused short-term positive effects on lake ecosystem health: A five-year follow-up study at the integrated lake ecosystem level. *Sci. Total Environ.* **2019**, *686*, 753–763. [CrossRef]
22. Zhong, J.; Fan, C. Advance in the study on the effectiveness and environmental impact of sediment dredging. *J. Lake Sci.* **2007**, *19*, 1–10.
23. Zhong, J.; Wen, S.; Zhang, L.; Wang, J.; Liu, C.; Yu, J.; Zhang, L.; Fan, C. Nitrogen budget at sediment–water interface altered by sediment dredging and settling particles: Benefits and drawbacks in managing eutrophication. *J. Hazard. Mater.* **2021**, *406*, 124691. [CrossRef]
24. Spalding, R.F.; Exner, M.E. Occurrence of Nitrate in Groundwater—A Review. *J. Environ. Qual.* **1993**, *22*, 392–402. [CrossRef]
25. Burkart, M.R.; Simpkins, W.W.; Morrow, A.J.; Gannon, J.M. Occurrence of total dissolved phosphorus in unconsolidated aquifers and aquitards in Iowa. *J. Am. Water Resour. Assoc.* **2004**, *40*, 827–834. [CrossRef]
26. Tomer, M.D.; Schilling, K.E.; Cambardella, C.A.; Jacobson, P.; Drobney, P. Groundwater nutrient concentrations during prairie reconstruction on an Iowa landscape. *Agric. Ecosyst. Environ.* **2010**, *139*, 206–213. [CrossRef]
27. de Wit, M.; Behrendt, H.; Bendoricchio, G.; Bleuten, W.; van Gaans, P. The contribution of agriculture to nutrient pollution in three European rivers, with reference to the European Nitrates Directive. *Eur. Water Manag. Online* **2002**, *19*. Available online: https://www.ewa-online.eu/files/downloads/publications/E-Water_Journal/90_2002_02.pdf (accessed on 5 November 2024).
28. Everham, E.M. *Lake Trafford Limnological and Biological Assessment and Lake Management Coordination. Final Report*; Technical Report; South Florida Water Management District: West Palm Beach, FL, USA, 2015.
29. Genereux, D.; Bandopadhyay, I. Numerical investigation of lake bed seepage patterns: Effects of porous medium and lake properties. *J. Hydrol.* **2001**, *241*, 286–303. [CrossRef]
30. Wallace, K.M. Watershed Delineation in a Flat Landscape with Competing Topographic and Hydraulic Controls and Its Implications for TMDL and BMAP Development. Master's Thesis, University of Florida, Gainesville, FL, USA, 2017.
31. Kirk, J.A.; Wise, W.R.; Delfino, J.J. Water budget and cost-effectiveness analysis of wetland restoration alternatives: A case study of Levy Prairie, Alachua County, Florida. *Ecol. Eng.* **2004**, *22*, 43–60. [CrossRef]
32. Dolan, D.M.; Yui, A.K.; Geist, R.D. Evaluation of River Load Estimation Methods for Total Phosphorus. *J. Great Lakes Res.* **1981**, *7*, 207–214. [CrossRef]
33. Belanger, T.V.; Mikutel, D.F. On the use of seepage meters to estimate groundwater nutrient loading to lakes. *J. Am. Water Resour. Assoc.* **1985**, *21*, 265–272. [CrossRef]
34. Amodio, M.; Catino, S.; Dambruoso, P.R.; de Gennaro, G.; Di Gilio, A.; Giungato, P.; Laiola, E.; Marzocca, A.; Mazzone, A.; Sardaro, A.; et al. Atmospheric Deposition: Sampling Procedures, Analytical Methods, and Main Recent Findings from the Scientific Literature. *Adv. Meteorol.* **2014**, *2014*, 161730. [CrossRef]
35. Anderson, K.A.; Downing, J.A. Dry and wet atmospheric deposition of nitrogen, phosphorus and silicon in an agricultural region. *Water Air Soil Pollut.* **2006**, *176*, 351–374. [CrossRef]
36. Gales, M.E., Jr.; Julian, E.C.; Kroner, R.C. Method for Quantitative Determination of Total Phosphorus in Water. *J.-Am. Water Work. Assoc.* **1966**, *58*, 1363–1368. [CrossRef]
37. Trussell, R.P. The Percent Un-Ionized Ammonia in Aqueous Ammonia Solutions at Different pH Levels and Temperatures. *J. Fish. Res. Board. Can.* **1972**, *29*, 1505–1507. [CrossRef]
38. Belanger, T.V.; Mikutel, D.F.; Churchill, P.A. Groundwater seepage nutrient loading in a Florida Lake. *Water Res.* **1985**, *19*, 773–781. [CrossRef]
39. Harper, H.H. *Evaluation of Hydrologic and Nutrient Loadings from Groundwater Seepage to Lake Jesup*; Environmental Research & Design, Inc.: Orlando, FL, USA, 2013. Available online: http://erd.org/ERD%20Publications/Eval%20of%20Hydrologic-Nutrient%20Loadings%20from%20Groundwater%20Seepage%20to%20Lake%20Jesup-July%202013.pdf (accessed on 5 November 2024).

40. Thomas, S.; Lucius, M. Groundwater seepage nutrient loading in a recently dug wet detention stormwater pond. *Fla. Sci.* **2016**, *79*, 132–146.
41. Keerthan, L.; RamyaPriya, R.; Elango, L. Geogenic and anthropogenic contamination in river water and groundwater of the lower Cauvery Basin, India. *Front. Environ. Sci.* **2023**, *27*, 1001052. [CrossRef]
42. South Florida Water Management District (SFWMD). *2023 South Florida Environmental Report—Volume I: The South Florida Environment*; South Florida Water Management District (SFWMD): West Palm Beach, FL, USA, 2023.
43. Xia, Y.; Zhang, M.; Tsang, D.C.W.; Geng, N.; Lu, D.; Zhu, L.; Igalavithana, A.D.; Dissanayake, P.D.; Rinklebe, J.; Yang, X.; et al. Recent advances in control technologies for non-point source pollution with nitrogen and phosphorous from agricultural runoff: Current practices and future prospects. *Appl. Biol. Chem.* **2020**, *63*, 8. [CrossRef]
44. Kęsicka, B.; Kozłowski, M.; Stasik, R.; Pińskwar, I. Controlled Drainage Effectiveness in Reducing Nutrient Outflow in Light of Climate Changes. *Appl. Sci.* **2023**, *13*, 9077. [CrossRef]
45. Lintern, A.; McPhillips, L.; Winfrey, B.; Duncan, J.; Grady, C. Best Management Practices for Diffuse Nutrient Pollution: Wicked Problems Across Urban and Agricultural Watersheds. *Environ. Sci. Technol.* **2020**, *54*, 9159–9174. [CrossRef]
46. Lawrence, G.B.; Lovett, G.M.; Baevsky, Y.H. Atmospheric deposition and watershed nitrogen export along an elevational gradient in the Catskill Mountains, New York. *Biogeochemistry* **2000**, *50*, 21–43. [CrossRef]
47. Poor, N.; Pribble, R.; Greening, H. Direct wet and dry deposition of ammonia, nitric acid, ammonium and nitrate to the Tampa Bay Estuary, FL, USA. *Atmos. Environ.* **2001**, *35*, 3947–3955. [CrossRef]
48. Barcan, R.; Kassis, Z.R.; Teaf, C.M.; Danley-Thomson, A.; Covert, D.J.; Missimer, T.M. Dry and Wet Atmospheric Deposition Composition in Southwest Florida: Environmental and Health Implications. *Atmosphere* **2023**, *14*, 102. [CrossRef]
49. Nowell, H.K.; Wirks, C.; Val Martin, M.; van Donkelaar, A.; Martin, R.V.; Uejio, C.K.; Holmes, C.D. Impacts of Sugarcane Fires on Air Quality and Public Health in South Florida. *Environ. Health Perspect.* **2022**, *130*, 087004. [CrossRef]
50. Chen, S.; Chen, L.; Liu, X.; Pan, Y.; Zhou, F.; Guo, J.; Huang, T.; Chen, F.; Shen, Z. Unexpected nitrogen flow and water quality change due to varying atmospheric deposition. *J. Hydrol.* **2022**, *609*, 127679. [CrossRef]
51. Lewandowski, J.; Meinikmann, K.; Krause, S. Groundwater–Surface Water Interactions: Recent Advances and Interdisciplinary Challenges. *Water* **2020**, *12*, 296. [CrossRef]
52. Li, Y.; Wang, L.; Yan, Z.; Chao, C.; Yu, H.; Yu, D.; Liu, C. Effectiveness of dredging on internal phosphorus loading in a typical aquacultural lake. *Sci. Total Environ.* **2020**, *744*, 140883. [CrossRef] [PubMed]
53. Yan, J.; Li, F. Effects of sediment dredging on freshwater system: A comprehensive review. *Environ. Sci. Pollut. Res.* **2023**, *30*, 119612–119626. [CrossRef]
54. Li, J.; Sellner, K.; Place, A.; Cornwell, J.; Gao, Y. Mitigation of CyanoHABs Using Phoslock(®) to Reduce Water Column Phosphorus and Nutrient Release from Sediment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 13360. [CrossRef] [PubMed]
55. Chen, M.; Cui, J.; Ding, S.; Gong, M.; Ren, M.; Tsang, D.C.W. Successful control of internal phosphorus loading after sediment dredging for 6 years: A field assessment using high-resolution sampling techniques. *Sci. Total Environ.* **2018**, *616–617*, 927–936. [CrossRef]
56. Yu, J.; Fan, C.; Zhong, J.; Zhang, L.; Zhang, L.; Wang, C.; Yao, X. Effects of sediment dredging on nitrogen cycling in Lake Taihu, China: Insight from mass balance based on a 2-year field study. *Environ. Sci. Pollut. Res.* **2016**, *23*, 3871–3883. [CrossRef]