SOUTH FLORIDA WATER MANAGEMENT DISTRICT

Long-Term Water Chloride and Nutrient Budgets for East Lake Tohopekaliga

WR-2014-002

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EXECUTIVE SUMMARY

Water and nutrient budgets were developed for East Lake Tohopekaliga; an 11,968-acre lake near St. Cloud Florida. These budgets were based on monitoring data collected by the South Florida Water Management District. Daily net inflows were calculated from evaporation, rainfall and flows measured in Boggy Creek and at structures S-59 and S-62. Boggy Creek, S-62 and rainfall contributed 35, 25 and 27% of the total inflow to the lake. Comparison of daily changes of volumes and the net inflows indicated that 13% of the inflow volume (determined from stage storage calculations) was not measured. S-59 and evaporation comprised 66 and 32% of the outflow with unmeasured outflows making up the final 2%.

Daily water quality values were estimated by a linear extrapolation of water quality monitored on a monthly basis. These daily estimates were multiplied by the flows and volumes to determine loads and in-lake mass of chloride, nitrogen and phosphorus. Chloride, used as a conservative tracer, indicated that 25% of the loads to the lake were from unmeasured sources.

Phosphorus and nitrogen net loads revealed that unmeasured sources contributed 25 and 15% of the loads, respectively to the lake. Ongoing investigations suggest that minor tributaries to the lake are the source of these missing flows and loads. Improvements underway through a nutrient reduction plan (CDM 2011) should reduce the nutrient contributions from minor tributaries and maintain nutrient conditions in East Lake Tohopekaliga.

INTRODUCTION

East Lake Tohopekaliga (Toho) is an 11,968-acre lake in central Florida, on the Osceola slope, just south of Orlando and east of the City of Kissimmee (Figure 1, Griffith et al. 1997). One of the Upper Kissimmee Chain of Lakes, East Toho is a mesotrophic circular lake primarily underlain by a sand bottom (Belanger et al. 1985). As a "headwater lake" it is an important component of the Kissimmee Chain of Lakes and Lake Okeechobee. The surrounding land use has changed dramatically in the past 40 years from approximately 50% agriculture (pasture and citrus, McCaffrey et al. 1976) to less than 15% (Zhang 2013 personal communication) and an increase in urban land use from less than 13% to approximately 43%.

Outflow at S-59 from East Lake Toho is a major input to Lake Tohopekaliga, which is considered impaired due to the imbalance of flora and fauna (CDM 2011). This impairment may be related to the continued loading of nutrients to the lake. A nutrient reduction plan has been developed and is being implemented for Lake Tohopekaliga (CDM 2011).

This report supports this nutrient reduction plan for Lake Tohopekaliga through the development, documentation and analysis of water, chloride (CL) and nutrient budgets for East Lake Toho. This analysis uses measured and estimated data from calendar years 1996 to 2012. Water and CL budgets define the magnitude of sources and sinks of inputs and outputs to the lake along with uncertainty. Total phosphorus (TP) and total nitrogen (TN) budgets estimate the current retention/removal capacity of the lake for TP and TN. This report estimates the load contributions from unmeasured inflows and the lake capacity to remove nutrients from the water column. In addition, these budgets are analyzed for significant trends in loads, discharge, in-lake concentrations and retention/removal capacity. A separate report has evaluated the nutrient and water budgets for Lake Tohopekaliga (James 2014).

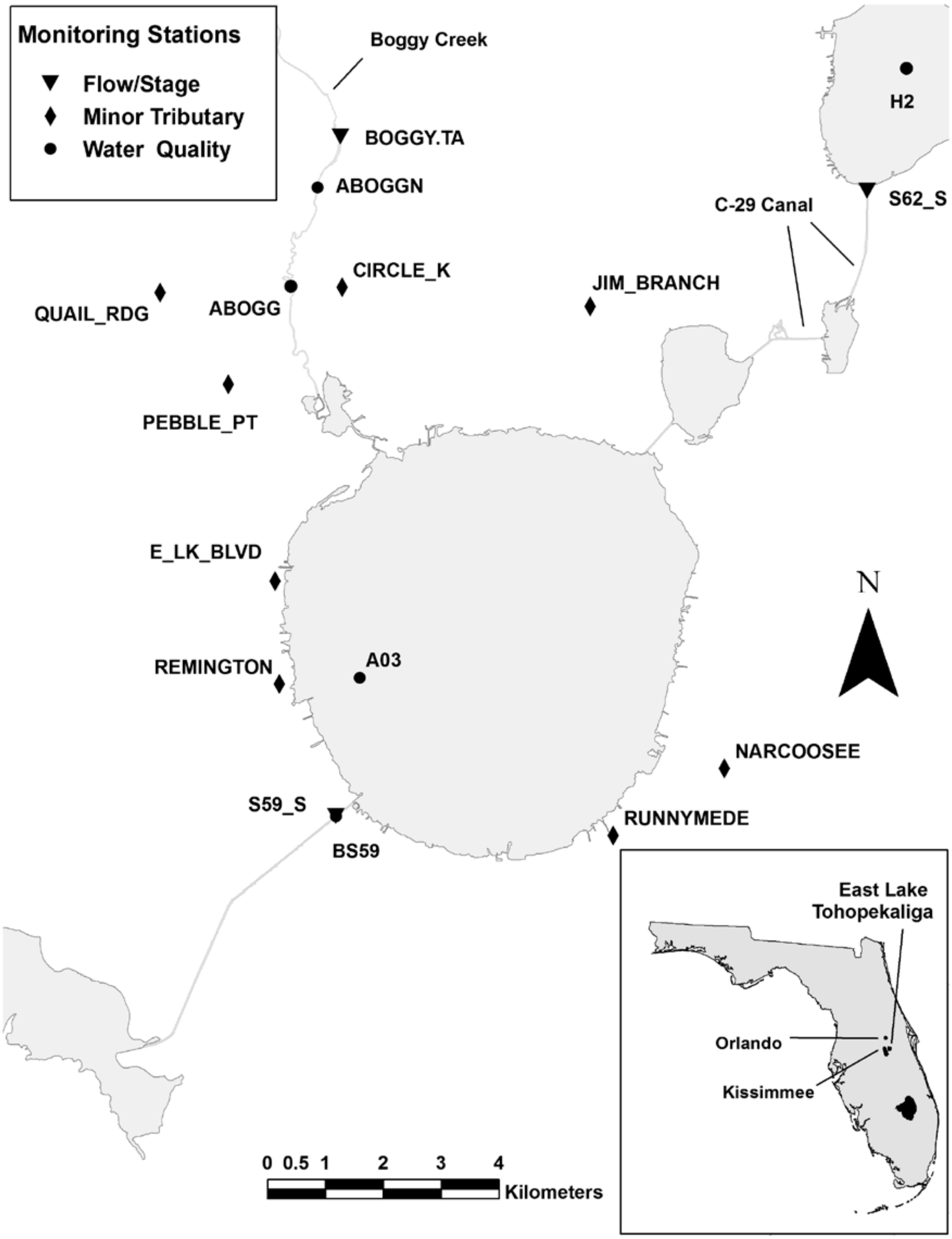

Figure 1. Map of East Lake Tohopekaliga showing flow/stage, long term water quality monitoring and minor tributary sampling locations

METHODS

Major inflows to East Lake Toho are Boggy Creek to the north, and S-62, which discharges from Lake Hart to the C-29 canal that flows into East Lake Toho from the northeast (Figure 1). Discharge from East Lake Toho is primarily through structure S-59. Daily inflow is measured at Boggy Creek (BOGGY.TA) and S-62 (S62_S). Outflow is measured at S-59 (S59_S: Table 1, Figure 1). Rainfall is measured at S-59 (used before 2006) and is estimated by next generation radar (NEXRAD)-based daily values after 2005 (SFWMD 2013a, 2013b). Evaporation is determined from the National Aeronautics and Space Administration's (NASA's) North American Land Data Assimilation System (NLDAS) (NASA 2013). These rain and evaporation measurements, reported in inches, are transformed to volumes by multiplying their respective value by the area of the lake (11,968 acres) and dividing by 12 (inches per foot) to obtain daily rain and evaporation estimates in acre-feet per day.

Water quality at inflow, in-lake and outflow locations (Figure 1, Table 1) have been sampled monthly to every other month for the period covered in this report, 1996–2012. Water samples taken within the lake and its tributaries are measured for CL, TN and TP using standard methods (USEPA 1983, APHA 1998). Samples are collected and handled based on Quality Assurance Quality Control programs developed by the South Florida Water Management District (SFWMD) (SFWMD 1999, 2011a, 2011b).

Minor tributaries to the lake have been sampled monthly since September 2011 by Osceola County staff as part of the five-year Lake Toho Nutrient Reduction Plan (Figure 1, Table 1, CDM 2011). While flow is not measured, flow or no-flow conditions are recorded. These samples are sent to the SFWMD for analysis. Simple summary statistics (mean, standard deviation, maximum, minimum, mean and number of samples) have been calculated for samples collected when flow is observed. The median values for TP, TN, and CL are used to estimate their respective contributions from unmeasured minor tributaries (see below). A Kruskal-Wallis Test (SAS 1989) is used to determine if these water quality measurements are significantly different among sample locations.

Nutrient budgets are developed using Microsoft Excel spreadsheets and annual summed or averaged estimates (where appropriate) of loadings, mass and volume are analyzed graphically and with simple statistical measurements. A Kendall's Tau test adjusted for serial correlation (Reckhow et al. 1992) is used to determine if significant increasing or decreasing trends exist for monthly estimates of flows, loads and concentrations of nutrient budget-related data.

Table 1. Sampling sites, parameters and location (see Figure 1 for location).

Station	DBKEY[1]	Sample[2]	Units[3]	Year Start	Year End	Latitude	Longitude
BOGGY.TA	113	flow	cfs	1968	2012	281216	811838
S59_S	15533 WN290	flow	cfs	1993	2012	281556	811840
S62_S	15539 WN265	flow	cfs	1993	2012	282147	811303
S59_R	16567 VN290	rainfall	inches	1995	2010	281556	811840
ELTOHO	NA	rainfall (NEXRAD)	inches	2005	2012	281738	811705
ELTOHO	NA	evaporation (NLDAS)	inches	1996	2012	281738	811705
S59_H	15531 WN265	stage	ft NGVD	1993	2012	281556	811840
ABBOG.GN	NA	water quality	mg/L	2009	2012	282148	811852
A03	NA	water quality	mg/L	1981	2012	280924	812144
ABBOGG	NA	water quality	mg/L	1981	2010	282050	811910
BS59	NA	water quality	mg/L	1982	2012	281556	811840
H2	NA	water quality (OSC)	mg/L	1962	2012	282256	811232
CIRCLE_K	NA	water quality (NRP)	mg/L	2011	2012	282052.6	811837.1
E_LK_BLVD	NA	water quality (NRP)	mg/L	2011	2012	281807.6	811919
JIM_BRANCH	NA	water quality (NRP)	mg/L	2011	2012	282042.2	811559.5
NARCOOSEE	NA	water quality (NRP)	mg/L	2011	2012	281623.1	811433.8
PEBBLE_PT	NA	water quality (NRP)	mg/L	2011	2012	281957.9	811948.9
QUAIL_RDG	NA	water quality (NRP)	mg/L	2011	2012	282049.4	812032.5
REMINGTON	NA	water quality (NRP)	mg/L	2011	2012	281709.9	811916.3
RUNNYMEDE	NA	water quality (NRP)	mg/L	2011	2012	281545.5	811544.2

[1] DBKEYS from DBHYDRO, NA – Not Applicable (water quality stations do not have DBKEYS and ELTOHO – NEXRAD and evaporation – represent the whole lake).

[2] flow: daily averaged; rainfall and evaporation: daily sum; stage (National Geodetic Vertical Datum [NGVD]): daily averaged; water quality: CL, TN, and TP collected monthly to every other month, water quality (OSC) are samples taken by Osceola County on Lake Hart, water quality (NRP) are samples taken on minor tributaries by Osceola County for the Lake Tohopekaliga Nutrient Reduction Plan (CDM 2011).

[3] units: cfs – cubic feet per second; ft NGVD – feet National Geodetic Vertical Datum; and mg/L – milligrams per liter.

WATER BUDGET

Lake water level is measured daily at S-59 (Table 1, Figure 1). Volume is determined from a stage-storage lookup table developed from plate 8-4 of the Lake Okeechobee and Everglades Agricultural Area Master Water Control Manual (USACE 1996, Figure 2). Monthly changes of volume are determined by subtracting the first day of the month's value ($Vol_{t1(m)}$) from the first day of the next month's value ($Vol_{t1(m+1)}$, Equation 1):

$$\Delta Vol_m = Vol_{t1(m+1)} - Vol_{t1(m)} \qquad \text{(Equation 1)}$$

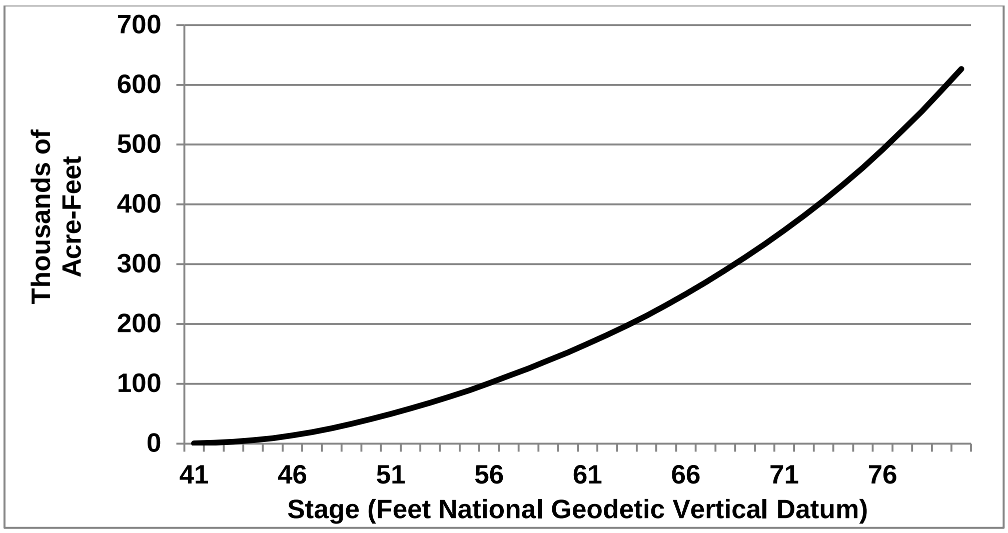

Figure 2. Stage storage relationship for East Lake Tohopekaliga (adapted from USACE 1996).

Where ΔVol_m is the change in volume for month m. All volumes are in acre-feet. Volume changes based on input – output budgets also are determined on a monthly basis (Equation 2):

$$\Delta \widehat{Vol}_m = Q_{boggy,m} + Q_{s-62,m} + Rain_m - Evap_m - Q_{s-59,m} \qquad \text{(Equation 2)}$$

Where $Q_{boggy,m}$, $Q_{S-62,m}$, $Q_{S-59,m}$ are flows (in acre-feet per month) at Boggy Creek, S-62, and S-59, respectively. $Rain_m$ and $Evap_m$ are rainfall and evaporation in acre-feet per month. Because the estimate of $\Delta \widehat{Vol}_m$ does not include all inflows to the lake through seepage, minor inflows, groundwater recharge and potential outflows through groundwater discharge, it is assumed that these can be estimated from the difference between ΔVol_m and $\Delta \widehat{Vol}_m$ (Equation 3):

$$if \begin{cases} \Delta Vol_m - \Delta \widehat{Vol}_m > 0 \rightarrow Q_{unmeasured\ in,m} = \Delta Vol_m - \Delta \widehat{Vol}_m \\ Q_{unmeasured\ out,m} = 0 \\ \Delta Vol_m - \Delta \widehat{Vol}_m < 0 \rightarrow Q_{unmeasured\ out,m} = -\left(\Delta Vol_m - \Delta \widehat{Vol}_m\right) \\ Q_{unmeasured\ in,m} = 0 \end{cases} \qquad \text{(Equation 3)}$$

$Q_{unmeasured\ in,m}$ is the estimated unmeasured inflow including minor tributary inflow, runoff and groundwater recharge, and $Q_{unmeasured\ out,m}$ is the estimated unmeasured discharge out of the lake and into groundwater. These are determined on a month-to-month basis, in part to smooth out daily noise from stage recordings, which if summed would add additional error to both unmeasured inflow and outflow.

Monthly runoff, flows, rain and evaporation are summed for each calendar year. These data along with the initial and final volume estimates are used to develop annual water budgets of the lakes.

CHLORIDE BUDGETS

The water budgets are validated using CL as a conservative tracer. Because CL is not removed from water, its concentrations acts as a marker. By comparing the change in mass of CL within a water body to the net loads (in loads-out loads), the accuracy of the water budget can be determined (e.g., are any major inflows or outflows missing?). In-lake measurements taken at A03 (Figure 1) are extrapolated from sample date to daily values using a linear interpolation procedure in SAS (SAS 1989). Similarly Boggy Creek, S-62 and BS59 samples are interpolated to a daily basis to estimate the daily concentration values for these inflow and outflow locations.

The initial monthly in-lake estimates are multiplied by the volume of the first day of the month to obtain initial month mass estimates of the lake (Equation 4):

$$M_{obs,cl,t1(m)} = \frac{Vol_{t(m)} * C_{lake,cl,t1(m)} * 1233.48}{1,000,000} \quad \text{(Equation 4)}$$

Where $C_{lake,cl,t1(m)}$ is the linear interpolated concentration of CL in milligrams per liter (mg/L) or grams per cubic meter (g/m^3) in the lake for the first day of the month, 1233.48 is the conversion from acre-foot to cubic meters and 1,000,000 converts grams to metric tons. $M_{obs,cl,t1(m)}$ is the observed mass in metric tons.

Atmospheric deposition of CL is estimated from two sources summed together. The first source is dry deposition of CL, which is based on observations from one location (IRL 141) monitored by the Clean Air Status and Trends Network (CASTNET) program nearby (USEPA 2011). These observations are input to the Aggregated Multi-Layer Model (MLM) (USEPA 2011) to estimate monthly deposition fluxes. The fluxes are averaged for the period of record (2001–2008) and multiplied by the lake area to provide constant estimates of 5.1 ton per year for CL. Estimates of wet atmospheric deposition, the second source, are determined using the average annual concentrations for 2005 to 2010 obtained at station FL32 from the National Trends Network National Atmospheric Deposition Program (2011). These are multiplied by the rainfall and averaged over these six years to obtain an average rainfall load of 70.9 tons per year. Total atmospheric load ($L_{atm,cl}$) is estimated as a sum of the wet and dry deposition and is held constant at 76.0 tons per year or 6.3 tons per month.

Surface loads are calculated on a daily basis and summed for each month of each year (Equation 5a,b,c):

$$L_{s-62,cl,m} = \sum_{1}^{t_m} \frac{Q_{S-62,t} * C_{H2,cl,t} * 1233.48}{1,000,000} \quad \text{(Equation 5a)}$$

$$L_{boggy,cl,m} = \sum_{1}^{t_m} \frac{Q_{boggy,t} * C_{boggy,cl,t} * 1233.48}{1,000,000} \quad \text{(Equation 5b)}$$

$$L_{S-59,cl,m} = \sum_{1}^{t_m} \frac{Q_{S-59,t} * C_{BS59,cl,t} * 1233.48}{1,000,000} \quad \text{(Equation 5c)}$$

$L_{s-62,cl,m}$ $L_{boggy,cl,m}$ $L_{S-59,cl,m}$ are the monthly loads of CL at the major tributaries S-62, Boggy Creek, and S-59, respectively, estimated by summing the daily measured flows (from one to the last day of the given month t_m) $Q_{S-62,t}$, $Q_{boggy,t}$ and $Q_{S-59,t}$ by the appropriate daily estimated concentrations of CL in the lake determined by linear interpolation: $C_{H2,cl,t}$, $C_{boggy,cl,t}$ and $C_{BS59,cl,t}$ at H2, Boggy Creek and S-59, respectively (Figure 1).

Loads for unmeasured inflow are determined on a monthly basis using a constant concentration $C_{minor\ trib,cl}$, which is the median value of minor tributary samples (Equation 6):

$$L_{unmeasured\ in,cl,m} = Q_{unmeasured\ in,m} * C_{minor\ trib,cl} \quad \text{(Equation 6)}$$

Discharge to groundwater is determined by multiplying the in-lake estimated concentration by the groundwater flow (Equation 7):

$$L_{unmeasured\ out,cl,m} = Q_{unmeasured\ out,m} * \bar{C}_{A03,cl,m} \quad \text{(Equation 7)}$$

Where $L_{unmeasured\ out,cl,m}$ is the estimated unmeasured flow loads out of the lake based on the monthly average estimate $\bar{C}_{A03,cl,m}$.

The monthly mass prediction is estimated by adding the monthly sums of all measured loads into the lake minus the discharges out of the lake to the mass predicted on the first day of the month (Equation 8):

$$M_{pred,cl,t1(m+1)} = M_{pred,cl,t1(m)} + L_{S62,cl,m} + L_{boggy,cl,m} +$$

$$L_{unmeasured\ in,cl,m} + L_{atmos,cl} - L_{s59,cl,m} - L_{unmeasured\ out,cl,m} \quad \text{(Equation 8)}$$

Monthly loads are summed by year to develop the yearly mass budgets. The residual error is determined by comparing the change in mass based on in-lake concentrations and volume, which is compared to the change in the observed masses derived from Equation 8 (Equation 9):

$$e_{cl,y} = (M_{obs,cl,t1_{y+1}} - M_{obs,cl,t1_y}) - (L_{s59,cl,y} + L_{shing,cl,y} + L_{unmeasured\ in,cl,y} + L_{atmos,cl} - L_{s62,cl,y} - L_{unmeasured\ out,cl,y}) \quad \text{(Equation 9)}$$

Where y is time in years. $M_{obs,cl,t1_y}$ is the observed measured mass on the first day of year y, and $M_{obs,cl,t1_{y+1}}$ is the observed mass on the first day of the next year (y+1). The percent residual term is simply $\frac{e_{cl,y}}{\bar{M}_{obs,cl,y}} * 100\%$ where $\bar{M}_{obs,cl,y}$ is the average observed mass for year y.

PHOSPHORUS AND NITROGEN NUTRIENT CONCENTRATIONS

Unlike the conservative tracer CL, phosphorus is removed from the water column of a lake through biological uptake as well as settling of organic material and co-precipitation with calcium. Assuming that the water budget is accurate and replacing CL with TP (Equations 4 through 8), Equation 9 now defines the amount of phosphorus that is retained in the lake (e.g., removed from the water column Equation 10).

$$S_{p,y} = (M_{obs,p,t1_{y+1}} - M_{obs,p,t1_y}) - (L_{s62,p,y} + L_{boggy,p,y} + L_{unmeasured\ in,p,y}$$

$$+L_{atmos,p} - L_{s59,p,y} - L_{unmeasured\ out,p,y}) \quad \text{(Equation 10)}$$

The net sedimentation coefficient (σ_y) is defined as

$$\sigma_y = \frac{S_{p,y}}{\bar{M}_{obs,p,y}}. \quad \text{(Equation 11)}$$

Where $\bar{M}_{obs,p,y}$ is the mean observed mass of phosphorus in the lake for a given year y.

Using Equations 10 and 11, Havens and James (2005) analyzed annual TP budgets of Lake Okeechobee and determined the removal of TP over time. While TN is even more complicated in lakes because of processes of nitrogen fixation by cyanobacteria (Dierberg and Scheinkman 1987) and denitrification by bacteria (James et al. 2011a), the same equations can be used with TN budgets to determine the amount of net removal from the water column.

The average atmospheric loading rates of TN and TP for East Lake Tohopekaliga were determined from an analysis of Lake Cypress, a 4,100-acre lake located approximately 12 miles downstream and south of East Lake Toho. Atmospheric loads into Lake Cypress were estimated as 977 pounds per year (lbs/yr) of phosphorus (0.44 metric tons per year) and 32,713 lbs/yr (14.8 metric tons per year) of N (Gilbert 2011). Multiplying these load estimates by the ratio of the areas of East Lake Toho and Cypress (11,968 acres/4,100 acres) resulted in atmospheric load estimates of 1.29 metric tons of phosphorus per year and 43.3 metric tons of N per year for East Lake Toho.

RESULTS

WATER BUDGET

Daily stage, from 1996 to 2012 for East Lake Toho ranged from 55 to 59 feet National Geodetic Vertical Datum (NGVD) (Figure 3, top panel). This equated to volumes between 87 and 135 thousand acre-feet (Figure 3, bottom panel). Net inflow (sum of all inflows - sum of all outflows) ranged from -36,500 acre-feet per year in 1998 to +24,500 acre-feet in 2011 due to a major October storm (Figure 4A). Surface inflows to the lake were less than 30,000 acre-feet during droughts in 2000, and 2006 to 2007. Inflows were greater than 180,000 acre-feet in 2004 and 2005, which included major storm events—hurricanes Charlie, Frances, Jeanne and Wilma. Outflow ranged from a low of 8,290 acre-feet in 2007 to a high of 211,000 acre-feet in 2005. On average, 60% of the inflow was from Boggy Creek and S-62 discharges combined, 27% from rainfall, and 13% from unmeasured inflows (Figure 4B). On average, 66% of the outflow was discharged through the S-59 structure, 32% was evaporation and 2% unmeasured outflow (Figure 4C). One significant trend was found: evaporation increased significantly over time (Table 2).

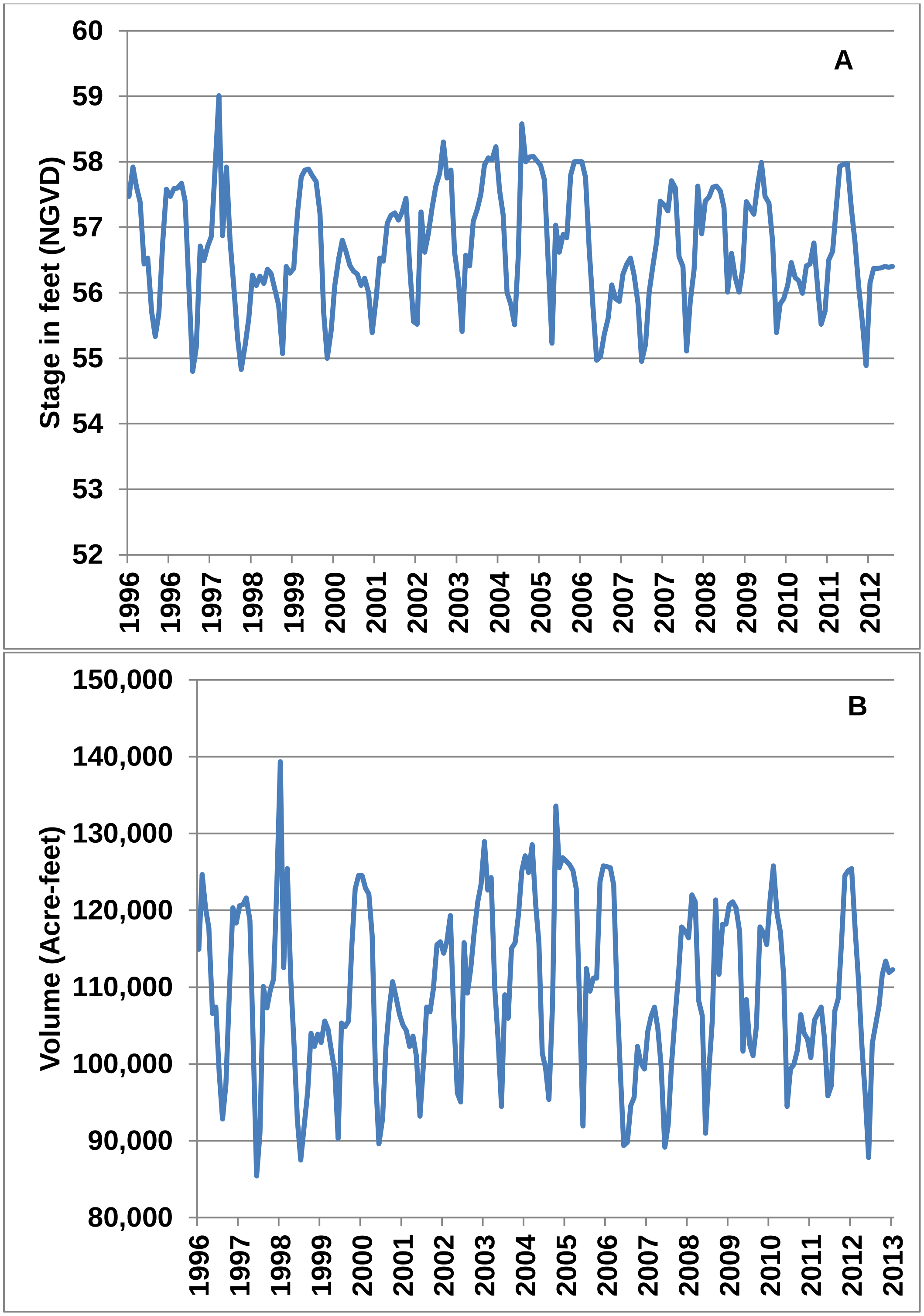

Figure 3. East Lake Tohopekaliga monthly A) stage and B) volume estimates from 1996 to 2013

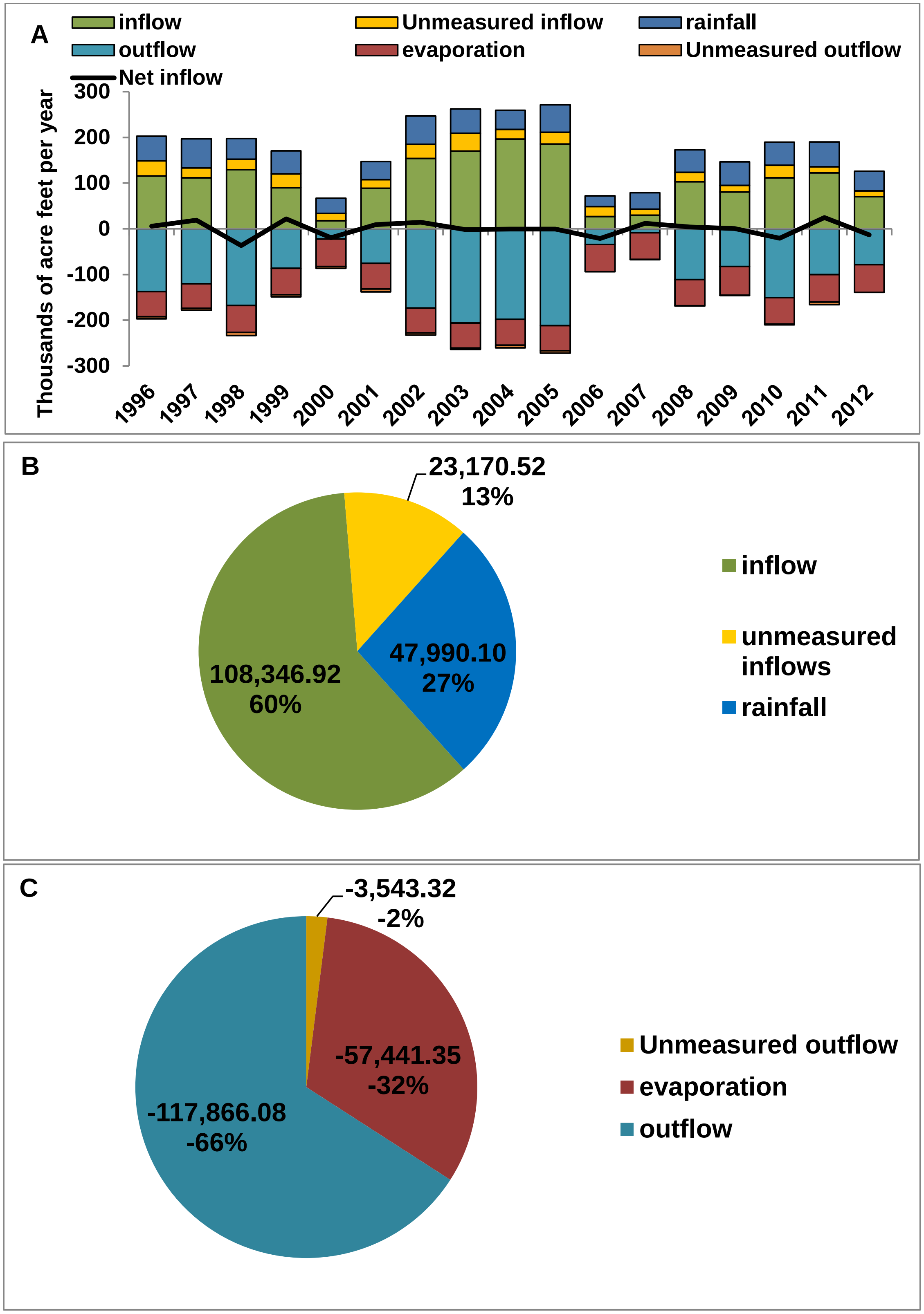

Figure 4. East Lake Tohopekaliga water budget A) annual budget for calendar years 1996 to 2012, B) average inflow per year, and C) average outflow per year.

Table 2. Kendall's Tau trend analysis of monthly estimated volume, chloride and chloride budget values from 1996 to 2012 (bolded values are significant at the P < 0.05 level).

Measurement	Source Sink	Tau Statistic	P-value with Serial Correlation	Slope Statistic
Stage (feet)	Lake	-0.009	0.931	-0.001
Evaporation (inches)	**Lake**	**0.186**	**0.033**	**0.019**
Rain (inches)	Lake	-0.050	0.482	-0.024
Rain-Evaporation (inches)	Lake	-0.098	0.208	-0.055
Flow (acre-feet)	S-62	-0.044	0.674	-0.042
	Boggy Creek	0.007	0.947	4.414
	Minor Tributaries	-0.030	0.562	0.000
	S-59	-0.045	0.623	-0.147
	Seepage	-0.085	0.065	0.000
Flow weight mean chloride concentration (mg/L)	**Lake**	**0.479**	**0.003**	**0.460**
	S-62	0.219	0.215	0.256
	Boggy Creek	-0.013	0.916	-0.008
	S-59	**0.431**	**0.007**	**0.424**
Chloride Load (metric tons)	S-62	-0.026	0.794	0.000
	Boggy Creek	0.021	0.830	0.155
	S-59	-0.004	0.970	0.000
	Seepage	0.083	0.070	0.000
	Net	-0.091	0.057	-2.441
	Residual	0.011	0.886	0.548
	Percent Error	0.001	1.000	0.000

MINOR TRIBUTARY WATER QUALITY

Water quality in the minor tributaries was rather variable with coefficients of variation ranging from 121 for TP to 35 for CL (Table 3). Wilcoxon Sign Rank Test of TP, TN, and CL were all significant ($p < 0.05$ analyses not shown) indicating that concentrations at the various sample locations were significantly different (Table 4). Of potential interest for future evaluation, includes E_LK_BLVD, Remington, Jim Branch and Circle_K for TP; E_LK_BLVD, Narcoosee, and Remington for TN; and Circle_K, E_LK_BLVD and Narcosee for CL.

CHLORIDE

The CL budgets were similar to the water budget (Figure 5A). CL mass in the lake ranged between an estimated two to three thousand metric tons. Of the seventeen years estimated by input and output loads, the residuals of five estimates were less than -20% of the observed mass (Figure 5B). Three of these years were prior to 2000. There was a significant increase in CL concentrations within the lake, which in-part could account for the reduced error of CL mass loads in more recent years (Figure 5C and Table 2).

Table 3. Phosphorus, nitrogen and chloride statistics at minor tributaries of East Lake Tohopekaliga (Figure 1), taken from September 2011 to December 2012 when waters were flowing.

Variable	Total Phosphorus	Total Nitrogen	Chloride
Mean	0.117	1.136	27.1
Median	0.065	0.987	25.5
Minimum	0.008	0.435	12.7
Maximum	0.850	2.887	46.8
75th Percentile	0.146	1.477	31.9
25th Percentile	0.036	0.791	20.9
Standard Deviation	0.141	0.509	9.4
Coefficient of Variation	120.9	44.8	34.8
N	84	84	43

Table 4. Phosphorus, nitrogen, and chloride statistics by station at minor tributaries from September 2011 to December 2012.

	Total Phosphorus			Total Nitrogen			Chloride		
Location	Mean	Standard Deviation	N	Mean	Standard Deviation	N	Mean	Standard Deviation	N
CIRCLE_K	0.098	0.049	10	1.149	0.786	10	32.4	4.9	4
E_LK_BLVD	0.437	0.198	9	1.568	0.289	9	35.4	7.1	4
JIM_BRANCH	0.135	0.084	11	0.778	0.349	11	14.6	1.1	6
NARCOOSEE	0.032	0.010	9	1.887	0.373	9	42.9	3.5	6
PEBBLE_PT	0.085	0.066	11	0.977	0.153	11	21.9	1.8	6
QUAIL_RDG	0.037	0.012	5	1.094	0.350	5	17.8	1.8	3
REMINGTON	0.147	0.042	9	1.353	0.189	9	28.6	2.6	4
RUNNYMEDE	0.053	0.013	9	0.888	0.123	9	24.4	3.9	4
TURNBERRY	0.019	0.010	11	0.717	0.202	11	25.6	2.9	6

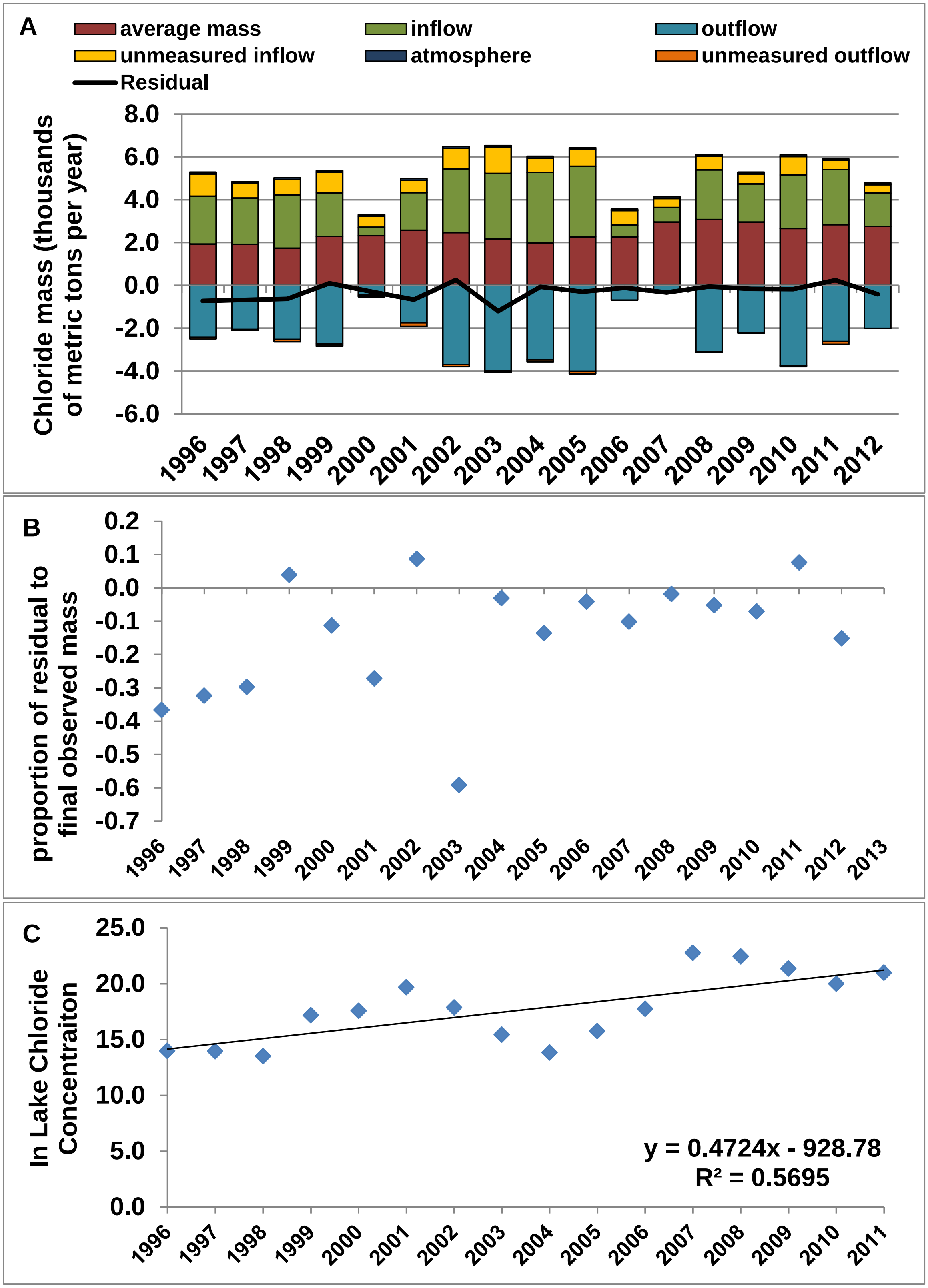

Figure 5. Chloride A) Annual budget 1996–2012 B) residual as a proportion of lake mass over time, and C) in-lake chloride concentration over time.

The average estimated CL inflow load was 73% of total load to the lake. Unmeasured inflow was 25% of the load and atmospheric deposition was the remaining 2% (Figure 6A). Average tributary outflow was 87% of the discharge load, followed by 4% for unmeasured outflow and 11% for the residual (Figure 6B). In addition to the significant increasing trend of in-lake CL concentration, there was also an increase in the flow-weighted mean concentration at S-59 (Table 2). There were no significant trends of any other measurements related to CL budgets, although net loads were almost significant (p = 0.057).

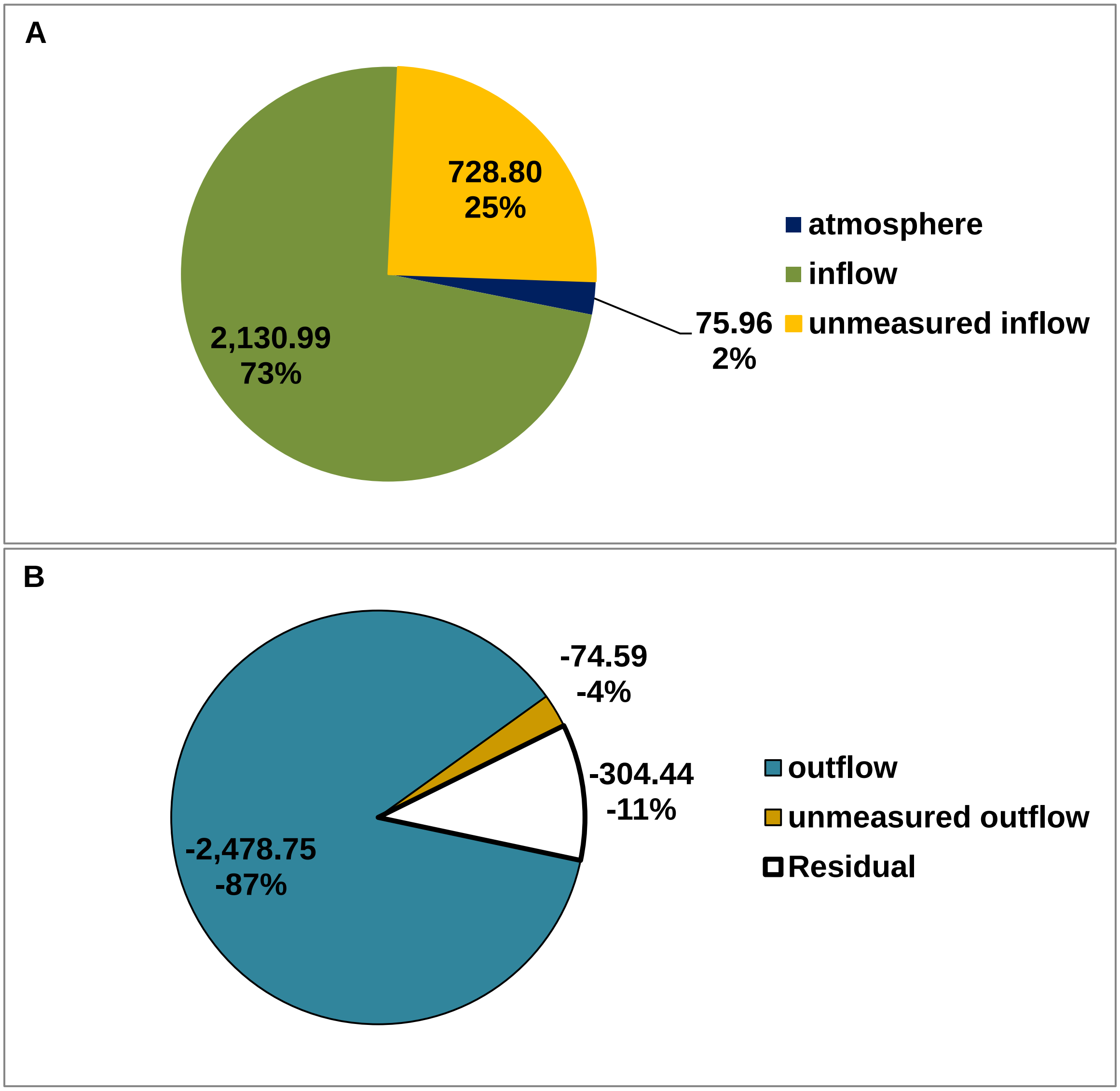

Figure 6. Chloride (A) average loads to lake and (B) average loads from lake.

PHOSPHORUS

Initial TP budgets showed that only one year (2003) out of the sixteen evaluated produced a net release of TP from the lake. A large outflow load was found for the month of January, which was caused by high flows at S-59 and a single extreme TP concentration measurement (83 micrograms per liter [µg/L] in January 2003). Including this value resulted in a monthly flow weighted concentration of 77 µg/L at S-59 (Figure 7). There were no comments or flags on this value, however a studentized residual analysis (SAS 1989) indicated that this value (collected January 22, 2003) and another (collected December 8, 2009) were significant outliers of measurements from BS-59. Excluding these values from the calculations reduced the TP discharge from the lake. This lower discharge resulted in a net removal of TP by the lake for that year (Figure 8A). In most years the net settling rate (sigma) was above -2 (Figure 8B). In three years, the value was -2.5 or less. These included two years with very high net nutrient loads (2001 and 2002), and a third year (2005) where the in-lake concentration and in-lake mass declined (Figure 8A).

Unmeasured inflow and outflow discharge were 25 and less than 1%, respectively, of the loads to and from the lake (Figure 9 A, B). Net settling was 56% of the estimated load removed from the water column (Figure 9B). There were no trends in budget related measurements; however there was a significant reduction of TP flow weighted concentration for Boggy Creek (Table 5).

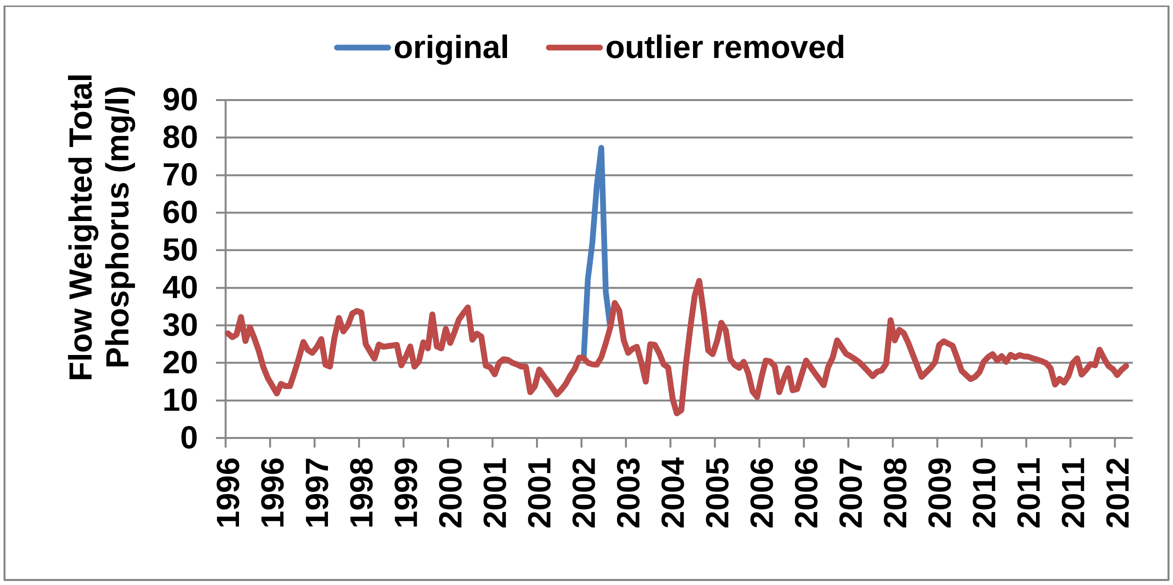

Figure 7. Monthly interpolated phosphorus concentration from S-59 with and without outlier (1/2003 – 83 µg/L) removed. (Note: mg/l – milligrams per liter)

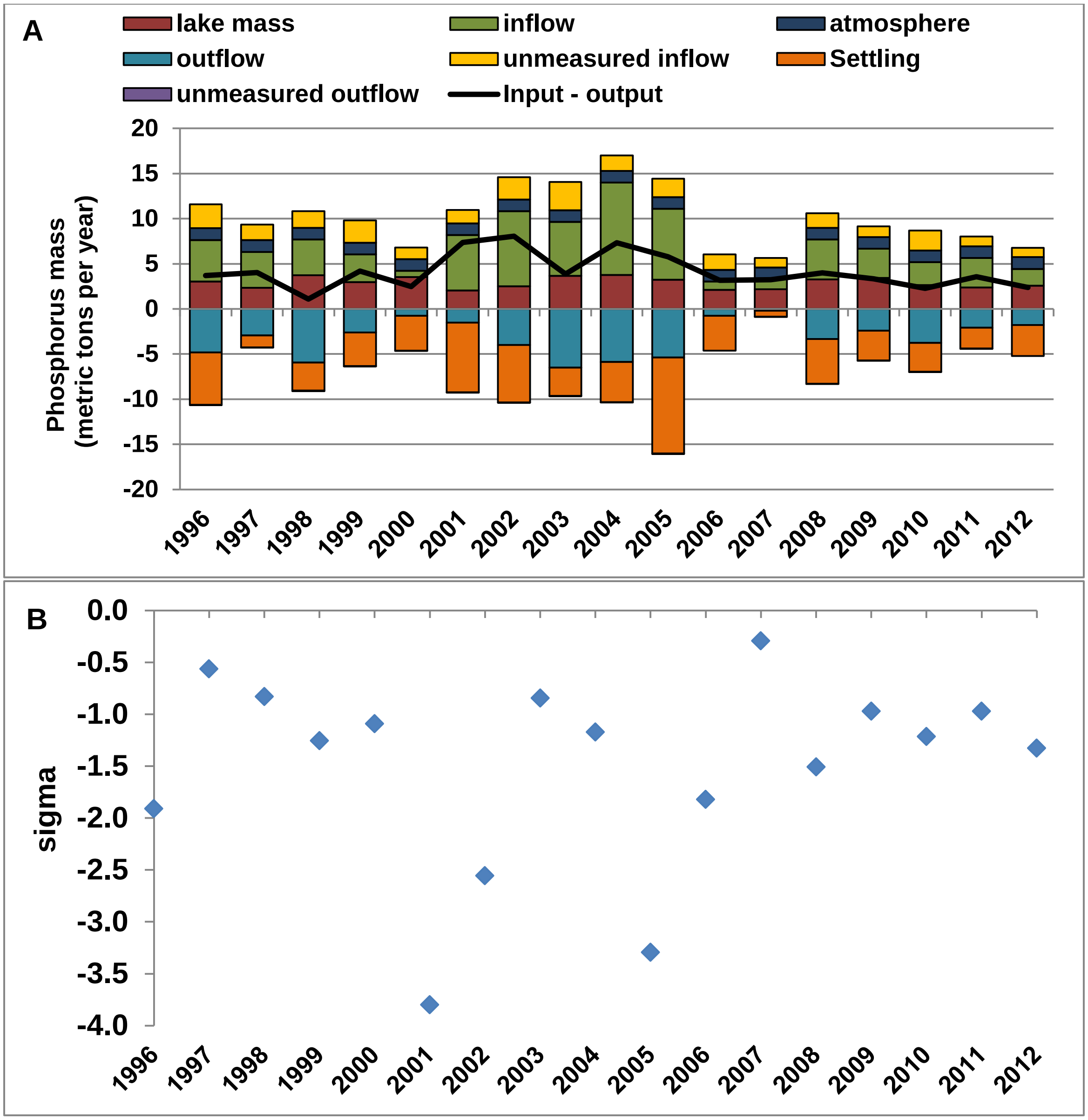

Figure 8 A) Annual estimated phosphorus budget for East Lake Tohopekaliga and B) annual net sedimentation coefficient assuming constant runoff concentration of 68 µg/l TP.

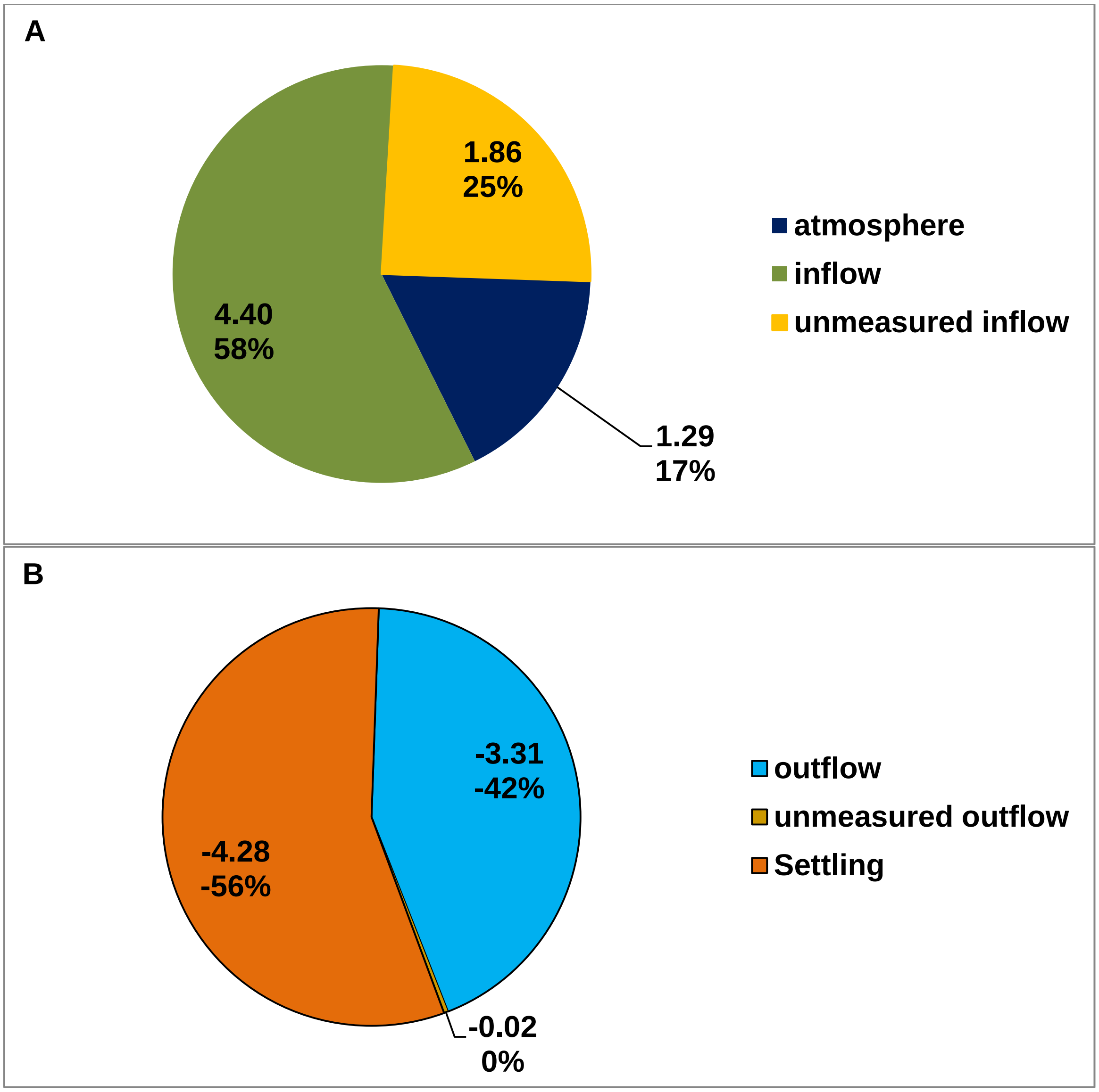

Figure 9. A) Average estimated phosphorus loads to East Lake Tohopekaliga in metric tons and B) average discharge and estimated net settling into the lake.

Table 5. Kendall's Tau trend analysis of monthly estimated phosphorus and nitrogen budget values from 1996 to 2012 (bolded values are significant at the P <0.05 level).

Measurement	Source Sink	Tau Statistic	P-value with Serial Correlation	Slope Statistic
Flow weighted mean phosphorus concentration (mg/L)	Lake	-0.089	0.444	0.000
	S-62	0.143	0.307	0.000
	Boggy Creek	**-0.476**	**< 0.001**	-0.001
	S-59	-0.177	0.084	0.000
Phosphorus load (metric tons)	S-62	0.015	0.889	0.000
	Boggy Creek	-0.153	0.150	-0.003
	S-59	-0.024	0.803	0.000
	Seepage	0.075	0.082	0.000
	Net	-0.066	0.305	-0.004
	Settling	0.031	0.695	0.006
	Sigma	0.048	0.523	0.003
Flow weighted mean nitrogen concentration (mg/L)	Lake	-0.125	0.277	-0.004
	S-62	0.256	0.071	0.016
	Boggy Creek	**-0.381**	**0.006**	-0.010
	S-59	-0.002	0.989	0.000
Nitrogen loads (metric tons)	S-62	-0.049	0.636	0.000
	Boggy Creek	-0.075	0.473	-0.027
	S-59	-0.032	0.726	0.000
	Seepage	0.085	0.066	0.000
	Net	-0.010	0.867	-0.012
	Residual	0.054	0.399	0.240
	Sigma	0.074	0.254	0.003

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As with TP loads, TN loads followed the inflow and outflow patterns (Figure 10A). The absorption removal (sigma) of TN was less variable (Figure 10B) in proportion to the in lake mass than TP (Figure 9B), in-part, because the lake mass of TN was much larger than TP (Figure 10A and 9A). Unmeasured inflow and unmeasured outflow contributed 15% and less than 1%, respectively, of the load of TP to and from the lake (Figure 11A, B). Removal of TN from the water column by other processes (plant uptake, settling, and denitrification) accounted for 45% of the loss from the water column. Like TP, there were no significant trends in budget related measurements for TN; however there was a significant declining trend of flow-weighted TN concentration for Boggy Creek (Table 5).

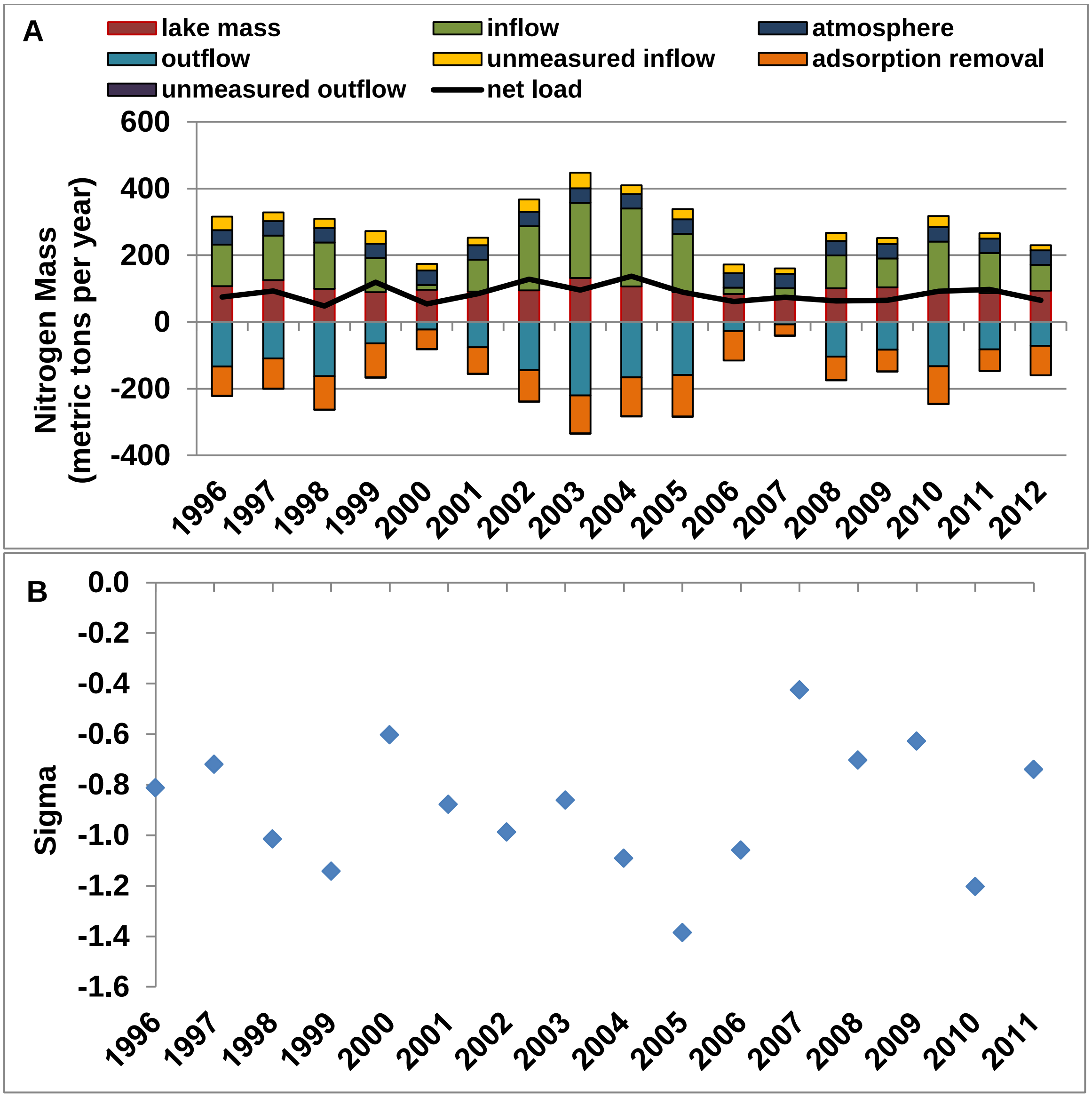

Figure 10. A) Annual estimated nitrogen budget for East Lake Tohopekaliga (metric tons) and B) proportion of nitrogen removal over time (sigma).

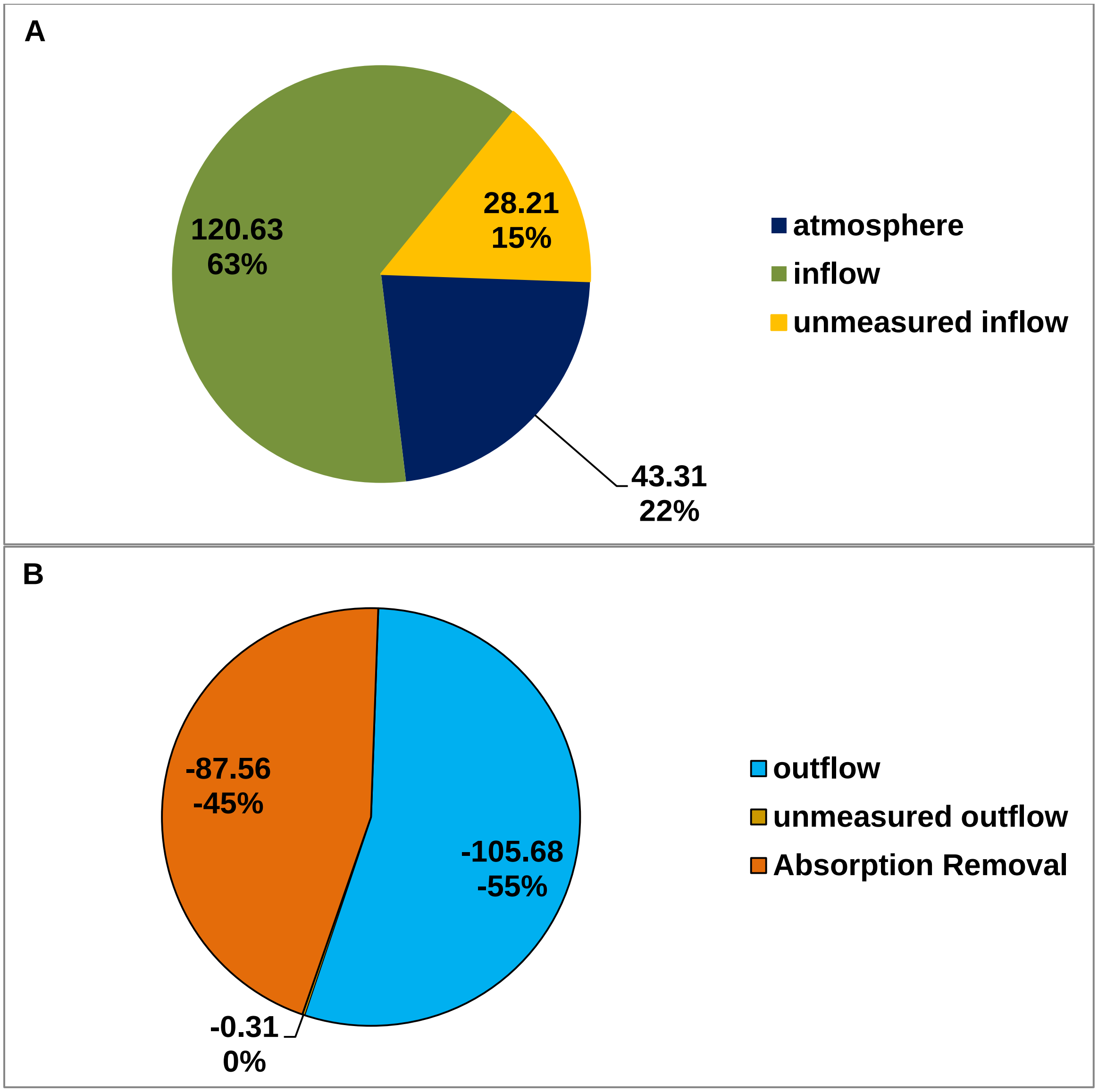

Figure 11. A) Average nitrogen loads to and B) average nitrogen removals from the lake.

DISCUSSION

A majority of the flow to and from East Lake Toho is captured in the water budgets based on measurements from major tributaries, rainfall, and evaporation. Part of the unmeasured inflow is likely groundwater recharge. This was measured directly by Belanger et al. (1985). They determined that this value was approximately 14% of the inflow, very close to the unmeasured inflow observed in the current budget. While Belanger et al. (1985) estimated the gross inflow using direct measurements; the value presented in this current analysis is based on Equation 3 and is a net monthly estimate that is summed annually. The similarity of these measurements is probably a coincidence because the measurement derivations and the measurements themselves are different.

The significant increase in evaporation found here (Table 2) is not understood. While it could explain increased CL within the lake, it is not consistent with other factors (e.g., no significant decrease in volume or flows). In addition no trends in evaporation have been found for Lake Tohopekaliga, which used alternate estimates (James 2014). Because the data are derived from an external source (NASA 2013), there is no way to verify it. It is likely that factors included in the evaporation estimate (solar radiation, temperature, and humidity) could influence this change, but such an investigation is beyond the scope of this report.

The unmeasured inflow and outflow are slightly underestimated, based on the 11% residual observed in CL budgets (Figure 6). In addition, the unmeasured inflow and outflow loads are slightly higher proportions of the total loads than the flows on which they are based, 25% for unmeasured inflow and 4% for unmeasured outflow as compared to the 13% and 2% for the water budgets (compare Figure 6, 4B, and 4C). Part of this error can be attributed to the assumption that the unmeasured CL inflow load has not changed over time. In this analysis it is based on a single median concentration value of all monitored minor tributary inflows for the past two years. Thus this load value is uncertain both in time and space. Atmospheric deposition (rainfall and dry deposition) is extremely minor (2% of load, Figure 6A) despite being a significant contributor to the water budget (Figure 4B).

The increasing trend of CL concentration in the lake and at the discharge location (S-59) does not appear to be related to any major changes of the loads or inflow concentrations. While increased evaporation would explain such a trend, there would have to be a decline in volume as well, which did not occur. Another, more reasonable explanation is that there has been increased CL load from the minor tributaries. This could arise from increased groundwater use and runoff. Future sampling may help to determine the unaccounted for source of CL.

TP budgets suggest that loads from atmospheric deposition and unmeasured inflow contribute modest amounts this nutrient to East Lake Toho, (Figures 8A, 9A). Much of this load (56%) is absorbed by the lake in the form of net settling (Figure 9B). While the net sedimentation coefficient (σ) varies from less than -0.5 to -3.8, no significant trends are observed (Figure 8B, Table 5). The highest settling and sedimentation rate occur in 2001 and 2002, which is attributed to the high net loads that occur in both of these years. The high settling rate in 2005 can be attributed to the large change in TP concentration in the lake from the beginning (affected by the hurricanes of 2004) to the end of that year. Only one trend was found, TP concentration flowing from Boggy Creek (Table 5). Values decline significantly from above 0.06 mg/L before 2000 to below 0.04 mg/L after 2009. Potential reasons for this improvement are improved sewage treatment and improve best management practices as well as changes in land use. The phosphorus/nitrogen budget tool (JGH Engineering 2013) could be used to determine which of these links are most likely.

Like the TP budgets, TN budgets also indicate that loads of atmospheric deposition and unmeasured runoff are modest inputs to East Lake Toho (Figure 11A). No nitrogen loads or budget estimates of lake residuals (e.g., biological and sediment removal processes) have changed significantly. As with TP there is only one significant trend observed for TN measurements, a reduction of flow-weighted concentration in Boggy Creek (Table 5). This TN concentration averages at or above 0.7 mg/l from 2001 to 2004 and below 0.7 mg/L after that (data not shown). As with TP, likely reasons for this improvement are improved sewage treatment and improved best management practices as well as changes in land use.

A monitoring program in place since 1981 has been used to evaluate trends in water quality within the lake (James et al. 2011b). These authors found significant increasing trends of dissolved inorganic nitrogen (DIN) and declining trends of turbidity and chlorophyll ***a*** from 1981 to 2007. In addition a significant decline of TN was observed from 1995 to 2007, potentially related to the significant downward trend of TN concentrations in Boggy Creek. This monitoring program was instrumental in the development of the nutrient budgets presented here. The program will continue to be useful in the evaluation of water quality in response to land use changes within the watershed of this headwater lake.

The change from a significant downward trend of TN from 1995 to 2007 (James et al. 2011b) to no observed trend in this report can be attributed to relatively stable to an non-significant increasing trend of TN values from 2005 to 2012, ranging from 0.4 to 1.0 mg/L (data not shown). The nutrient budgets also do not account for another load of TN to the lake, through nitrogen-fixation by cyanobacteria (Dierberg and Scheinkman 1987). This source may still be significant although budgets indicate that uptake settling and denitrification can easily counteract this extra load (Figure 10A)

As with CL, a major assumption for the unmeasured inflow from minor tributaries is that the median concentration values used to estimate these loads do not change over space or time. While the variations of these measurements are substantial (Tables 3 and 4), the uncertainty may be reduced by weighting the minor tributaries by flow estimates based on rainfall runoff models, which would require additional flow measurements.

SUMMARY

- Measurements at major inflows and outflows, as well as evaporation and rainfall explain a majority (87%) of the annual variation in lake volume.
- CL budgets indicate that unmeasured inflows and outflows are modest contributors to the lake budget, while atmospheric deposition is minor.
- There is a significant increasing trend of CL within the lake and in the discharge, which could be related to increased loading from unmeasured sources such as groundwater well fields.
- Unmeasured flows contribute approximately 25 and 15%, respectively, of TP and TN loads to East Lake Toho.
- Atmospheric deposition contributes 17 and 22% respectively, of TP and TN loads to the lake.
- The lake absorbs approximately 56% of the TP loads and 45% of the TN loads.
- There is no significant trend of TP net sedimentation coefficient.
- There is no significant trend of TN removal.
- TN in the lake declined significantly between 1994 and 2007 (James et al. 2011) but this trend was no longer significant once additional years of data (2008 to 2012) were added, likely due to some increases of TN loads to the lake.

- Improvements of load estimates from minor tributaries could be accomplished through some direct measurement of flow and basin modeling (e.g., the phosphorus/nitrogen budget tool, (JGH Engineering 2013). Minor tributaries need to be evaluated more closely because these values could change the proportion of the budget attributed to these unmeasured flows and loads.

LITERATURE CITED

APHA. 1998. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Water Works Association and Water Pollution Control Federation, Washington, DC.

Belanger T.V., D.F. Mikutel and P.A. Churchill. 1985. Groundwater seepage nutrient loading in a Florida Lake. *Water Resources Bulletin* 19:773-781.

CDM. 2011. Lake Tohopekaliga Nutrient Reduction Plan. Tallahassee, FL. 103 pp.

Dierberg F.E. and M.M. Scheinkman. 1987. Contribution from nitrogen fixation (acetylene reduction) to the nitrogen budget of Lake Tohopekaliga (Florida). *Hydrobiologia* 154:61-73.

Gilbert D. 2011. TMDL Report Nutrient, TMDL For Lake Cypress, WBID 3180A. Florida Department of Environmental Protection, Tallahassee, FL.

Griffith G.E., D.E. Canfield, C.A. Horsburgh and J. M. Omernik. 1997. Lake Regions of Florida. USEPA Western Ecology Division, Corvallis, OR.

Havens K.E. and R.T. James. 2005. The phosphorus mass balance of Lake Okeechobee, Florida: Implications for eutrophication management. Lake Reservoir Managment 21(2):139-148.

JGH Engineering. 2013. Nutrient Budget Tool Update. Submitted to South Florida Water Management District, West Palm Beach, FL.

James R.T., W. Gardner, M. McCarthy and S. Carini. 2011a. Nitrogen dynamics in Lake Okeechobee: Forms, functions, and changes. *Hydrobiologia* 669(1):199-212.

James R.T., K.E. Havens, P. McCormick, B. Jones and C. Ford. 2011b. Water Quality Trends in Shallow South Florida Lakes and Assessment of Regional vs. Local Forcing Functions. *Critical Reviews in Environmental and Science Technology* 41(S1):576-607.

James RT. 2014. Long Term Water Chloride and Nutrient Budgets for Lake Tohopekaliga. West Palm Beach, FL.

McCaffrey, P.M., W. Hinckley, R. Margill and G. Chern. 1976. Report of Investigations in the Kissimmee River - Lake Okeechobee Watershed. Florida Department of Environmental Regulation, Tallahassee, FL.

NASA. 2013. North American Land Data Assimilation System (NLDAS), National Aeronautics and Space Administration. Available online at http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=NLDAS0125_M. Accessed December 16, 2013.

National Atmospheric Deposition Program. 2011. Monitoring Our Changing Chemical Climate. Available online at http://nadp.sws.uiuc.edu/. Accessed October 25, 2011.

Reckhow K.H., K. Kepford and W. Warren-Hicks. 1992. Methods for the Analysis of Lake Water Quality Trends. School of the Environment, Duke University, Durham, NC.

SAS. 1989. SAS/STAT® Users Guide: Version 6. SAS Institute, Inc., Cary, NC.

SFWMD. 2011a. Field Sampling Quality Manual. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2011b. Chemistry Laboratory Quality Manual. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 1999. SFWMD Comprehensive Quality Assurance Plan - 1999. South Florida Water Management District, West Palm Beach, FL.

SFWMD. 2013a. Nexrad-ET, South Florida Water Management District. Available online at http://my.sfwmd.gov/nexrad/arcims/default.htm. Accessed July 25, 2013.

SFWMD. 2013b. DBHYDRO, South Florida Water Management District. http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu. Accessed July 8, 2013.

USACE. 1996. Master Water Control Manual: Volume 3, Lake Okeechobee and Everglades Agricultural Area. United States Army Corps of Engineers, Jacksonville, FL.

USEPA. 2011. Clean Air Status and Trends Network (CASTNET), United States Environmental Protection Agency. Available at http://java.epa.gov/castnet/. Accessed October 28, 2011.

USEPA. 1983. Methods for Chemical Analysis of Water and Wastes. Methods Development and Quality Assurance Research Laboratory, United States Environmental Protection Agency, CO.