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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

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Abstract: A very detailed water budget analysis was conducted on Lake Trafford in South Florida. The inflow was dominated by surface water influx via five canals (61%), with groundwater influx constituting 12% and direct rainfall constituting 27%. Lake discharge was dominated by sheet flow (69%) and evapotranspiration (30.5%), with groundwater recharge of the hydraulically connected unconfined aquifer accounting for only 0.5%. The removal of 30 M tons (4.4×10^6 m^3) of organic sediment impacted the groundwater influx, causing enhanced groundwater flow into the deeper parts of the lake and mixed flow along the banks, creating a rather unusual pattern. The large number of groundwater seepage meters used during this investigation led to a very reliable set of measurements with occasional failure of only a few meters. A distinctive relationship was found between the wet-season lake stage, heavy rainfall events, and pulses of exiting sheet flow from the lake. Estimation of the evapotranspiration loss using data collected from a weather station on the lake allowed the use of three different models, which, when averaged, produced results comparable to Lake Okeechobee (South Florida). A limitation of this investigation was the inability to directly measure sheet-flow discharges, which had to be estimated as a residual within the calculated water budget.

Keywords: subtropical natural lake; water budget; eutrophication; organic sediment; sediment dredging

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1. Introduction

The ecological balance of natural lakes consists of a delicate equilibrium between the nutrient supply and biological uptake within a water body, which notably includes uptake by the primary producers such as emerged and submerged macrophytes, attached and planktonic microalgae, and bacteria. Nutrients transfer upward through the food chain, where they are then fully or, more often, partially recycled throughout the ecosystem. As a result, organic-rich sediments accumulate over time. Natural eutrophication in shallow lakes thus slowly results in an ecosystem change. For example, the accumulation of organic sediment over centuries can lead a body of water to shift from a lake to a wetland, a wet meadow and, finally, to a terrestrial system [1]. However, cultural eutrophication from both allochthonous and autochthonous sources of nitrogen and phosphorus nutrient loading accelerates the natural processes of eutrophication [2,3]. These excessive nutrient influxes force the ecosystem to evolve into various endpoint states, including the unfortunately too-commonly observed hypereutrophic state characterized by turbid waters dominated by prolific microbial communities commonly accompanied by harmful algae blooms (HABs) [4–6]. High organic sediment and flocculate accumulation/sedimentation rates result in a lack of aquatic vegetation, anoxia, and/or toxin releases, causing fish deaths [7–9].

Impaired water bodies in a hypereutrophic state thus necessitate remediation to reestablish the nutrient balance and improve the health of the ecosystem [10]. Cultural eutrophication is likely the Earth's most widespread water quality problem and is the second leading cause of waterbody impairment under the Clean Water Act [11] for lakes in the United States [2,12,13].

Investigating the causes and effects of nutrient imbalances in lakes requires the development of nutrient budgets, which, in turn, creates the need to develop a detailed water budget for this specific kind of water body [14]. Combined nutrient and water balance models are typically implemented in lentic systems, such as lakes and wetlands, to identify sources of loading and eutrophication [15–18]. Understanding the lake water and nutrient budgets prior to implementing remedial strategies is necessary to avoid any unexpected results occurring.

Lake Trafford is a shallow subtropical lake located near the unincorporated community of Immokalee in Collier County, Florida (Figure 1). Lake Trafford is the center low spot of a shallow 81.2 km^2 basin and is a discharge basin for the local unconfined aquifer. While the lake has no defined tributaries, it acts as the headwaters of the Corkscrew Swamp and the Imperial and Cocohatchee River watersheds. It contributes shallow seepage to these areas during the dry season and overflows its banks when water levels reach an altitude of 6.0 m NAVD'88. When water levels are above this threshold, water discharges to the Corkscrew Swamp as well as south through the Camp Keais Strand and Stumpy Strands, thus impacting the Fakahatchee Strand and Golden Gate Estates Critical Project Area. Water eventually makes its way to the coast through the 10,000 islands (Figure 2) [19,20].

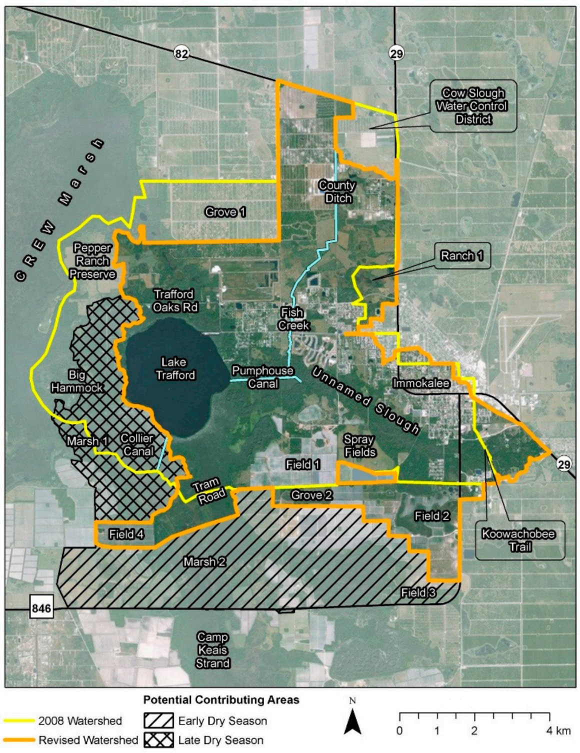

Figure 1. Lake Trafford watershed boundary delineated in 2017 [21] and revised from Kang and Gilbert's [22] watershed delineation.

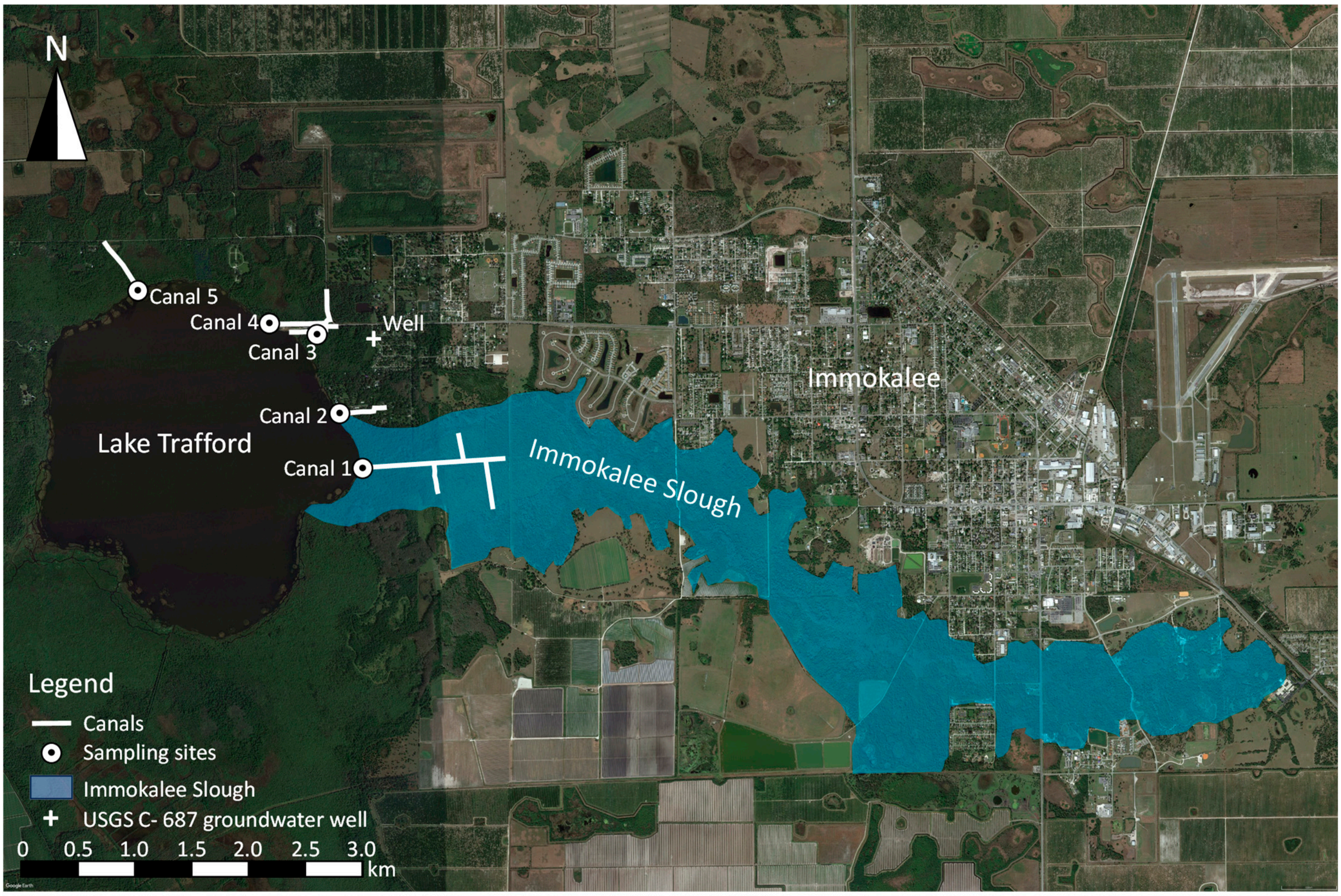

Figure 2. Satellite image of Lake Trafford and the adjacent land to its east. The Immokalee Slough is highlighted in opaque blue. Each canal is delineated with a white line and the sampling stations in those canals are marked with white circles. Canal 1 can be seen in the terminating area of the slough.

Lake Trafford was historically known as the premier freshwater boating and fishing destination in Southwest Florida after the first public boat ramp opened in the early 1960s [19]. The lake was known for its clear water, sandy bottom, and diverse and expansive coverage of submerged and emergent aquatic vegetation. Over the years, local development and the establishment of many farms caused anthropogenic nutrient loading in Lake Trafford to increase and led to the extensive proliferation of the submerged rooted macrophyte *Hydrilla verticillata*. *Hydrilla* is an invasive exotic species from the warmer regions of Asia that was accidentally introduced into the lake in 1969. With optimal conditions of light, temperature, and nutrients, this plant can grow up to 2.5 cm/day and a single tuber can grow more than 6000 new tubers per m^2 [23]. *Hydrilla* beds can smother native vegetation (e.g., *Vallisneria americana* and *Potamogeton illinoensis*) and reduce the habitat suitability for fish at elevated densities [24]. *Hydrilla* can grow in dark, turbid waters, requiring only 0.75% of incoming solar radiation [25]. It can also grow in a wide variety of conditions and has been known to double its water body coverage in as little as six weeks, which occurred at Lake Trafford [25].

To control *Hydrilla* growth, Lake Trafford was treated with herbicides from the 1970s to the 1990s. The subsequent death and decay of *Hydrilla* caused increased organic sediment accumulation on the lake bottom. This increased internal nutrient loading and allowed for the perpetual disturbance of the bottom sediment due to the lack of rooted vegetation, leading to a decreased water clarity [26]. Consequently, 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 the organic sediment once the *Hydrilla* was eradicated (i.e., the turbid state of the alternative stable states, as described and summarized in Scheffer et al. [27]). The large amounts of organic sediment that had accumulated from the decaying *Hydrilla* created an average 0.74 m thick organic sediment layer, with up to 2 m accumulating in some areas [28]. The results were a reduction in the lake water volume, increased BOD, and recurrent algae blooms, which collectively led to massive fish kills (e.g., 50,000 dead fish in 1996) [19]. 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 [22]. 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.

Reversing the nutrient-rich turbid state of a lake dominated by phytoplankton to its previous clear state dominated by native plants poses a great challenge, since the effort involved in such a shift is greater than what it took to initially make the hydrosystem shift to the turbid state (a phenomenon called hysteresis [27]). One of the remedial methods applied to the lake was the removal of the excess organic sediment by dredging. Per the muck measurement performed in January 2004 [28], all of the estimated 4.8×10^6 m^3 of accumulated organic muck was removed by dredging from 2006 to 2010. Other measures were taken in the lake drainage basin to reduce nutrient discharges.

Sediment dredging can induce a switch towards the initial clear state, although this strategy may have unexpected or negative impacts [20,29,30]. While this restoration effort for Lake Trafford has been an important curative step in the lake's recovery with encouraging results including the growth of the bass population, with some notably large specimens, the lake continues to exhibit cyanobacterial algae blooms and *Hydrilla* growth over the native vegetation [31]. In addition, the hydrology of the lake has been changed through the dredging activity, which has unknown consequences. Therefore, the water budget of the lake has been altered to some degree. The water budget calculation methodology described by Evans [14] was initiated, which is described in detail in Section 2 of this paper.

The purpose of this research was to measure the post-dredging water budget of Lake Trafford to ascertain what changes occurred in the inflow and outflow processes of the lake through the removal of the low-hydraulic-conductivity organic sediment. There have been few investigations of natural shallow subtropical lakes (solution lakes, as termed by Hutchinson [32]) conducted in terms of hydrology and water budgets. This documentation will be useful to other scientists and engineers involved in lake restoration and management. An important aspect of this research is to assess the unexpected impacts of sediment dredging on lake hydrology. The primary objectives of this research were to measure the water balance of Lake Trafford after dredging to determine what changes occurred in the lake inflow and outflow processes due to the removal of organic sediments with low hydraulic conductivity. In addition, an analysis was undertaken to measure the water balance and determine which factors influence the inflow and outflow volumes.

2. Materials and Methods

2.1. Hydrogeology of Lake Trafford

Lake Trafford lies within the water-table aquifer, which is the uppermost aquifer in the Surficial Aquifer System [33]. This aquifer is unconfined and consists of an upper layer of medium- to fine-grained quartz sand overlying shell, coralline limestone, and a variety of other limestone lithologies. Where the elevation of the land surface is below 7.6 m, the quartz sand unit occurs with the Fort Thompson Formation of late-Pleistocene age, with the underlying shell and limestone occurring with the Pinecrest Member of the Tamiami Formation of late-Pliocene age [34,35]. At higher elevations, the quartz sand is also part of the Tamiami Formation. Shell deposits are commonly found below the former organic deposits in Lake Trafford [36].

The hydraulic conductivity of the sediments in connection to Lake Trafford ranges from 30 to >1000 m d^{-1} [33]. Bennett [36] developed a groundwater flow model of the Surficial Aquifer System using the MODFLOW code. This model indicates an area of lateral groundwater flow beneath the Lake Trafford watershed caused by changes in the land surface altitude east of the lake. Based on this model, the groundwater influx into the lake is expected to be strongest on the northern and eastern banks.

2.2. Measurement of the Lake Bathymetry

A post-dredging bathymetry survey of Lake Trafford was conducted in June 2015 from a Tracker® topper 1436 aluminum Jon boat outfitted with a tiler Lehr 5HP outboard using a Lowrance HDS-7 Gen2 console coupled with a Point-1 GNSS directly mounted on top of a 200kHz SONAR transducer with a 22-degree beamwidth. Over the course of three consecutive days, the boat covered the entire lake at a speed of less than 8 km/h and with tracks equidistant of about 10 to 20 m. The sounding data were uploaded to cloud computing software www.biobasemaps.com (accessed on 18 April 2024) to extract the raw data as a comma separated file. After correcting for the depth of the transducer (0.16 m), the sounding depths were then computed in NAVD'88 elevation format using the elevation of the Lake Trafford water surface recorded via the USGS station 02291200 located across the water quality station Canal 2 (Figure 2). The soundings for the average NAVD'88 lake elevation at 5.53 m were then computed and interpolated in Surfer version 27 (Surfer 27, www.goldensoftware.com, accessed on 18 April 2024) using the kriging interpolation method and the appropriate variogram. Volumes and planar surface areas for various NAVD'88 lake levels were also computed in Surfer 27 and their reciprocal relationships were fitted with fourth-order (volumes) and second-order (planar surface areas) polynomial regressions in Microsoft® Excel® for Microsoft 365 MSO version 2403.

2.3. Sediment and Floc Accumulation in Lake Trafford

The combined pre-dredging sediment and floc (i.e., muck) accumulation in Lake Trafford was measured by ART Engineering LLC consulting firm (www.art-engineering.com, accessed on 18 April 2024) in January 2004 using AquaScan Radar Survey Technology [28]. Since the raw data were not available, the map of pre-dredging muck accumulation was digitized and the isocontour values were determined on a two-dimensional map using the "2D XY" feature of the free online software PlotDigitizer (www.plotdigitizer.com, accessed on 18 April 2024). These generated data for each isocontour were then combined and interpolated in Surfer 27 using the kriging method and the appropriate variogram. As a verification method, the volume of muck was computed in Surfer 27 and compared to the one determined by ART Engineering LLC [28].

2.4. Measured Components of the Lake Trafford Water Budget

A water budget for a natural lake was created using a basic relationship that quantifies the hydrological inputs and outputs of the system (Equation (1)). This relationship is as follows:

$$\Delta S = (P_{gross} + GW_{in} + SW_{in}) - (ET + GW_{out} + SW_{out}) \quad (1)$$

where ΔS is the change in storage of the lake, P_{gross} is the precipitation into the lake, GW_{in} is the inflow of groundwater, SW_{in} is the surface water runoff/inflow, ET is the evapotranspiration, GW_{out} is the outflow water into the ground, and SW_{out} is the surface water outflow [14,18]. Each facet of the water budget was measured for Lake Trafford either experimentally, by modeling, or through subtraction and deduction. Water budgeting for lakes requires that the bathymetry and total volume of the lake be known to determine the change in water storage (Section 2.2).

2.5. Measurement of Groundwater Fluxes in and out of the Lake

Upward and downward fluxes of groundwater were quantified every other week from 14 October 2015–15 October 2015 (event 1) to 24 October 2016–25 October 2016 (event 28) using homemade groundwater seepage meters (Figure 3). Each meter was made from half of a standard steel 200 L drum (0.85 m tall and 0.58 m ID), which was transversally cut with an angle grinder equipped with a cutting wheel. A hole was then made near the rim of the drum to insert a bulkhead connector, into which a 10 cm long 2.7 cm OD schedule 40 PVC tube was glued. This snorkel allowed the volumetric loss or gain of water to be measured using an 8 L 1.5 mil (0.04 mm wall thickness) clear polypropylene bag. Its opening was secured with thick rubber bands over the snorkel (Figure 3). Groundwater fluxes were measured every other week (i.e., twice a month) from a total of 25 seepage meters placed at 20 locations throughout the lake. Meters 1–14 were situated within the littoral zone, while meters 15–20 were in open, deeper water (Figure 3). More meters were used in the littoral zone of the lake, where most groundwater exchanges typically occur [37,38]. Five sites received duplicate seepage meters that were placed directly adjacent to one another. These duplicate meters were used to assess the precision of the duplicate groundwater flux measurements in proximity using the root-mean-square error (RMSE). A total of four duplicate meters were used to assess the shallow-water meter accuracy (Sites 3, 5, 10, and 13) and one was used to assess the deeper water meters' accuracy (Site 15).

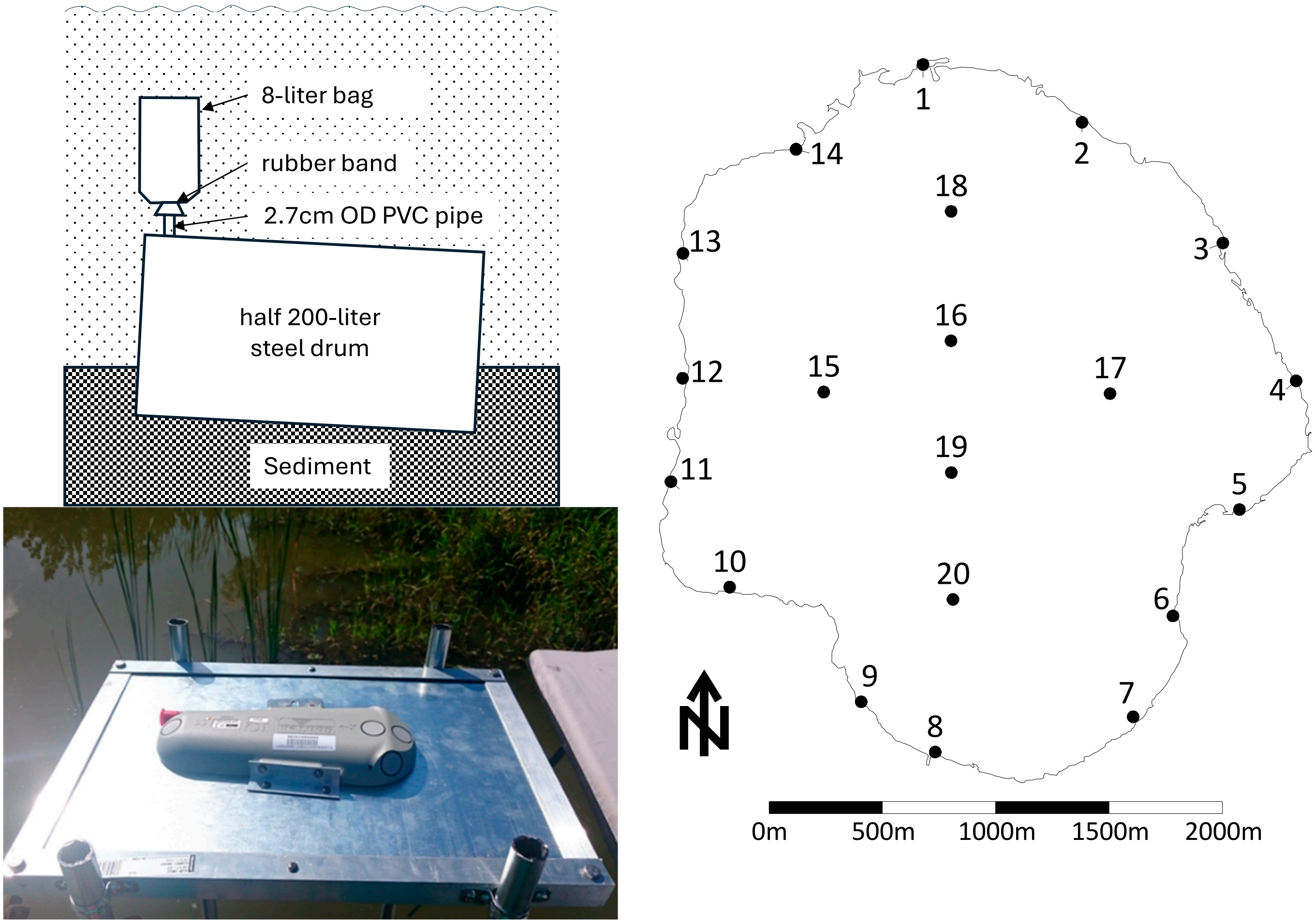

Figure 3. (**Top Left**) Diagram of the slightly tilted groundwater seepage meter with its collecting bag attached. (**Bottom Left**) Sontek IQ flow velocimeter for canal water flow measurement. (**Right**) Location of the seepage meters (closed dots) within Lake Trafford. Meters 3, 5, 10, and 13 were used to estimate the seepage variation for a given location.

Littoral seepage meters were spaced evenly around the lake perimeter in June 2015 when water levels were lowest, and they were placed as shallow as possible. Depth and spacing around the lake were the primary drivers of meter placement, but other factors influenced their positioning as well. For example, large stands of emergent vegetation often forced meters to be placed further from the shore or further down the bank. Additionally, an airboat tour company operating in Lake Trafford created many "airboat trails" where their boats frequently traveled. These areas were avoided to prevent collisions with meters and erroneous fluxes from boat pressure waves. All seepage meters were allowed to settle for three months before the official sampling began: long enough for adequate settling and accurate flow results [38–42].

Seepage rates were measured every other week for a period of 24 h each time. For each sampling event, the 8 L black polypropylene bag was filled with 1 L of lake water, except for two randomly chosen sites per sampling event, at which the bags received deionized (DI) water.

After twenty-four hours, each bag was removed and measured volumetrically. Bags that were filled with DI water were also measured for specific conductance to determine the conductivity of the groundwater flux.

The volumetric flow rate (Q) for each site was then determined using Equation (2):

$$Q = \frac{V_{start} + V_{final}}{dt} \quad (2)$$

where V_{final} is the volume final in the bag, V_{start} is the initial volume in the bag, and dt is the elapsed time. Flux velocity was also calculated by dividing Q by the cross-sectional area of the seepage meter (0.26 m^2), which was useful for comparing flux rates between systems with varying meter designs. A correction coefficient of 1.10 was applied to all flow rates [38].

For each event, spatial changes in the groundwater flow rates were mapped via kriging interpolation with Surfer 27. Additionally, using the average flow rate for the 28 events, an average flow rate map was also produced. Surfer 27 was also used to calculate the groundwater discharge and recharge (i.e., the summation of all flow rates for the whole lake) for each event, as well as the average for all 28 events, expressed in m^3 d^{-1}. Further, the groundwater discharge and recharge between sampling dates was interpolated using a daily time step using a Bessel spline interpolation using the SRS1 cubic spline V2.51 version Add-Ins for Microsoft Excel (www.srs1software.com, accessed on 18 April 2024). The interpolated values were then used in the daily water budget model.

2.6. Measurement of Surface Water Influx from Canals

Each of Lake Trafford's five dead-end, runoff collection canals were equipped with a Xylem Sontek IQ (Canals 1, 4, and 5; www.xylem.com, accessed on 18 April 2024) or Sontek IQ+ (Canals 2 and 3) to record the flow. These IQ and IQ+ models are ideal for measuring water velocity and discharge in shallow canals and culverts. The cross-sectional bathymetry of each canal was measured manually using a surveyor level and stadia rod and entered into the Sontek-IQ software V4.1 version (www.xylem.com). This allowed the software to calculate Q through each canal by monitoring the stage and water velocity. IQ/IQ+ units were placed in areas where the canal was straight with well-defined banks (as much as possible). The IQ/IQ+ units were mounted on platforms constructed of angle and sheet aluminum attached to four mounting legs made of galvanized piping (Figure 3). The platforms were adjusted so that their height was approximately 10 cm from the top of the sediment. The true height off the bottom for each IQ/IQ+ unit was input into the Sontek-IQ Software, allowing the software to adjust to the true stage of the canal. The noise in the flow data was elevated originally, with highly up-and-down readings within a span of 10 min. After months of troubleshooting with the manufacturer, this was remedied by disabling the two side-mounted acoustic beams and using only the two center-line beams for velocity measurements beginning in April 2016. Data collected before April were used for all canals with the exception of Canal 3, which had much higher noise due to an incidental change in the tilt from an unknown causality. The data for Canal 3 were transformed to reduce noise during that period due to high noise within the daily averages (Supplementary Materials, Figure S1). Daily averages for the other four canals were deemed representative despite noise in the raw data.

Each IQ/IQ+ unit was connected via SDI-12 communication to a Xylem WaterLOG Storm3 data logger to record the canal discharge every ten minutes with a five-minute scanning duration. The flow rate (Q; $m^3\ s^{-1}$), mean velocity ($m\ s^{-1}$), water level (m), and water temperature (°C) were all recorded. The Storm3 data loggers and the IQ/IQ+ power adapters were housed in weatherproof electrical NEMA boxes mounted onto a platform on the shore. All equipment was powered with a 12 V 105 Ah deep-cycle marine battery housed in a lockable box; this battery was swapped every two weeks.

2.7. Measurement of Rainfall into the Lake and Estimation of Evapotranspiration

Ambient weather data were collected using various devices, all mounted to a permanent platform located in the southern portion of the lake and powered by a 12 V deep-cycle battery which was kept charged using a south-facing 100-watt solar panel. A Davis Instruments wireless weather station Vantage Pro2 (www.davisinstruments.com, accessed on 18 April 2024), equipped with air and soil temperature sensors, a humidity sensor, a rain gauge, and an anemometer (wind speed and direction), was used to collect the bulk of the meteorological data. The standard anemometer placement was at a height of 10 m above the lake stage with a distance of at least four times the height of the obstruction, away from any potential wind breaks [43]. However, infrastructure and budgetary restraints limited the placement height of the anemometer to 1/3 of the standard height (3.3 m) from the water surface at the high-water-level mark (i.e., 6.0 m NAVD'88). The soil temperature sensor was affixed to a platform leg, approximately 1 m below the high-water-level mark. Rainfall rates were measured using the standard tipping bucket found on the Davis Vantage Pro2 (1 tip = 0.2 mm rainfall). Bird activity was problematic during the very early stages of data collection, but the addition of bird spikes around the edges of the rain bucket helped prevent it from becoming clogged with bird droppings. Additionally, a Teledyne ISCO 674 rain gauge (www.teledyneisco.com, accessed on 18 April 2024, 1 tip = 0.1 mm) was used as a backup and to cross-check rainfall rates between the two rain gauges. This rain gauge was connected via analog connection to a Strom3 data logger.

A Kipp & Zonen NR Lite 2 Net Radiometer (www.kippzonen.com, accessed on 18 April 2024) was used to monitor both the incoming and reflected solar radiation, producing a net radiation value. The Kipp & Zonen™ NR Lite 2 Net Radiometer was connected via analog connection to a Strom3 data logger. This unit has two thermopile sensors facing opposite directions (one facing the sky and one facing the water's surface below). The unit produced readings in volts, which were then converted to watts of net radiation per square meter. The measurement of the net radiation was valuable for determining evaporation rates.

Data from the weather station were logged every fifteen minutes into the Davis Instruments WeatherLink® USB data logger, which was plugged into the weather station console housed inside a waterproof box. The logger was connected via USB connection to an ECS LIVA mini-PC (www.ecs.com.tw, accessed on 18 April 2024) tethered to a 4G LTE modem and running the WeatherLink® v5.8.3 software so that data could be downloaded to a mini PC and uploaded to an FTP site. A USB camera was also connected to the mini PC so that weather data and videos were livestreamed on a created website. This was carried out to avoid vandalism, as the videos were backed up and the public was made aware of the study and of the livestream via conspicuous signage around the boat ramp.

Using the data collected from the weather station, three evaporation models could then be applied to the surface of the lake. Although evaporation from lakes and reservoirs is often estimated from pan evaporation, such measurements are subject to many potential errors including pan environment bias, operator bias, the estimation of rainfall on the pan, reading errors, data recording errors, and others [44,45]. Thus, evaporation from water surfaces is rarely measured experimentally [46]. Therefore, evaporation rates were determined via modeling.

To estimate evaporation from Lake Trafford, three models were used: the Modified Turc model [47]; Equation (3), the Simple Method [45]; Equation (4), the Abtew Marsh model [45]; and Equation (5). These three evaporation estimation models are considered the most appropriate tools to estimate the evaporation of open water bodies located in subtropical South Florida [45], and they are written as follows:

Modified Turc model

$$E = \frac{K_2(23.89R_s + 50)T_{max}}{(T_{max} + 15)} \tag{3}$$

Radiation–temperature-based model (Simple Method)

$$E = K_1 \frac{R_s}{\lambda} \tag{4}$$

Abtew Marsh model

$$E = \frac{1}{K_3} \frac{R_s T_{max}}{\lambda} \tag{5}$$

where E = lake evaporation (mm d^{-1}); K_1 = a coefficient dependent on the surface type (0.53 for open water); R_S = solar radiation (MJ m^{-2} day^{-1}); T_{max} = maximum daily air temperature at 2 m height (°C); K_2 = a coefficient, 0.0123; K_3 = a coefficient (°C), for which 52.6 °C is selected for this shallow lake in the South Florida region; and λ = latent heat of vaporization of water (MJ kg^{-1}).

Evaporation rates (mm d^{-1}) were then applied to the planar surface area of the lake at the time of weather data collection. This was executed using the lake stage–surface planar area curve described in Section 2.2.

2.8. Change in Storage

The water surface elevation was measured using the USGS Site ID 02291200 station, and an additional backup pressure transducer, the Solinst Levelogger® 3001, was fitted inside a perforated 5.08 cm OD schedule 40 PVC pipe, which was attached to one of the legs of the platform supporting the weather station. The NGVD'29 elevation of the transducer in the water column was determined using a Trimble R8 GNSS receiver (www.trimble.com, accessed on 18 April 2024). Data were downloaded every other week manually onto a laptop PC via RS232 connection. All surface water elevations were transformed to NAVD'88 format and computed so that they were relative to the average Lake Trafford surface water level of NAVD'88 5.53 m. Water volume could then be determined using the relation described in Section 2.2.

2.9. Final Water Budget

The final water budget for Lake Trafford used the measured or computed water fluxes to determine the unknown flux volume of surface runoff as sheet flow. Sheet flow for this study was considered as diffuse runoff directly into the lake (not into the five canals) and surface water outflow to the surrounding wetlands during high water levels. Sheet flow was calculated as the difference between the measured net water flux and the true change in storage. Using this method, only net sheet flow values could be calculated. Thus, it is unknown what percentage of the total water influx entering Lake Trafford is truly runoff and what percentage of the true water efflux is sheet flow.

3. Results

3.1. Bathymetry

The post-dredging bathymetry of Lake Trafford shows a shallow lake that, for a surface stage of NAVD'88 5.53 m, has a mean depth of 1.6 m and a maximum depth of about 2.6 m for a surface planar area of 6.03 km^2 and a volume of 9,899,657 m^3 (Figure 4). The bottom topography is uneven, with the deepest parts of the lake occurring from the approximate center toward the northwest.

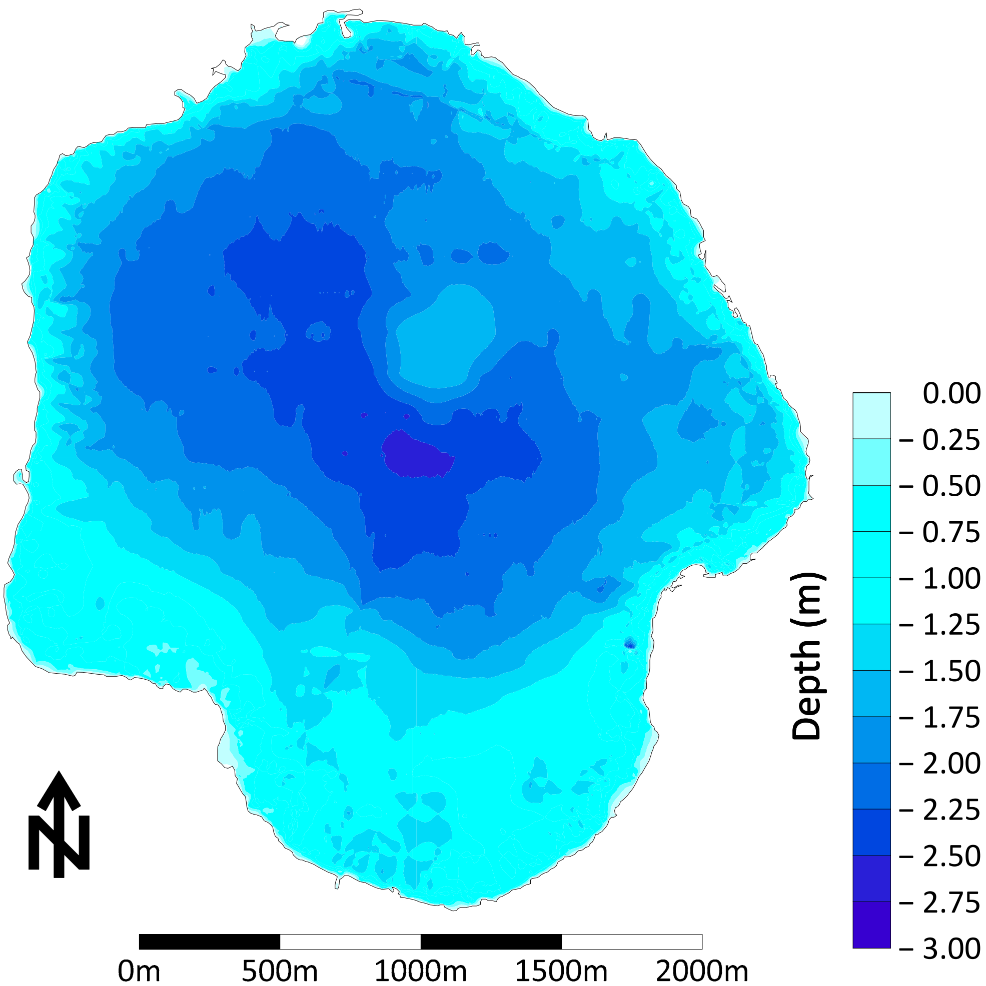

Figure 4. Bathymetric map of Lake Trafford for a surface water elevation of NAVD'88 5.53m. Bathymetry data were used to determine volumes and planar surface areas at various lake levels using Surfer 27.

3.2. Groundwater Inflow

Groundwater/surface water interactions were found to occur in all areas of Lake Trafford, including at sampling locations in deeper portions of the lake (Figure 4). Groundwater discharge rates were recorded to be as high as 28.24 L m^{-2} day^{-1}, and recharge rates were recorded to be as low as -7.64 L m^{-2} day^{-1}, although the average volumetric flow (Q) was much more modest at 1.16 L m^{-2} day^{-1}. The groundwater flow patterns throughout Lake Trafford changed over time. Measured changes based on "flow maps" created with Surfer 27 for each of the 28 sampling events are presented in the Supplementary Materials (Figure S2). Average values for the groundwater inflow and outflow are presented in Figure 5. The highest inflow rates were found at the shoreline in the southernmost part of the lake, with the highest inflow extending to the north to near the middle of the lake. The outflow areas (recharge) were found to be along the shorelines of the west and southwest parts of the lake.

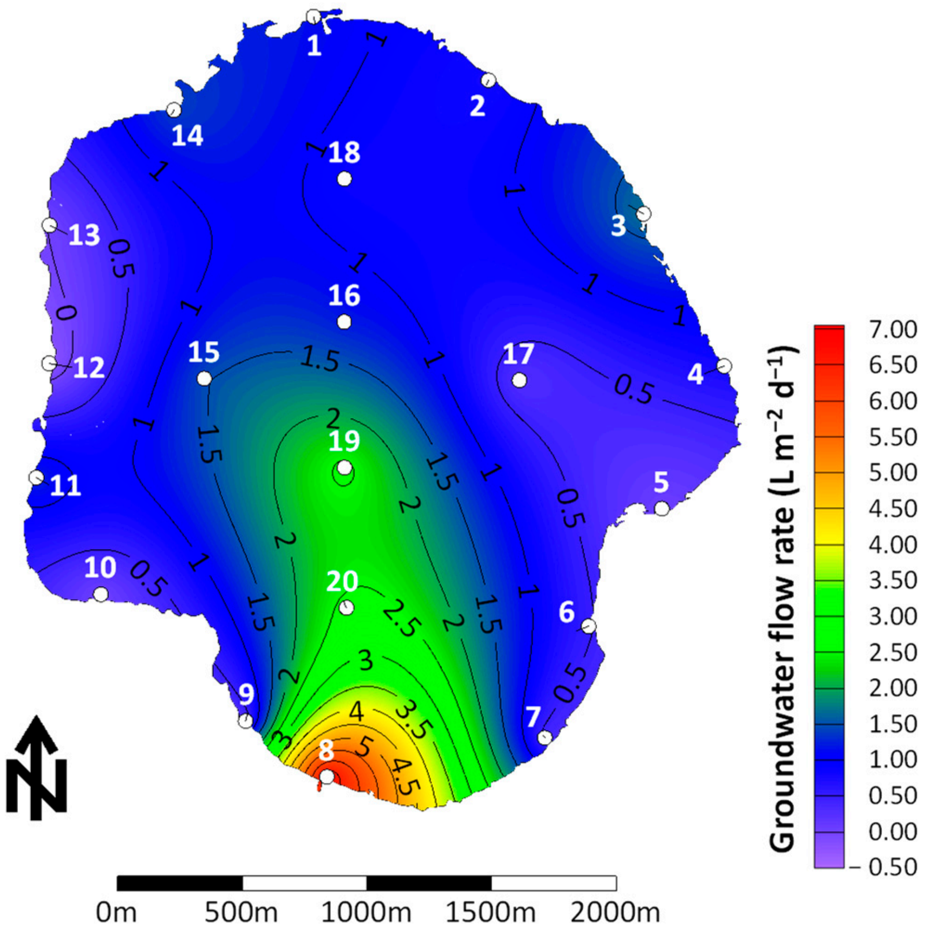

Figure 5. Map of the average groundwater flow rates (L m^{-2} d^{-1}) using all flow data from the 28 sampling events. Note that meters 8, 19, and 20 had high positive flow averages, while meters 2, 3, 5, 6, 10, 12, and 13 had low or negative averages. Meter numbers are shown on the map next to their locations (closed white dots).

A comparison of the flow rates between the duplicate meters at five of the sites in the lake using root-mean-square error (RMSE) values reveals some high RMSE values, which indicates that there was sometimes high spatial variation in the groundwater fluxes (Table 1).

Table 1. RMSE values for each pair of duplicates, grouped by sampling site. Lower RMSE values indicate better replication between two meters.

Groundwater Site	Meter A (Mean Flux) (L m^{-2} d^{-1})	Meter B (L m^{-2} d^{-1})	RMSE
3	1.607	1.518	2.201
5	0.058	0.262	0.782
10	0.326	−0.231	1.152
13	−0.008	−0.004	0.695
15	1.308	1.718	2.034

Groundwater discharge and recharge rates for each of the 28 events and the average for the study are found in Figure 6. The mean groundwater discharge into Lake Trafford of 8075 ± S.D. 4775 m^3 d^{-1} represents roughly 0.07% of the lake volume for a water level of 5.53 m (NAVD'88), while the mean recharge (outflow) of −347 ± S.D. 509 m^3 d^{-1} represents 0.003% of this volume. Overall, there was greater groundwater discharge (in) than groundwater recharge (out) in all sampling events, except for sampling event 7

(4 January 2016–5 January 2016, 1487 L m^{-2} d^{-1} discharge, −2649 L m^{-2} d^{-1} recharge). The interpolated daily groundwater discharge and recharge rates during this study are depicted in Figure 7. Over the course of data collection, the net groundwater flow exchanged 26.3% of the overall lake volume (3,110,558 m^3; Figure 8).

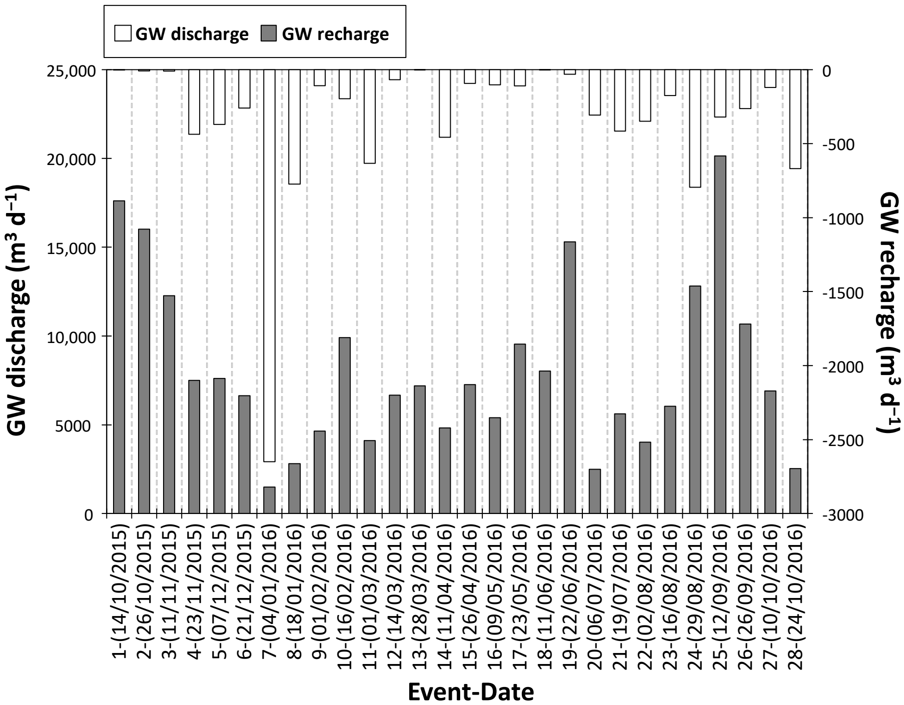

Figure 6. Total groundwater discharge (gray bars) and recharge (white bars) in m^3 d^{-1} for each sampling event 1 through 28 (associated dates in parentheses).

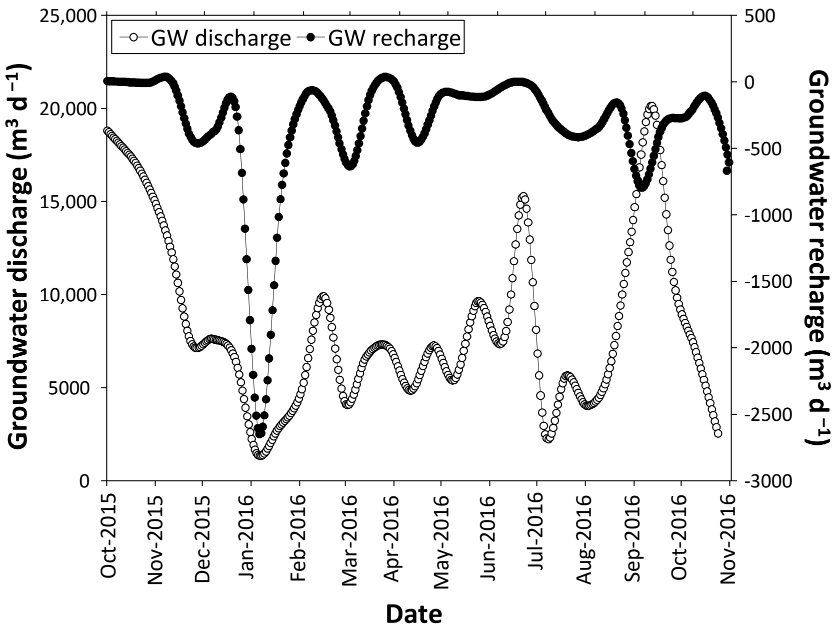

Figure 7. Groundwater discharge (closed black circles) and recharge (open circles) interpolated between biweekly sampling events using a Bessel spline function.

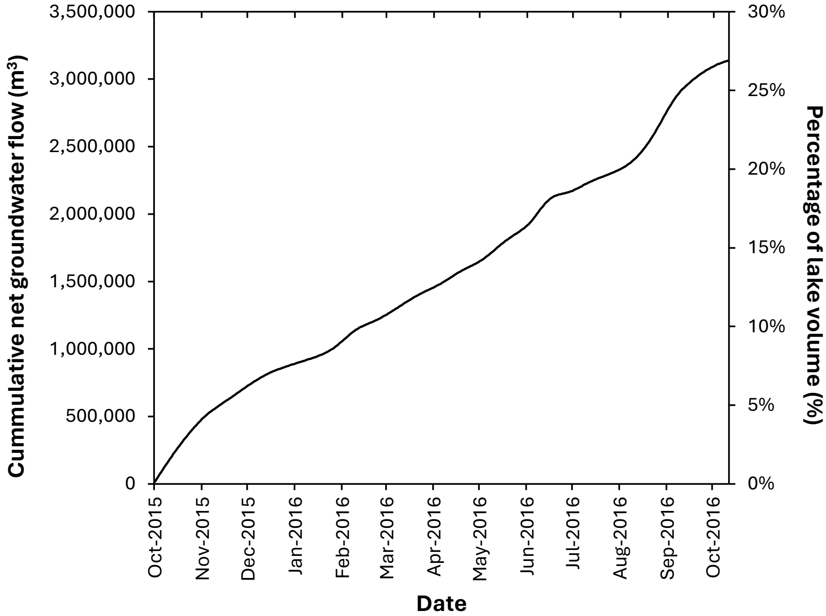

Figure 8. Time series of cumulative net groundwater flow in both total cubic meters (m^3) and percent (%) of average lake volume. A total of 26.3% of the average lake volume entered the lake via groundwater net flow over the course of data collection.

3.3. Surface Water Inflow

Canal discharge (Q) was highly variable both between the canals and temporally within each canal (Figure 9). The discharge from Canal 1 was significantly higher than that from the other four canals. The mean Q of Canal 1 was 29,921 ± S.D. 25,055 m^3 d^{-1}, which is 248% higher than the combined average discharge from Canals 2, 3, 4, and 5 of 12,041 ± S.D. 6455 m^3 d^{-1}. Canal 1 represented 71.3% of all the canal discharge into Lake Trafford during the study period and was the most responsive to rain events. Note that Canal 1 causes partial drainage of the Immokalee Slough (Figure 2).

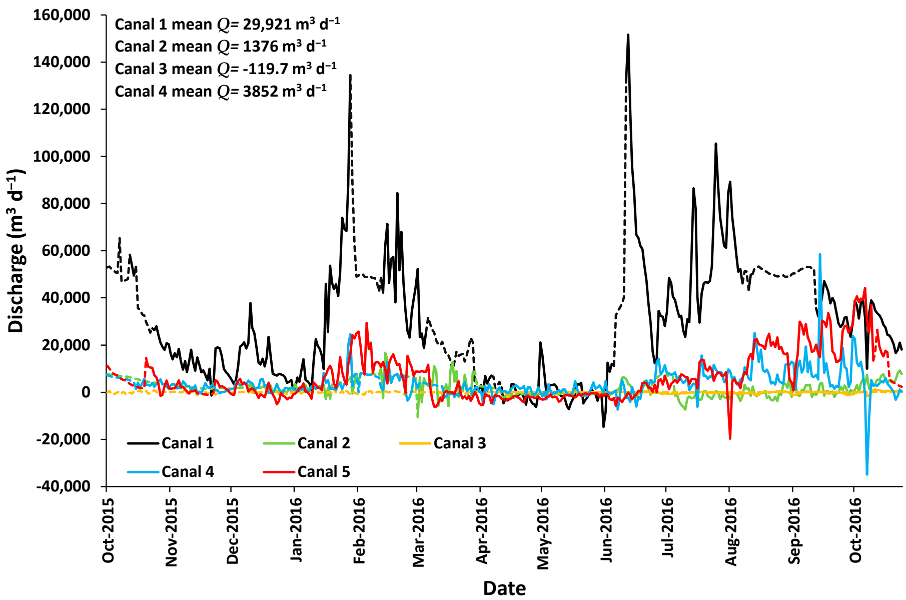

Figure 9. Hydrographs of each of the canal discharges (Q, m^3 d^{-1}) from 1 October 2015 to 24 October 2016. Mean daily Q is also reported for comparisons. Estimated portions of the hydrographs appear as dashed lines (cf. text for more information).

Q from each canal was influenced by rainfall (Figure 10), except for Canal 2 and Canal 3, which did not show a significant response to rainfall events. The discharge from the canals was also correlated with the local groundwater level, particularly for Canal 1 (Figure 11).

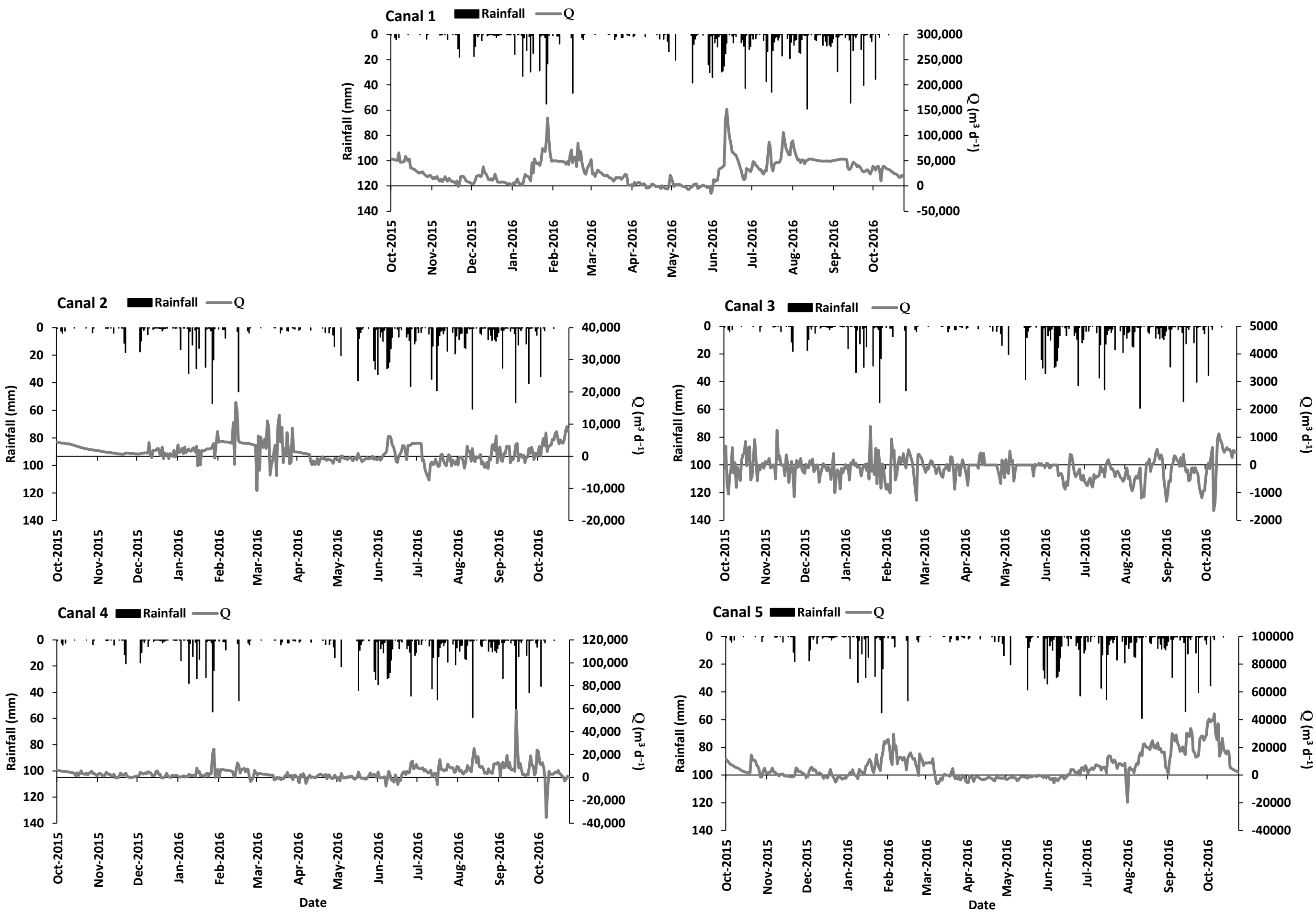

Figure 10. Canal discharge plotted over rainfall for all five canals. Note that the scales for Q are not standardized to best show the response of discharge to rainfall. Canals 1, 4, and 5 appear to be the most responsive to rain events.

Several of the Sontek IQ flow meters experienced malfunctions during data collection (unrelated to the previously described noise issue), leading to periods of missing discharge data for several canals. The relationship between discharge and groundwater elevation allowed for the estimation of these missing Q data for Canals 1 and 2. Canals 4 and 5 were better correlated with the lake stage. The short periods of estimation can be seen as the dashed line portion of the hydrograph time series in Figure 9. Other canals (namely Canals 4 and 5) were more strongly correlated with the lake surface elevation.

Canal 3 also experienced periods of missing flow data due to Sontek malfunction, but also recorded high levels of noise during the first half of the study (1 October 2015–3 April 2016) due to an incidental change in pitch (tilt) after installation. After this issue was corrected, the flow measurements were much more consistent. To reduce the noise in the earlier data to comparable levels, the standard deviations of each dataset (pre 3 April 2016 and post 3 April 2016) were compared. The ratio (determined to be 11.72:1) was used as a divisor to reduce the values of the pre-3 April 2016 dataset to values with similar noise to the post-3 April 2016 levels. While this method does include inherent uncertainty, it should be noted that Canal 3 had the lowest discharge of the five canals surveyed and is a minute factor for the water budget of Lake Trafford.

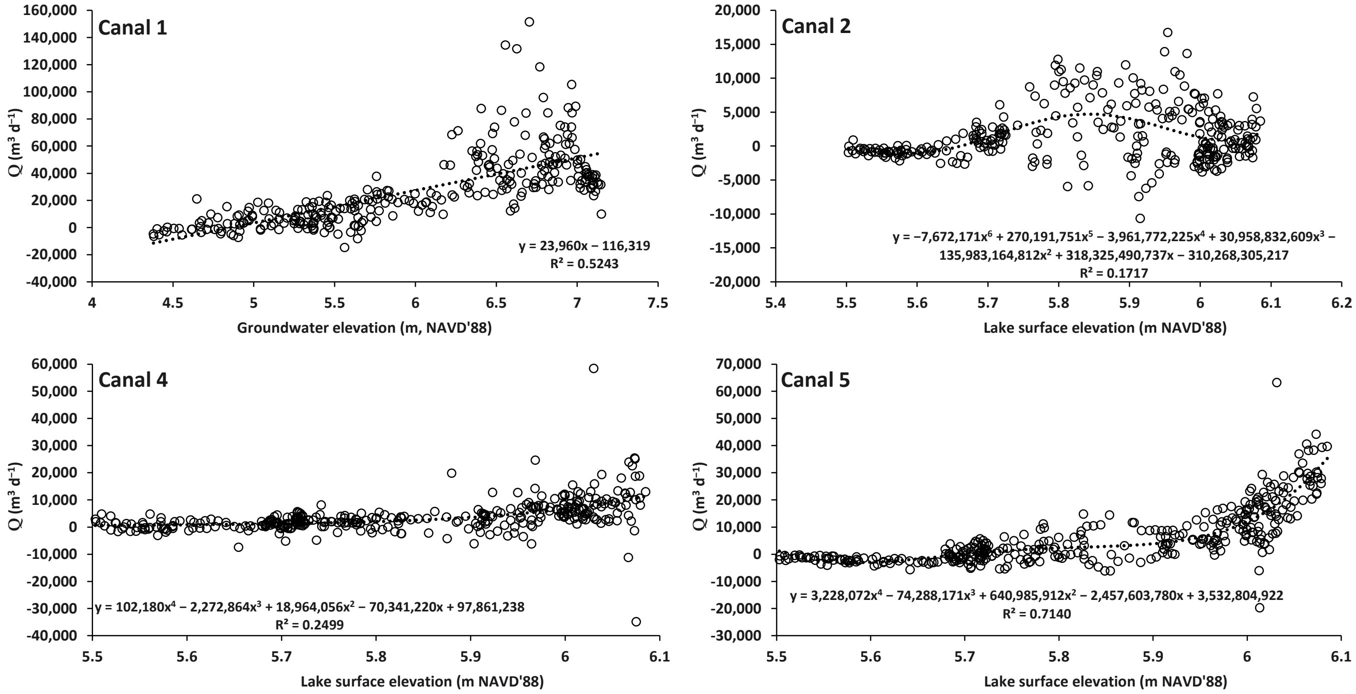

Figure 11. Scatterplots comparing groundwater level or lake stage to canal discharge (Q). Each dashed line indicates the best fit linear or polynomial function. Canal 2 had very low discharge throughout the study period and thus a strong predictive relationship was not found. Note that Canal 3 is not featured because its discharge was around zero.

3.4. Meteorological Data—Rainfall, Evapotranspiration, and Change in Storage

Expected seasonal trends can be observed in the data recorded at the center lake weather station. The period of missing temperature and humidity data was caused by a malfunction of the temperature and humidity sensors at the weather station from 29 December 2015 to 12 January 2016. Temperature and humidity data from a nearby weather station located 9 km northeast at the IFAS extension in Immokalee (Weather Station 450, 26.46225° N, 81.44033° W, https://fawn.ifas.ufl.edu/station.php?id=450, accessed on 10 December 2016) were used to fill in this period. The weather station attracted larger numbers of birds over time, mainly cormorants (*Nannopterum auritum*), which were not deterred by any commercial devices to prevent them from perching on the platform and instruments, especially both rain gauges. For the sake of comparison, a second station not left unattended for a couple of weeks and visited by birds (IFAS rain gauge) was used and a linear regression plot of the sum of precipitation measurements over two weeks from both locations showed that the IFAS rain gauge had 25% more precipitation than the Lake Trafford rain gauge (slope of 1.25, R^2 = 0.88, $p < 0.01$).

The total rainfall from 1 October 2015 to 31 October 2016 was 1222 mm, which delivered an average of 18,887 m^3 d^{-1} of water via direct precipitation to Lake Trafford. Measurements of rainfall were correlated with water and air temperature during the study period (Figure 12). These data are important in correlation with the solar radiation measurements in the calculation of free surface evaporation from the lake.

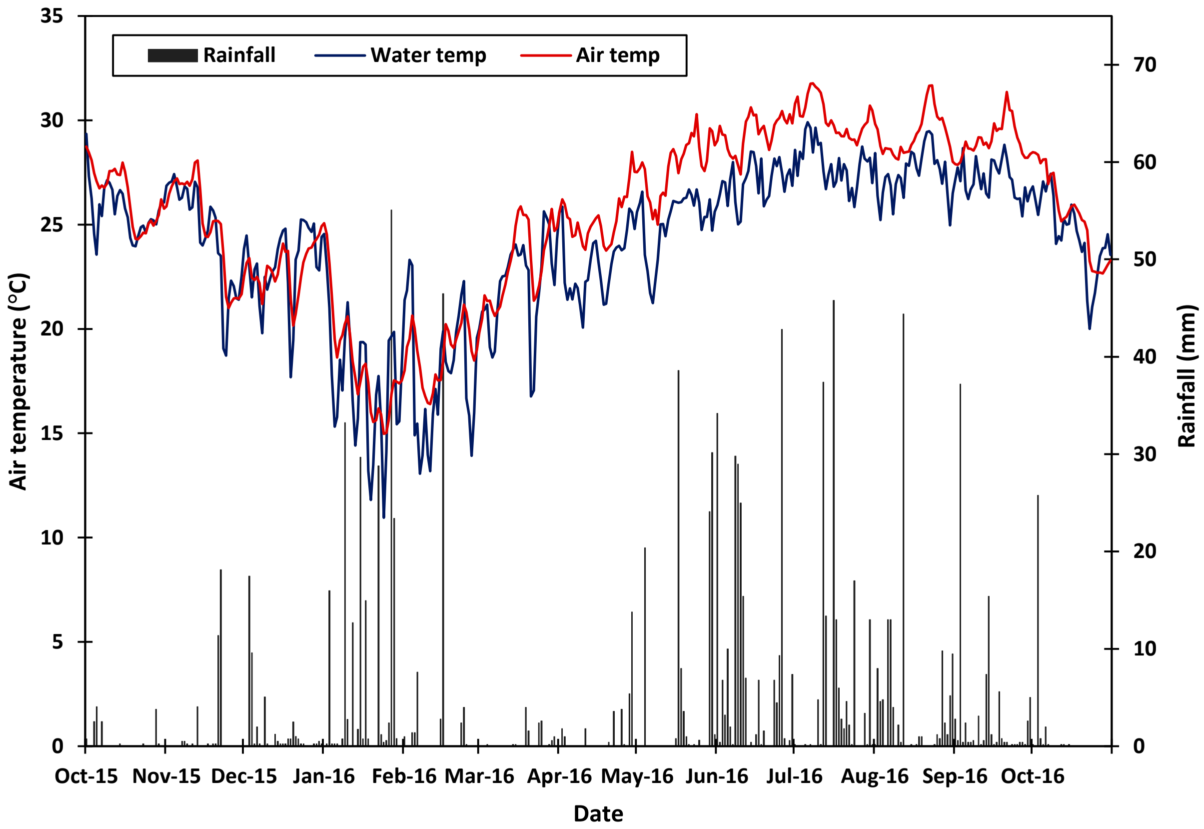

Figure 12. Air temperature (red line) and water temperature (blue line) plotted with rainfall (black bars). Water temperature and air temperature reached their lowest points in January, which also unexpectedly saw the highest amounts of rainfall.

Solar radiation was linearly correlated with net radiation (slope 1.06, R^2 = 0.86, $p < 0.01$; Supplementary Materials, Figure S3), but some daily averages with larger discrepancies occurred, and were likely caused by the perching birds shading one sensor or the other (Figure 13).

Measuring both the gross radiation and net radiation allowed for the calculation of reflected radiation by taking the difference between the two. However, the discrepancies caused by bird activity resulted in some days having negative reflected radiation (cf. negative values in Figure 13). Additionally, gross solar radiation was not measured at the Lake Trafford weather station until 18 January 2016. These missing data were substituted with data from the IFAS weather station for the final water budgeting.

Combining the data from this study with IFAS data, the mean solar radiation during the period of data collection was 189.3 ± S.D. 64.6 W m^{-2}, while the mean net radiation was an average of 19% lower, at 153.5 ± S.D. 53.8 W m^{-2}. It follows from these values that the average reflected radiation during the study period was 35.9 ± S.D. 23.5 W m^{-2}.

Figure 14 shows the results of the three evaporation models applied to the data in the time series. The models correlated well and produced a higher evaporation curve during the warmer months, with lower overall evaporation levels in the wintertime. Taking the average of the three models, the mean daily lake evaporation was 3.58 ± S.D. 1.36 mm d^{-1} and had a daily evaporative volume of 21,644 ± S.D. 8177 m^3 d^{-1}.

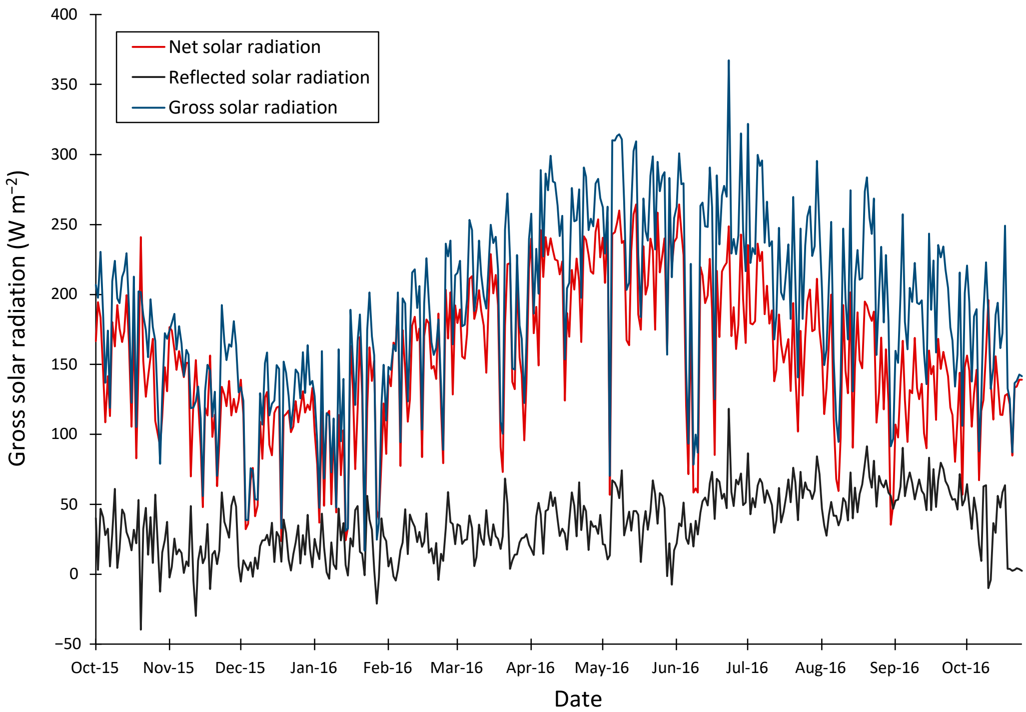

Figure 13. Changes in gross solar radiation, net solar radiation, and reflected solar radiation over time. Note the points of negative reflected solar radiation, where perching birds likely shaded the gross solar radiation sensor.

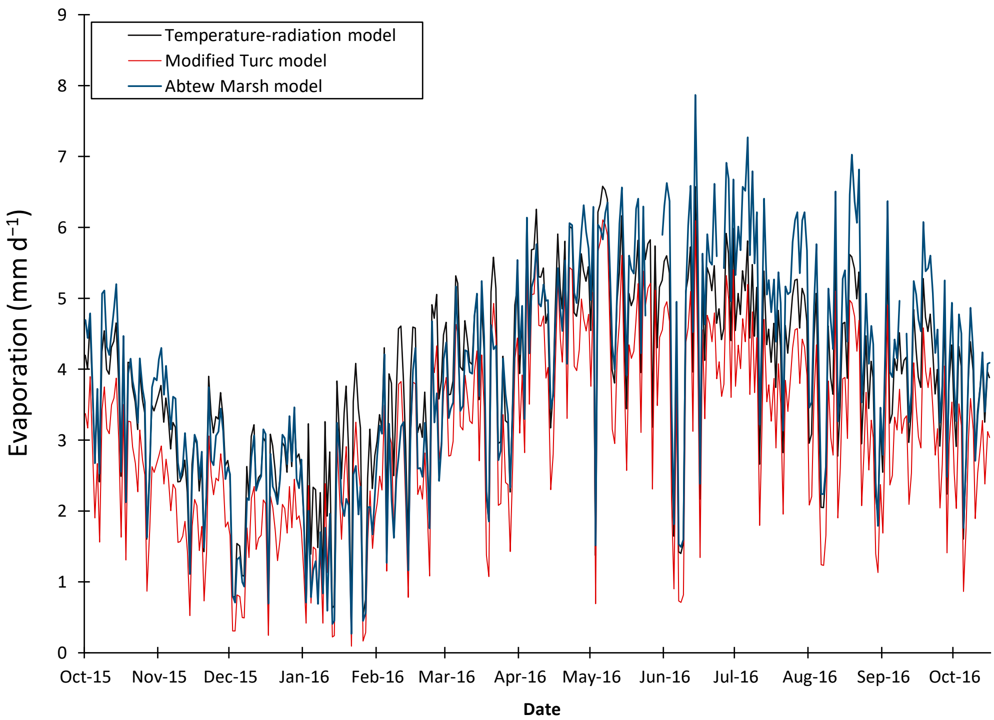

Figure 14. Results of the three evaporation models ("E") applied to Lake Trafford. An expected seasonal trend is present, with decreased evaporation rates in the winter months, increasing throughout the spring. Heavy rains and cloud cover caused several days of minimal evaporation in late June.

The lake stage reached maximum levels during January and February and again during June through September (Figure 15). The nine-year (2007–2016) average stage for Lake Trafford was 5.85 m NAVD'88 (Figure 15). The stage during the study period (October 2015–October 2016) was continuously above average, with the minimum stage falling to 5.90 m in late May 2016. The stage volume curve and stage planar surface area curve are also presented in Figure 15 and show the volume and planar surface area increasing as the stage increases, with the surface area maxing out at the 5.53 m NAVD'88 boundary.

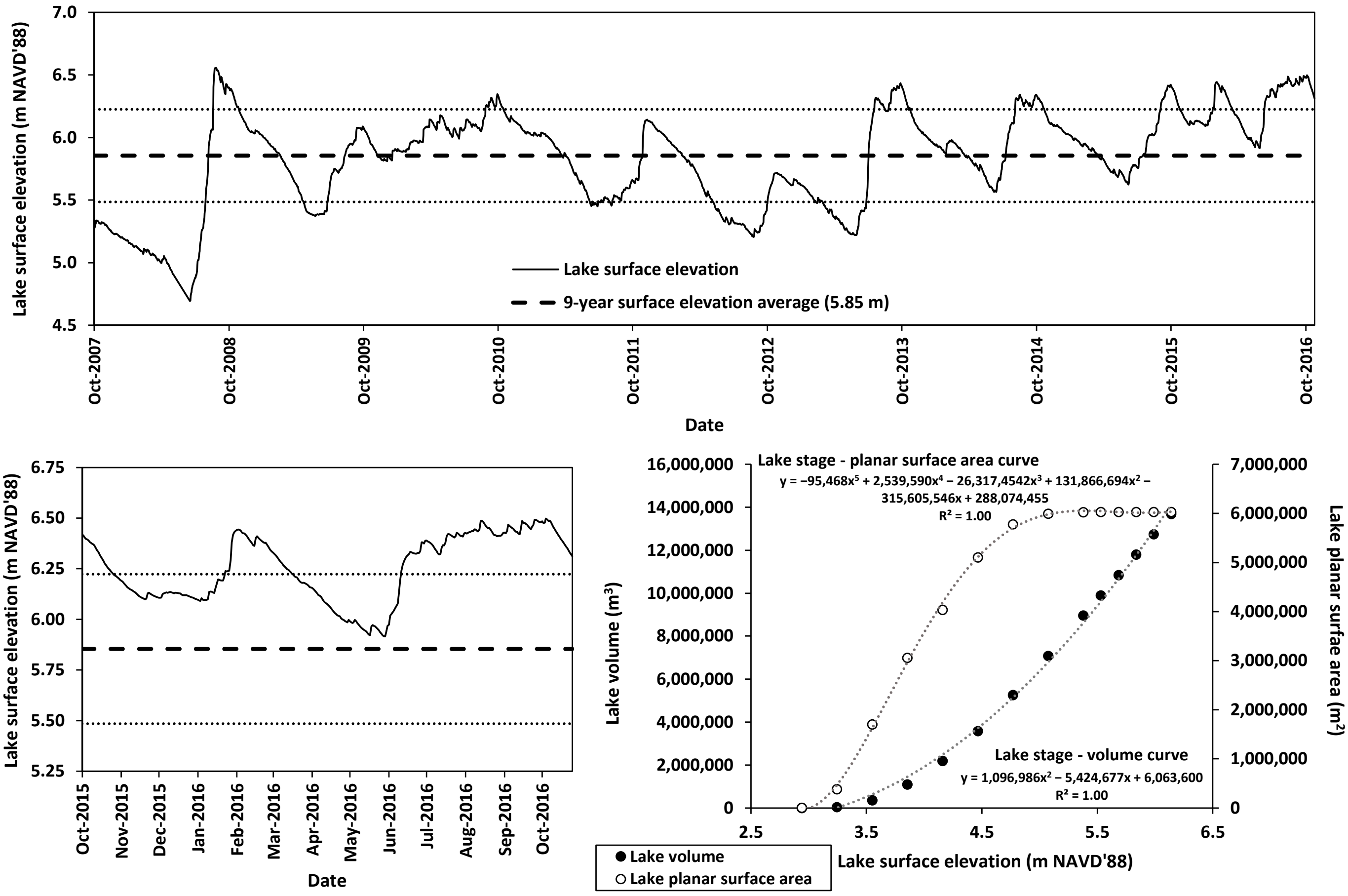

Figure 15. (**Top**) Time series of lake surface elevation (USGS 02291200) over nine years, with the bold dotted line representing the average stage over that period and the thin dotted lines indicating z-scores of +1 and −1. (**Bottom Left**) Time series of lake surface elevation during this study. The lake level was highest at the start of the project, in February after the El-Niño rains, and throughout the rainy season (June through October 2016). The lake stage was higher than average throughout the entire study period. A stage–volume curve and a stage–planar surface area curve were established for Lake Trafford to calculate the lake volumes and surface areas based on lake stage (**Bottom Right**).

3.5. Water Budget

The influxes into Lake Trafford were dominated by Canal 1, which delivered an average of 43% (29,921 $m^3\ d^{-1}$) of all water into the lake during the study period (Figure 16; Table 2). All of the canals combined delivered 61% (35,066 $m^3\ d^{-1}$) of the total volume. The effluxes were similarly dominated by sheet flow, which accounted for 69% (−49,052 $m^3\ d^{-1}$) of the water leaving the lake during the study period. Groundwater discharge was a smaller contributor, delivering 12% (8320 $m^3\ d^{-1}$) of the water into the lake, while groundwater recharge (outflow) accounted for only 0.5% (−333 $m^3\ d^{-1}$) of all effluxes.

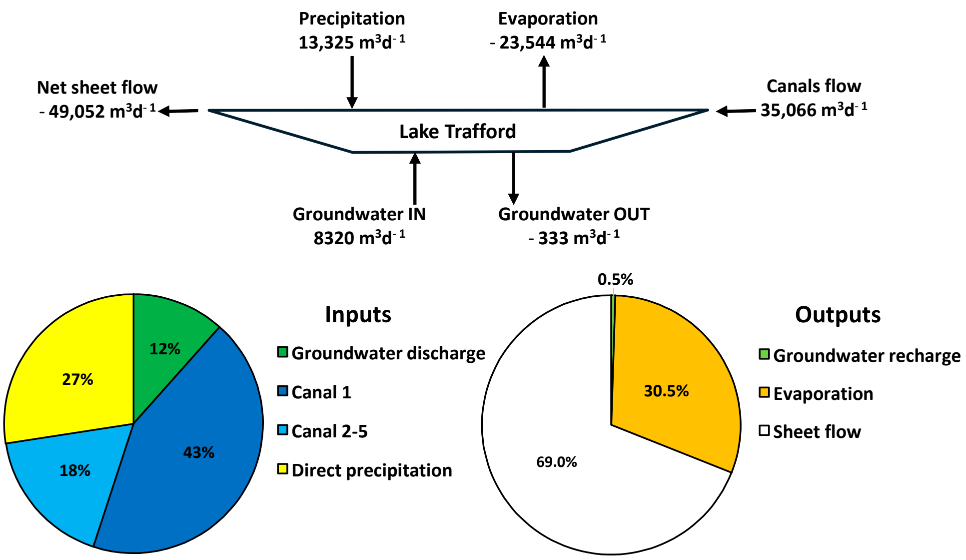

Figure 16. Top diagram: Final daily water budget of all fluxes for Lake Trafford over the course of the study period. The mean net sheet flow was negative and was thus depicted as an efflux. Bottom pie chart: Relative percentage of inputs and outputs for the water budget. Sheet flow is only represented in the outputs chart due to the inability to separate positive and negative flows from the calculated net sheet flow. The discharge from Canal 1 is separated from Canals 2 through 5 to show its magnitude compared to the other incoming water fluxes.

Table 2. Mean, standard deviation (S.D.), and min/max values for each facet of the water budget. Q from all five canals was pooled. Values were rounded to the nearest cubic meter.

Statistic	Lake Volume (m^3)	Rainfall Volume (m^3 d^{-1})	Canals (m^3 d^{-1})	GW in (m^3 d^{-1})	GW out (m^3 d^{-1})	ET (m^3 d^{-1})	Net Sheet Flow (m^3 d^{-1})
Average	11,483,262	13,325	35,066	8320	−333	23,544	−49,052
S.D.	884,197	44,892	40,237	4600	464	15,004	80,441
Min	9,792,532	0	−13,508	1322	−2649	2522	−243,249
Max	13,188,166	331,501	185,919	20,135	0	70,280	355,396

During the study period, the mean net sheet flow was negative, at −49,052 ± S.D. 80,441 m^3 d^{-1}, indicating there was more water moving out of the lake via sheet flow than into the lake. Additionally, the high standard deviation indicates that the sheet flow was also highly variable.

Figure 17 shows the change in net sheet flow over time by comparing the true lake volume to the budgeted lake volume. The two lines represent the modeled change in volume from the previous time step and the true change in storage using the known stage–volume relationship. The difference between these two lines represents the volume of net sheet flow moving in or out of Lake Trafford. As the lines diverge, there is a larger volume of sheet flow entering or leaving the lake. It is evident that more sheet flow moved out of the lake than in, and this mostly occurred at high surface water levels (6.00 m NAVD'88 and higher). As water levels decreased in the spring, positive sheet flow was more commonly seen, but at a lesser magnitude than the negative fluxes seen at higher water levels. The minimum net sheet flow value calculated was −245,067 m^3 d^{-1} on 12 August 2016, while the maximum net sheet flow calculated was 342,524 m^3 d^{-1} on 28 January 2016 after the largest rain event during the study period (55.1 mm).

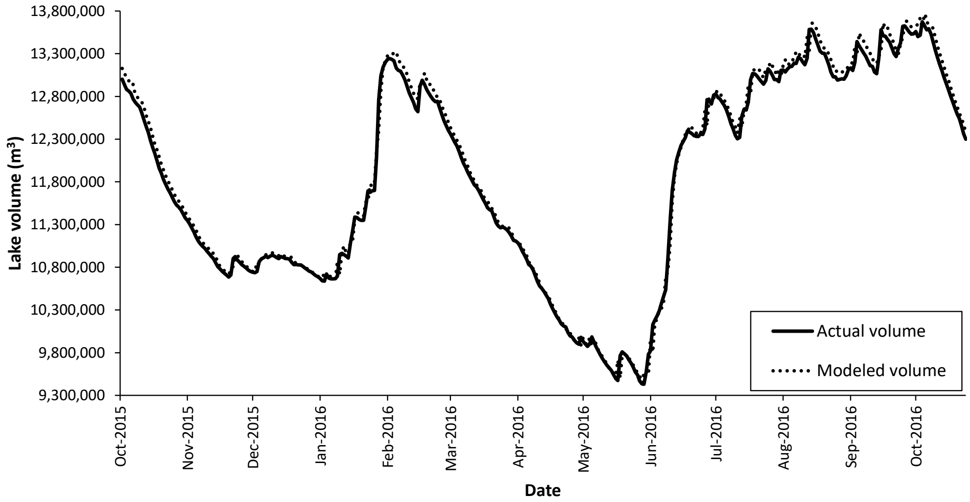

Figure 17. Time series of both the actual volume in Lake Trafford and the modeled volume as a sum of the measured water budget components. The difference between the modeled volume and the actual volume was used to calculate the net sheet flow. Time periods where the modeled volume is higher than the actual volume indicate a net negative sheet flow moving out of the lake. Time periods where the modeled volume is lower than the true volume indicate a net positive sheet flow.

3.6. Organic Sediment Removal

Maps showing the pre-dredging and post-dredging thickness of the organic sediment in Lake Trafford are shown in Figure 18. The pre-dredging average muck accumulation was 78.0 ± S.D. 40.0 cm (median 84.0 cm), with the muck being 150 cm thick in the center of the lake (Figure 18). The muck averaged at 6.6 ± S.D. 5.0 cm (median 6.0 cm), with muck as thick as 29.0 cm in the northwest corner of the lake within the littoral zone. The center west of the lake still had about 15 to 17 cm of muck (Figure 18). Most muck was removed from the center of the lake and its north portion, but not so much from its periphery and its south portion (map not shown due to it being very similar to the pre-dredging map). The total estimated volume of muck removed was 4.4×10^6 m^3 compared to 4.8×10^6 m^3 of the estimated entire muck in Lake Trafford (92% of muck removed in total).

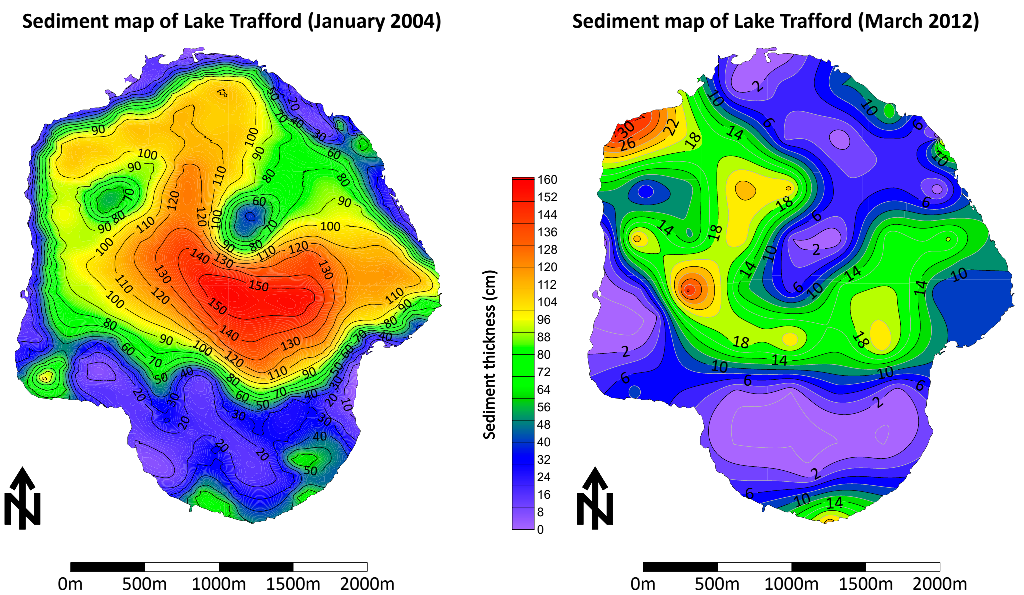

Figure 18. Organic sediment accumulation pre (2004 left map) and post (2012 right map) dredging in Lake Trafford. Dredging occurred between 2006 and 2010. Note the five-fold difference between the scales.

4. Discussion

4.1. Influence of Groundwater Flow

The groundwater discharge and recharge values for Lake Trafford are within the normal range of values typical of Florida lakes [37,48]. Groundwater flow measurements throughout the course of the study indicated that groundwater flow occurred in all areas of Lake Trafford at some point throughout data collection, including at deeper water sites. In most cases, groundwater discharge occurs in the shallow areas of lakes, where the lake level and groundwater level differences are most pronounced. Figure 19 shows the difference in water level and groundwater level according to a nearby USGS monitoring well (USGS 262554081283801 C-687) during the study. Water level elevation discrepancies were as high as one meter, and groundwater elevation was found to be both above and below the lake level elevation at various points during the study period. Groundwater discharge closely mirrored the groundwater elevation at the beginning of the study but became less correlated as El-Niño-related rains began in January. This may be due to rainfall and sampling time biases.

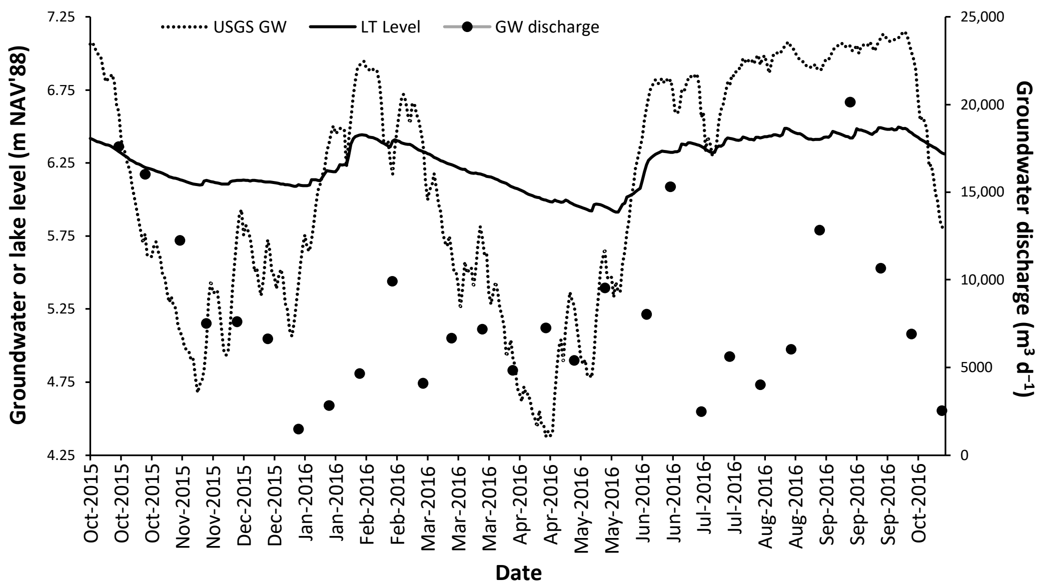

Figure 19. Changes in groundwater (USGS well) and lake elevations over the course of the study, along with the measured groundwater discharge (black dots). Increased groundwater discharge should be expected when the groundwater elevation (dotted line) is higher than the lake water elevation (black line).

The time of sampling relative to rainfall was a driver for the measured groundwater seepage, with the flow rates taken days after rainfall being low or mostly negative compared to sampling events with no rainfall. This paradigm was expected, as Schiffer [49] points out that rainfall can increase lake water elevation faster than groundwater elevation, thus creating a negative or balanced hydraulic head, limiting groundwater discharge into a waterbody. It is unknown if the groundwater discharge would have increased to higher levels in the days after sampling. A single day of sampling was used as the average flow rate for each biweekly event. Because of this, the actual groundwater inflow may be much higher than that recorded during each biweekly event and may correlate better with the local groundwater elevations.

Deep seepage meters were the most predictable of all the sampling locations, with seepage bag volumes increasing in almost every event. This is an atypical occurrence in most lakes [49,50]. Groundwater discharge in the center of lakes is typically indicative of a high potentiometric head moving water upward from deeper in the aquifer. This condition is less common, and it is unclear if Lake Trafford falls into this category. However, the very shallow depth of this lake likely limits the impacts of deep seepage. Furthermore, with all five (plus the duplicate) seepage meters showing groundwater discharge in these areas, it is unlikely that this measured flow is erroneous. The latest hydrogeological report for Collier County indicates that the base of the Surficial Aquifer System is deep in this area, and the Lower Tamiami confining unit is absent or insignificant [33]. The heterogeneity of this hydraulically connected aquifer influences the potential for deep upward seepage, in that the uppermost quartz sand unit has a vertical hydraulic conductivity at least two orders of magnitude less than the underlying shell and limestone.

Another possible reason for the atypical spatial patterns of groundwater discharge is the influence of sediment dredging. Genereux and Bandopadhyay [51] found that increased discharge further offshore in shallow lakes typically occurs when the lakebed is covered with dense organic sediment with a low hydraulic conductivity. Mapping of the sediment thickness was conducted in Lake Trafford (this study) and compared with the sediment thickness prior to dredging [28] and showed the expected reduction in organic sediment accumulation in especially the central portion of the lake (Figure 18). In addition to the lower thickness of the organic sediment, it is likely that the density of the organic material was lessened during dredging. This also increases the vertical hydraulic conductivity and allows less inhibition of groundwater inflow. The alteration of the vertical hydraulic conductivity in the center of the lake merits further investigation.

4.2. Usage of Groundwater Seepage Meters

The use of groundwater seepage meters is often accompanied by a plethora of problems, such as bag breakage or loss [52]. However, in this study, the seepage measurements were mostly successful, with only 23 bags being lost/detached or broken out of 685 total bag deployments (96.6% successful bag deployments). Only eight meters needed to be reseated due to "blowout", and three meters lost their marker buoy. This is a much lower unsuccessful bag deployment ratio than other studies using groundwater seepage meters (e.g., Harper [48]: 55% of bags lost). This relative success likely stems from the short sampling period for the groundwater flow, as it was limited to 24 h. This short duration, while ideal for bag preservation, introduces other issues. For example, shorter sampling durations lack temporal resolution compared to extended bag placement times and may be more influenced by temporary conditions, such as hydraulic head loss post rainfall.

Flow through the seepage meters may also have been lower due to the relatively high water levels experienced during the study period. Seepage meters were placed in June of 2015 when water levels were approximately 5.1 m NAVD'88. The lake stage never fell below 5.5 m NAVD'88 during sample collection, leaving the meters deeper and further from the true boundary of the lake than would have been ideal [50]. Having several groups of seepage meters to be used at various levels of the lake stage would have solved this issue [53], but would have been costly and especially difficult to implement since the lake boundary is very undefined as it extends to a densely vegetated flood plain/wetland when the lake water level is high.

4.3. Canal Influence

Canal discharge was, as expected, dependent on rainfall, with the flows being mostly stagnant during extended dry periods. Data quality was good, but the Sontek IQ units were often unreliable and led to many gaps in Q data when they needed to be removed for repair. The vast majority of discharge occurred from Canal 1, which also had the highest concentrations of nitrogen and phosphorus, making it a substantial source of water and nutrients for Lake Trafford.

It is hypothesized that Canal 1 may experience much more flow due to its connection with the Immokalee Slough (Figure 2), 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 from 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.

It is likely that higher positive sheet flow volumes would have been observed under a more typical hydrological pattern for this area (i.e., for a non-El-Niño year), with a lower stage during the winter and spring months. Using the final water budget inputs, the lake water volume turns over 2.13 times a year for a residence time of 171 days.

The canal flow was measured directly in this study and these data may be useful for modeling the flow from these canals in the future. The canals correlated well with the groundwater level and rainfall. Using Automated Neural Networks (ANNs), a more accurate estimation of canal discharge would likely be possible using known groundwater levels, rainfall totals, and other engineered data features.

4.4. Rainfall

Rainfall totals in the Corkscrew area (SFWMD station name "CORK.HQ_R", latitude north 262,301.294, longitude west 813,459.278) averaged 1484 mm per year from 1959 to 2007 (DBHYDRO, 2007). The rainfall total during the 2015–2016 study period was found to be 1222 mm as measured at the installed weather station on Lake Trafford and 1582 mm at the IFAS Immokalee FAWN station. Rainfall during the wet season followed the typical historical patterns, while the dry season was much wetter than average. Using statistical modeling methods from the South Florida Water Management District [54], the amount of rainfall measured between November 2015 and May of 2016 is considered a "1 in 10-year event", or an event that only occurs in 10% of years. Rain gauges equipped with a tipping bucket underestimate rainfall a fortiori when the rainfall rate is high over a short period of time. This could partially explain the lower-than-average rainfall during summer 2016 recorded at the installed weather stations. Algorithms are often used to estimate the correct rainfall during said high-precipitation events.

4.5. Water Budget

The final calculated water budget showed groundwater to be a relatively small contributor and it was measured at only 30% of the rate estimated in the TMDL HSPF model [22]. However, the true groundwater discharge may have been higher than that recorded, as previously discussed. Evaporation and sheet flow are the primary hydrological outputs from Lake Trafford, with groundwater recharge only accounting for 0.5% of the outflow. The evaporation estimates agree with the TMDL report estimates, differing by only 2.3%. The average evaporation rate observed was very similar to those of other lakes in Florida (Lake Trafford: 3.59 mm d^{-1}, Lake Okeechobee: 3.61 mm d^{-1} [55]).

There is a very clear relationship between lake stage and sheet flow. As the stage increased, the net sheet flow became increasingly negative. As the stage decreased, the net sheet flow became more positive. This fits logically with the assertion that Lake Trafford feeds the wetlands to its south and west with overflowing water when its water levels approach 6.0 m NAVD'88. The net sheet flow value became increasingly negative as the lake stage increased above 5.7 m NAVD'88, reaching its highest value around 6.0 m NAVD'88. Rainfall also appears to have driven positive sheet flow values, with diffuse runoff entering the lake after rain events. This can be seen as an upward spike in the net sheet flow following larger rain events. These spikes can also be found in the stage elevation, as runoff and direct precipitation increased the lake levels.

A negative net sheet flow was the norm during the study period, again related to the much-wetter-than-average winter of 2015–2016. Due to the methodology used in this study, it is unknown how much of the net sheet flow calculated was incoming sheet flow and how much was outgoing sheet flow. It is possible that the higher water levels not only increased the outgoing sheet flow but the increased rainfall also increased the incoming sheet flow, albeit to a lesser degree. The lack of resolution in this regard is a limitation of this project. Moreover, it is unclear how much runoff is channeled by the five canals before entering the lake. It is possible that the amount of direct surface runoff outside of the canals is small, and somewhat insignificant. This hypothesis may be backed up by the TMDL established for Lake Trafford. Using a wet year from the TMDL sampling period to better compare with the conditions of this study (2005–1650 mm rainfall), the daily runoff average was estimated to be 38,358 m^3 d^{-1} [22]. Discharge from the canals in this study was averaged at 35,066 m^3 d^{-1}. More data would be useful to confirm that the majority of runoff entering Lake Trafford enters through the canals. If true, this would also make remediation and load reduction projects easier to accomplish.

4.6. Future Study

Further areas of study that could prove to be valuable have been highlighted in this project. Because the Lake Trafford boundary is often ambiguous and highly vegetated, a piezometer study with sites that extend beyond the lake boundary into the surrounding wetlands may be better suited for monitoring groundwater discharge and recharge around the lake than seepage meters alone. 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.

Because of the observed changes in the water budget and the related changes in the nutrient budget, continued detailed monitoring of Lake Trafford should occur. In addition, some experimental work on reducing the hydraulic conductivity of the bottom sediments should be conducted in areas where enhanced hydraulic conductivity has led to high nutrient influx concentrations. Managing the lake water quality beyond what has been accomplished to date requires continued future experimentation and scientific assessments.

5. Conclusions

Lake Trafford is a small subtropical lake with an average volume of 11,483,252 m^3 located in South Florida. It has been impacted by cultural eutrophication caused by an excessive loading of nutrients. A key aspect of lake restoration is understanding the water balance of a lake so that remedial actions can be designed to improve the water quality. Therefore, a detailed investigation into the water budget of Lake Trafford was conducted, with direct measurements of the groundwater influx and exit, the surface water influx via canals, the direct rainfall input, and other various parameters that control free surface evaporation, as well as modeling of the evaporation loss and estimation of the sheet flow out of the surface water as a residual parameter of the calculated water balance. Based upon a thorough literature review, this one-year investigation is one of the most detailed studies ever conducted for any subtropical lake.

The inflow into the lake was dominated by surface water flows via canals and amounted to 61% of the total influx. Groundwater was found to contribute only about 30% of the inflow to the lake, and rainfall contributed the remaining 9%. The inflows from the lake were evaporation, groundwater recharge, and surface flow during high-water periods. Discharge from the lake was dominated by evapotranspiration at 30.5% and sheet flow at 61%. The groundwater recharge exiting the lake was about 0.5% of the outflow. Sheet flow only occurred when the lake stage exceeded 6.0 m NAVD'88, with wet-season rainfall being the primary factor controlling the lake stage increase, leading to sheet flow exit. The estimation of seasonal sheet flow was the primary limitation in this investigation in that there is no means of measuring it directly.

The removal of 30 M metric tons of organic sediment seems to have impacted the interaction of groundwater with Lake Trafford. It likely increased the flow rate in the deeper parts of the lake and had mixed results along the lake banks. The current post-remedial lake condition may have led to the rather unusual pattern of groundwater entry into the lake.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16081188/s1. Figure S1: Scatterplots of discharge from Canal 3 before correction and after correction. Standard deviation of high noise data was compared to low noise data (post-Sontek error correction) and the ratio was used has a devisor for the high noise data set. Figure S2: Maps of interpolated groundwater discharge for all 28 events. The bathymetry of Lake Trafford is also provided. Figure S3: Scatterplot of daily averages of gross solar radiation from the Davis weather station and net solar radiation from the Kern NR2 Lite.

Author Contributions: S.T. was the project manager for this research, took part of several parts of the study, collected information in the field, digitized the sediment maps, and mentored M.A.L. for his thesis and D.L.D. for her limnology class graduate work project, as well as edited the final paper. M.A.L. used this research for his MS thesis, collected the field data, and made the calculations. J.-Y.K. worked on all aspects of the surface water parts of this project and performed the calculations for the ET estimates. E.M.E.III worked on nearly all aspects of this project, collected data, and was on M.A.L.'s MS thesis committee. D.L.D. collected the sediment thickness data and produced the sediment accumulation map as part of her graduate limnology class requirement. T.M.M. clarified the hydrogeologic and geologic aspects of this research and drafted the final paper. All authors participated in editing the final paper. All authors have read and agreed to the published version of the manuscript.

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References

1. Carpenter, S.R. Submersed vegetation: An internal factor in lake ecosystem succession. *Am. Nat.* **1981**, *118*, 372–383. [CrossRef]
2. Carpenter, S.R.; Caraco, N.F.; Correll, D.L.; Howarth, R.W.; Sharpley, A.N.; Smith, V.H. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* **1998**, *8*, 559–568. [CrossRef]
3. Schindler, D.W. Recent advances in the understanding and management of eutrophication. *Limnol. Oceanogr.* **2006**, *51*, 356–363. [CrossRef]
4. Pearl, H.W. Coastal eutrophication in relation to atmospheric nitrogen deposition: Current perspectives. *Ophelia* **1995**, *41*, 237–259. [CrossRef]
5. Smith, S.V.; Swaney, D.P.; Talaue-Mcmanus, L.; Bartley, J.D.; Sandhei, P.T.; McLaughlin, C.J.; Dupra, V.C.; Crossland, C.J.; Buddemeier, R.W.; Maxwell, B.A.; et al. Humans, hydrology, and the distribution of inorganic nutrient loading to the ocean. *BioScience* **2003**, *53*, 235–245. [CrossRef]
6. Dodds, W.K. Trophic state, eutrophication and nutrient criteria in streams. *Trends Ecol. Evol.* **2007**, *22*, 669–676. [CrossRef] [PubMed]
7. 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] [PubMed]
8. Art, H.W. *A Dictionary of Ecology and Environmental Science*, 1st ed.; Henry Holt and Company: New York, NY, USA, 1993.
9. Nixon, S.W. Eutrophication and the macroscope. *Hydrobiologia* **2009**, *629*, 5–19. [CrossRef]
10. Hutchinson, G.E. Eutrophication. The scientific background of a contemporary practical problem. *Am. Sci.* **1973**, *61*, 269–279.
11. U. S. Environmental Protection Agency (U.S.E.P.A.). Summary of the Clean Water Act of 1972. 33 U.S.C. §1251 et seq. 1972. Available online: https://www.epa.gov/laws-regulations/summary-clean-water-act (accessed on 20 March 2023).
12. U. S. Environmental Protection Agency (U.S.E.P.A.). *National Water Quality Inventory*; U. S. Environmental Protection Agency: Washington, DC, USA, 2017. Available online: https://www.epa.gov/sites/default/files/2017-12/documents/305brtc_finalowow_08302017.pdf (accessed on 20 March 2023).

13. Schindler, D.W. The dilemma of controlling cultural eutrophication of lakes. *Proc. R. Soc. B Biol. Sci.* **2012**, *279*, 4322–4333. [CrossRef]
14. Evans, W.L., III. *Lake Hydrology: An Introduction to Lake Mass Balance*, 1st ed.; Johns Hopkins University Press: Baltimore, MD, USA, 2021.
15. Mitsch, W.J.; Dorage, C.L.; Wiemhoff, J.R. Ecosystem dynamics and a phosphorus budget of an alluvial cypress swamp in southern Illinois. *Ecology* **1979**, *60*, 1116–1124. [CrossRef]
16. Grubbs, J.W. *Evaluation of Ground-Water Flow and Hydrologic Budget of Lake Five-O, a Seepage Lake in Northwestern Florida*; Water-Resources Investigations Report 94-4145; U.S. Geological Survey: Tallahassee, FL, USA, 1995. [CrossRef]
17. Swancar, A.; Lee, T.M.; O'Hare, T.M. *Hydrogeologic Setting, Water Budget, and Preliminary Analysis of Ground-Water Exchange at Lake Starr, a Seepage Lake in Polk County, Florida*; Water-Resources Investigation Report No. 2000-4030; U. S. Geological Survey: Tallahassee, FL, USA, 2000. [CrossRef]
18. 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]
19. Ceilley, D.W.; Thomas, S.; Everham, E.M., III. *Lake Trafford Management Action Plan. Lake Trafford Management Action Team*; Prepared for the South Florida Water Management District (SFWMD) Contract E: West Palm Beach, FL, USA, 2013.
20. Ferlita II, J.A. 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.
21. 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.
22. 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. Available online: https://floridadep.gov/sites/default/files/traffordfinal091208_0.pdf (accessed on 15 January 2024).
23. Sutton, D.; Portier, K.M. Density of tubers and turions of *Hydrilla* in South Florida. *J. Aquat. Plant Manag.* **1992**, *23*, 64–67.
24. Haller, W.T.; Sutton, D.L. Community structure and competition between *Hydrilla* and *Vallisneria*. *Hyacinth Control. J.* **1975**, *13*, 48–50.
25. Canfield, D.E.; 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.
26. Søndergaard, M.; Jensen, J.P.; Jeppesen, E. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* **2003**, *506*, 135–145. [CrossRef]
27. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591–596. [CrossRef]
28. ART Engineering. Lake Trafford Critical Restoration Project—Aquascan Radar Survey Report. *Consultant's Report to Collier County, FL, USA, 2004*. Available online: https://www.art-engineering.com/Projects/Lake-Trafford-Report.pdf (accessed on 15 January 2024).
29. Zhong, J.; Fan, C. Advance in the study on the effectiveness and environmental impact of sediment dredging. *J. Lake Sci.* **2007**, *19*, 1–10. [CrossRef]
30. Harper, H.H. *Evaluation of Sediment Impacts on Hydrologic and Nutrient Loadings from Groundwater Seepage to Lake Jesup*; Final Consultant's Report; Environmental Research & Design, Inc.: Orlando, FL, USA, 2013. Available online: http://erd.org/ERD%20Publications/Eval%20of%20Sediment%20Impacts%20on%20Hydrologic-Nutrient%20Loadings%20from%20Groundwater%20Seepage%20to%20Lake%20Jesup-June%202013.pdf (accessed on 10 March 2024).
31. Thomas, S.; Everham, E.M., III; Ceilley, D.W.; Lucius, M. *Lake Trafford Aquatic Vegetation Monitoring and Mapping*; Final Report; Technical Report; South Florida Water Management District: West Palm Beach, FL, USA, 2015.
32. Hutchinson, G.E. *A Treatise on Limnology, Geography, Physics, and Chemistry*; John Wiley & Sons: New York, NY, USA, 1957.
33. Geddes, E.; Richardson, E.; Dodd, A. *Hydrogeological Unit Mapping Update for the Lower West Coast Water Supply Planning Area*; Technical Publication WS-35; South Florida Water Management District: West Palm Beach, FL, USA, 2015. Available online: https://www.sfwmd.gov/sites/default/files/documents/ws-35_lwc_hydrogeologic_mapping_083115.pdf (accessed on 10 March 2024).
34. Missimer, T.M. Stratigraphic relationships of sediment facies within the Tamiami Formation of Southwest Florida: Proposed intraformational correlations. In *The Plio-Pleistocene Stratigraphy and Paleontology of South Florida*; Scott, T.M., Allman, W.D., Eds.; Special Publication No. 36; Florida Geological Survey: Tallahassee, FL, USA, 1992; pp. 63–92.
35. Missimer, T.M. Pliocene stratigraphy of South Florida: Unresolved issues of facies correlation in time. In *The Florida Neogene*; Scott, T.M., Ed.; Special Publication 37; Florida Geological Survey: Tallahassee, FL, USA, 1993; pp. 33–42.
36. Bennett, M.W. *A Three-Dimensional Finite Difference Ground Water Flow Model of Western Collier County, Florida*; Technical Publication 92-04; Hydrogeology Division, Department of Research and Evaluation, South Florida Water Management District: West Palm Beach, FL, USA, 1992. Available online: http://dpanther.fiu.edu/sobek/content/FI/12/09/03/10/00001/FI12090310.pdf (accessed on 10 March 2024).
37. Belanger, T.V.; Mikutel, D.F. On the use of seepage meters to estimate groundwater nutrient loading to lakes. *J. Am. Water Res. Assoc.* **1985**, *21*, 265–272. [CrossRef]

38. Rosenberry, D.O.; LaBaugh, J.W.; Hunt, R.J. Use of monitoring wells, portable piezometers, and seepage meters to quantify flow between surface water and ground water. In *Field Techniques for Estimating Water Fluxes between Surface Water and Ground water*; U. S. Geological Survey Techniques and Methods 4-D2; U.S. Department of the Interior: Reston, VA, USA, 2008. Available online: https://pubs.usgs.gov/tm/04d02/pdf/TM4-D2-chap2.pdf (accessed on 10 March 2024).
39. Erickson, D.R. A Study of Littoral Groundwater Seepage at Williams Lake, Minnesota, Using Seepage Meters and Wells. Master's Thesis, University of Minnesota, St. Paul, MN, USA, 1981.
40. Shaw, R.D.; Prepas, E.E. Anomalous, short-term influx of water into seepage meters. *Limnol. Oceanogr.* **1989**, *34*, 1343–1351. [CrossRef]
41. Rosenberry, D.O.; Lewandowski, J.; Meinikmann, K.; Nützmann, G. Groundwater—The disregarded component in lake water and nutrient budgets. Part 1: Effects of groundwater on hydrology. *Hydrol. Process.* **2015**, *29*, 2895–2921. [CrossRef]
42. Rosenberry, D.O.; Duque, C.; Lee, D.R. History and evolution of seepage meters for quantifying flow between groundwater and surface water: Part 1—Freshwater settings. *Earth-Sci. Rev.* **2020**, *204*, 103167. [CrossRef]
43. Fryberger, S.G.; Dean, G. Dune forms and wind regime. In *A Study of Global Sand Seas*; McKee, E., Ed.; U.S. Geological Survey Professional Paper 1052; U.S. Government Printing Office: Washington, DC, USA, 1979; pp. 137–170. [CrossRef]
44. Gunderson, L.H. Accounting for discrepancies in pan evaporation calculations. *Water Resour. Bull.* **1989**, *25*, 573–579. [CrossRef]
45. Abtew, W.; Obeysekera, J.; Iricanin, N. Pan evaporation and potential evapotranspiration trends in South Florida. *Hydrol. Process.* **2011**, *25*, 958–969. [CrossRef]
46. Jones, F.E. *Evaporation of Water with Emphasis on Applications and Measurements*; CRC Press: Boca Raton, FL, USA, 1992.
47. Turc, L. Estimation of irrigation water requirements, potential evapotranspiration: Simplified and updated formula. *Ann. Agron.* **1961**, *12*, 13–49.
48. Harper, H.H. *Evaluation of Hydrologic and Nutrient Loadings from Groundwater Seepage to Lake Jesup*; Final Consultant's Report; 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 10 March 2024).
49. Schiffer, D.M. *Hydrology of Central Florida Lakes—A Primer*; Technical Publication 1137; United States Geological Survey Circular: Tallahassee, FL, USA, 1998. [CrossRef]
50. Asbury, C.E. The Role of Groundwater Seepage in Sediment Chemistry and Nutrient Budgets in Mirror Lake, New Hampshire. Ph.D. Dissertation, Cornell University, Ithaca, NY, USA, 1990.
51. Genereux, D.; Bandopadhyay, I. Numerical investigation of lakebed seepage patterns: Effects of porous medium and lake properties. *J. Hydrol.* **2001**, *241*, 286–303. [CrossRef]
52. Belanger, T.V.; Montgomery, M.T. Seepage meter errors. *Limnol. Oceanogr.* **1992**, *37*, 1787–1795. [CrossRef]
53. Thomas, S.; Lucius, M.A. Groundwater seepage nutrient loading in a recently dug wet detention stormwater pond. *Fla. Sci.* **2016**, *79*, 132–146.
54. South Florida Water Management District (SFWMD), South Florida Water Management District Model (SWIMM), South Florida Water Management District, West Palm Beach, FL, USA, 1995. Available online: https://www.sfwmd.gov/science-data/sfwmm-model (accessed on 10 March 2024).
55. Abtew, W. Evaporation estimation for Lake Okeechobee in south Florida. *J. Irrig. Drain. Eng.* **2001**, *127*, 140–147. [CrossRef]