HydroQual
Environmental
Engineers & Scientists

MEMORANDUM

TO: Bruce Nelson
ALASD Executive Director

DATE: November 5, 2009

CC: Steven W. Nyhus Flaherty & Hood, P.A.
John C. Hall, Hall and Associates

RE: Estimate of Lake Winona Total Phosphorus Levels to Establish a Clear Water State

FROM: Thomas W. Gallagher

FILE: HAAS.003

HydroQual was asked to review the "Draft Lake Winona TMDL Phase 3 Report" prepared by AECOM for the Minnesota Pollution Control Agency in September 2009. To more completely understand the relationship between phosphorus, chlorophyll a, and transparency in Lake Winona, HydroQual also reviewed the following documents:

- Draft Lake Winona TMDL Phase 1 Report
  Data Summary and Modeling Strategy (Earth Tech, Inc. 2008)
- Lake Winona TMDL Phase 2 Report (AECOM, 2009)
- Phosphorus Release from Sediments in Lake Winona (Wang, Weiss, and Gulliver – 2009)
- Technical Memorandum on Lake Winona Site Specific Standard Assessment (Wenck; July 2, 2009)
- Technical Memorandum on Review of Water Quality Modeling in Support of the Draft Lake Winona TMDL Phase 3 Report (LimnoTech, September 28, 2009)

This memorandum includes an analysis of Lake Winona water quality data, a brief review of the BATHTUB modeling performed by AECOM, and an estimated range of lake phosphorus levels that would restore Lake Winona to a "clear water" lake.

Lake Winona Data Analysis

The Alexandria Lakes Area Sanitary District (ALASD) has sampled Lake Winona at two stations (South Lake and North Lake) approximately four times per year since 1984. Included in this monitoring program are measurements of total phosphorus (TP), chl-a, and secchi depth. HydroQual has summarized this data in Table 1 and graphically displayed it in Figure 1 in which chl-a and secchi depth are plotted versus total phosphorus. Carp were accidently introduced into Lake Winona in 2005 so data collected with carp in Lake Winona are distinguished by the solid symbols. The data indicate that the correlation of lake chl-a and secchi depth with Lake Winona total phosphorus changed after introduction of carp in 2005. For the same TP levels lake chl-a is higher and secchi depth shallower after introduction of carp. A potential effect of carp on the Lake Winona ecosystem that would increase phytoplankton and reduce secchi depth is resuspension of bottom sediments with a concurrent increase in lake TSS and phosphorus levels and reduction of secchi depth.

An additional data analysis was performed to develop an equation to compute lake secchi depth as a function of lake chl-a and total suspended solids (TSS) levels so that future Lake Winona secchi depths could be estimated for various combinations of lake chl-a and TSS values. Such analyses were not conducted by AECOM as part of the original modeling effort. AECOM conducted a monitoring program of Lake Winona, Lake Agnes, and Lake Henry during 2008 and 2009. Between July and October, 2008, AECOM measured chl-a, TSS, and secchi depth in Lake Winona one to three times per month. The mean of these four month's data is contained in Table 2 along with other computed variables. Table 2 contains the computed light extinction coefficient for each month based on the approximation $K_e = 1.7/\text{secchi depth}$. The component of light extinction due to absorption of light by algal cells is contained in the next column and was estimated by the equation $K_e(\text{algae})\,(1/\text{m}) = 0.017$ chl-a (ug/l). This approximation of $K_e(\text{algae})$ is tested against Lake Winona data and shown in Figure 2. Although there is significant scatter in the data, the increase in light extinction with increasing chl-a is reasonably well represented by a line with a slope of 0.017 indicating that for each 1 ug/l increase in chl-a the light extinction coefficient (K_e) increases by 0.017/m. With the assumption that light extinction in Lake Winona is due to light reduction by algae and TSS, the component of light extinction due to TSS is computed as the total light extinction coefficient minus the light extinction due to algae and is contained in the second to last column. Finally, the increase in light extinction per unit of TSS is the computed TSS light extinction coefficient divided by TSS and is contained in the last column. The average value of $K_e(\text{TSS})/\text{TSS}$ is 0.075 leading to the following equation for lake light extinction as a function of chl-a and TSS.

$$K_e\,(/\text{m}) = 0.017\ \text{chl-a (ug/l)} + 0.075\ \text{TSS (mg/l)}$$

The secchi depth corresponding to K_e can be computed from the relationship $K_e = 1.7/\text{secchi}$. These relationships will be used later to estimate possible future Lake Winona secchi depths for combinations of chl-a and TSS.

Review of BATHTUB Model

I agree with the BATHTUB model weaknesses identified in the LimnoTech memorandum. In particular model calibration should not be accomplished by varying the internal load of TP from the lake bottom sediment. The TP release from sediments in Lake Winona was measured and averaged 4.6 mg/m^2/day under aerobic conditions. It is highly probable that a sediment release near this value occurs every year so that model calibration for years when sediment release was set to zero is probably masking other sources of model error by eliminating an internal phosphorus source that has been measured.

The BATHTUB model used by AECOM is simply an empirical model that relates average lake total phosphorus levels to point and nonpoint source phosphorus inputs by a variety of empirical equations that include flow, volume and depth in computing average lake total phosphorus. The model user then selects one of many equations that compute average lake chl-a levels and secchi depth from the computed lake phosphorus concentration. Finally, the modeler may fine tune these empirical equations through the use of a "calibration factor" to force agreement between model and data. The BATHTUB model is highly empirical and may be adjusted to represent existing conditions. However, it is evident that a model of this nature can not make any credible prediction of the relationship between phosphorus inputs and lake chl-a and secchi depth for a "clear water" lake without carp when it has been calibrated to a turbid lake with carp. To be useful in predicting future water quality, these modified conditions must be represented by the model.

The BATHTUB model was calibrated against the 2004-2008 period which was dominated by years with carp in Lake Winona. Figures 3 and 4 show the BATHTUB calibration results for chl-a and secchi depth in comparison to Lake Winona data with (2005-2009) and without (1989-2004) carp. It is clear that the BATHTUB model does not represent Lake Winona conditions without carp. Because restoration of Lake Winona to a clear lake condition will require the removal of carp and a rebalancing of the fishery between piscivores, planktivores, and benthivores, the empirical BATHTUB model calibrated against lake data with carp is unsuitable for representing Lake Winona without carp. Given that the BATHTUB modeling does not provide any insight into Lake Winona phosphorus levels required to support a clear-water lake environment, an analysis is presented that uses existing Lake Winona data and clear-water lakes data to provide an estimated range of acceptable lake phosphorus.

Estimation of Lake Winona Target Total Phosphorus Levels for Establishing a Clear Water Lake

As a starting point for estimating Lake Winona target phosphorus levels required to establish a clear-water state an analysis of pre-carp Lake Winona data was performed. Figure 5 presents 1984-2004 Lake Winona data with equations representing the relationship suggested by these data. Lake chl-a levels increase with TP to a TP concentration of 300 ug/l and then level off at an average of approximately 120 ug/l but with significant scatter. It is likely that above a TP concentration of 300 ug/l algal growth is limited by light rather than phosphorus. As shown on the bottom panel of Figure 5 secchi depth decreases with increasing TP with the rate of secchi depth decrease lessening at higher TP levels.

Although Lake Winona is a shallow turbid lake, there are times at low TP concentrations when chl-a levels and secchi depth approach clear-water lake values. The equation describing these conditions on Figure 5 is used to estimate conditions in Lake Winona in a clear water state. At lake TP levels between 100 and 150 ug/l average lake chl-a concentrations would be between 25 and 40 ug/l with secchi depths of 0.75 to 0.90 m. These estimates are anticipated to under predict water quality attained during a clear water state when significant submerged vegetation has been reestablished. Secchi depths would be greater than this estimate after macrophytes are restored because sediment resuspension would be further reduced. An equation relating TP and lake chl-a levels in clear water lakes is provided in Figure 7 of the Wenck memorandum. This equation is based on four clear water lakes with a moderate to excellent Floristic Quality Index (FQI). This relationship is shown by the green line on Figure 6 with the solid portion of the line representing the relationship within the range of TP data from which it was derived and the dashed part of the line an extrapolation. There is a close agreement between the equation for the Lake Winona data and the equation derived from clear-water lakes suggesting that using the relationships derived from the low TP (less than 300 ug/l) Lake Winona data provides a reasonable estimate of Lake Winona chl-a, secchi depth, and TP at a clear water state.

The equation previously developed to relate secchi depth to lake chl-a and TP may also be used to estimate a range in expected secchi depths as a function of chl-a and TSS. Figure 7 is a graphical summary of this relationship and presents secchi depth versus chl-a for three lake TSS levels. TSS and chl-a levels of approximately 35 mg/l and 120 ug/l respectively represent average Lake Winona conditions before carp and yield a secchi depth of 0.36 m. However if as a consequence of lake restoration efforts chl-a levels are reduced to 40 ug/l and TSS to 5-10 mg/l future Lake Winona secchi depth may range between 1.2 m and 1.6 m.

Conclusions

Based on the comments and analyses presented in this memorandum, HydroQual concludes the following:

- The Lake Winona data (2004-2008) used to calibrate the BATHTUB model are not consistent with the 1984-2004 data representative of lake conditions with no carp.
- Because the removal of carp is a necessary step in the restoration of Lake Winona to a clear-water state the results of the BATHTUB modeling analysis are not useful in developing a relationship between lake TP, chl-a and secchi depth with no carp. In addition, the need for AECOM to significantly vary the internal phosphorus load for calibration on a yearly basis is an indication that the BATHTUB model does not accurately reflect cause – effect relationships in Lake Winona.
- An analysis of pre-carp Lake Winona data and data for clear-water lakes presented in the Wenck memorandum suggest that at lake TP levels of between 100 ug/l and 150 ug/l the average lake chl-a may range between 25 ug/l and 40 ug/l.
- With a reduction of average Lake Winona chl-a levels to 40 ug/l and TSS concentrations between 5 mg/l and 10 mg/l due to establishment of macrophyte beds that inhibit sediment resuspension, Lake Winona secchi depths may range between 1.2 m and 1.6m for TP ranging 100 to 150 ug/l.

TWG/lkj
HAAS.003\NELSON05NOV09MEM

	North Lake Winona			South Lake Winona		
	TP	**Chla**	**Secchi**	**TP**	**Chla**	**Secchi**
Year	mg/L	ug/L	m	mg/L	ug/L	m
1984	0.27	158	0.34	0.30	185	0.32
1985	0.36	151	0.29	0.41	111	0.31
1986	0.31	92	0.34	0.31	100	0.34
1987	0.26	157	0.46	0.36	186	0.38
1988	0.55	53	0.31	0.60	67	0.31
1989	0.45	108	0.53	0.47	105	0.53
1990	0.49	172	0.21	0.51	157	0.21
1991	0.44	170	0.21	0.44	161	0.21
1992	0.21	71	0.65	0.27	85	0.57
1993	0.33	57	0.42	0.26	102	0.42
1994	1.38	142	0.24	0.58	139	0.24
1995	0.52	104	0.38	0.47	153	0.38
1996	0.23	60	0.50	0.25	90	0.57
1997	0.17	34	0.50	0.20	45	0.46
1998	0.37	44	0.31	0.38	74	0.34
1999	0.34	70	0.27	0.36	77	0.23
2000	0.16	51	1.41	0.21	73	1.60
2001	0.25	128	0.76	0.32	184	0.92
2002	0.31	118	0.27	0.34	154	0.42
2003	0.24	95	0.42	0.26	98	0.46
2004	0.14	80	0.80	0.18	99	0.88
2005	0.21	114	0.42	0.22	120	0.34
2006	0.16	147	0.34	0.17	159	0.34
2007	0.23	256	0.31	0.27	264	0.31
2008	0.23	152	0.28	0.24	176	0.28
2009	0.21	169	0.31	0.25	184	0.31

Table 1. Lake Winona chlorophyll-a (Chla), total phosphorus (TP), and secchi disk (Secchi) data (1984-2009).

		TSS	Chla	Secchi	K_e	K_e (Algae)	K_e (TSS)	K_e (TSS)/TSS
Month	**Location**	**mg/L**	**ug/L**	**ft**	**(1/m)**	**(1/m)**	**(1/m)**	
					Note 1	Note 2	Note 3	
July	South	43	215	0.75	7.44	3.65	3.79	0.088
	North	40	189	0.73	7.64	3.21	4.43	0.11
August	South	45	222	0.88	6.34	3.77	2.57	0.057
	North	34	179	0.78	7.15	3.04	4.11	0.12
September	South	38	194	1.05	5.31	3.3	2.01	0.053
	North	26	164	1.15	4.85	2.79	2.06	0.079
October	South	33	147	1.5	3.72	2.5	1.22	0.087
	North	27	157	1.35	4.13	2.67	1.46	0.054
								AVG=0.075

Table 2. Calculated Light Extinction due to Algae and Total Suspended Solids for Lake Winona (2008).

Note 1: $K_e = \frac{1.7}{\mathrm{secchi}}$

Note 2: $K_e\ (\mathrm{algae}) - 1/\mathrm{m} = 0.017 \text{ x } \mathrm{chl-a}\ (\mu g/l)$

Note 3: $K_e\,(\mathrm{TSS}) = K_e\,(\text{from measured secchi}) - K_e\,(\mathrm{Algae})$

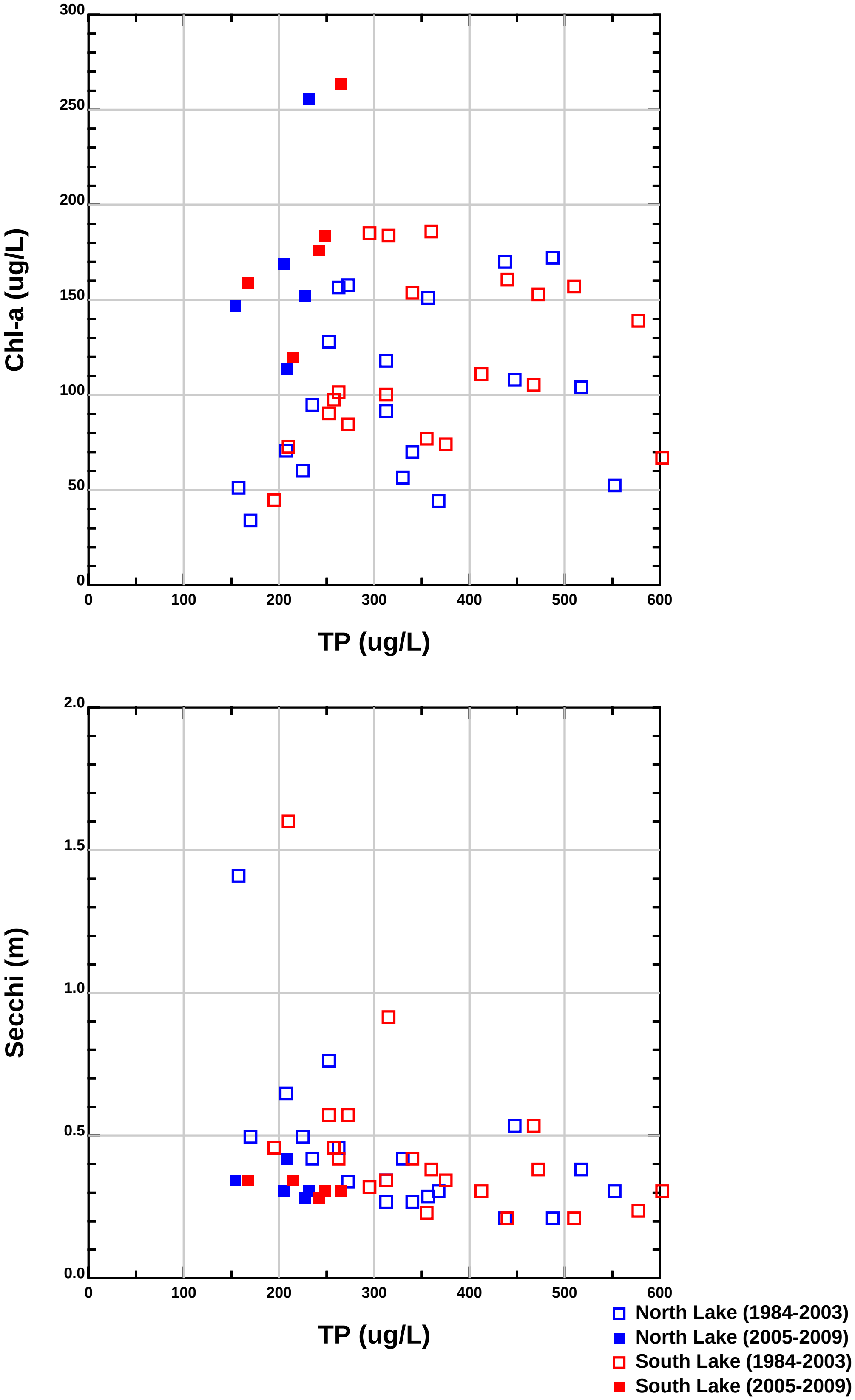

Figure 1. Lake Winona Chlorophyll-a, Total Phosphorus and Secchi Disk Data (1984-2009)

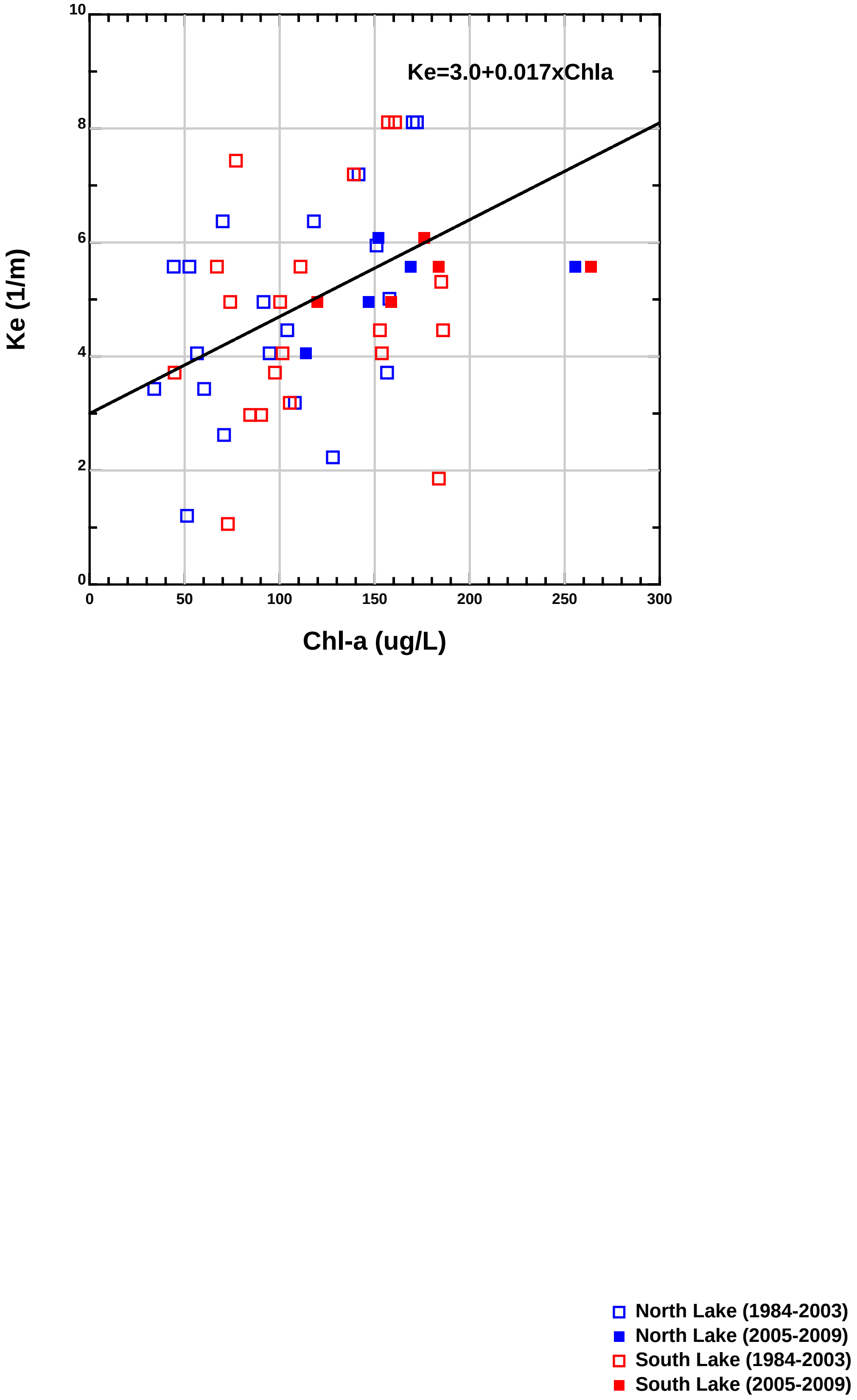

Figure 2. Lake Winona: Light Extinction - Chlorophyll-a Relationship

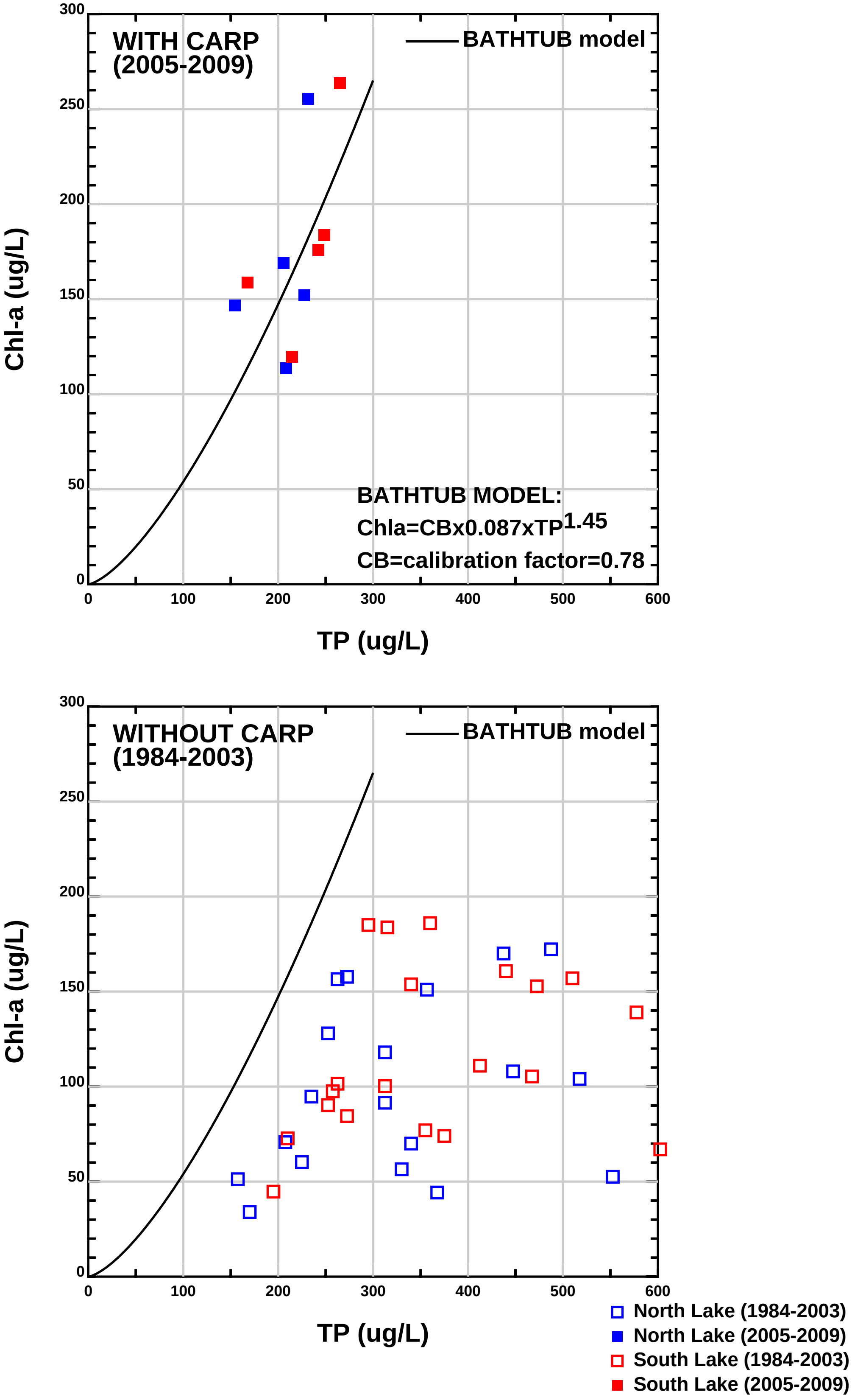

Figure 3. Lake Winona Chlorophyll-a and Total Phosphorus Data (1984-2009)

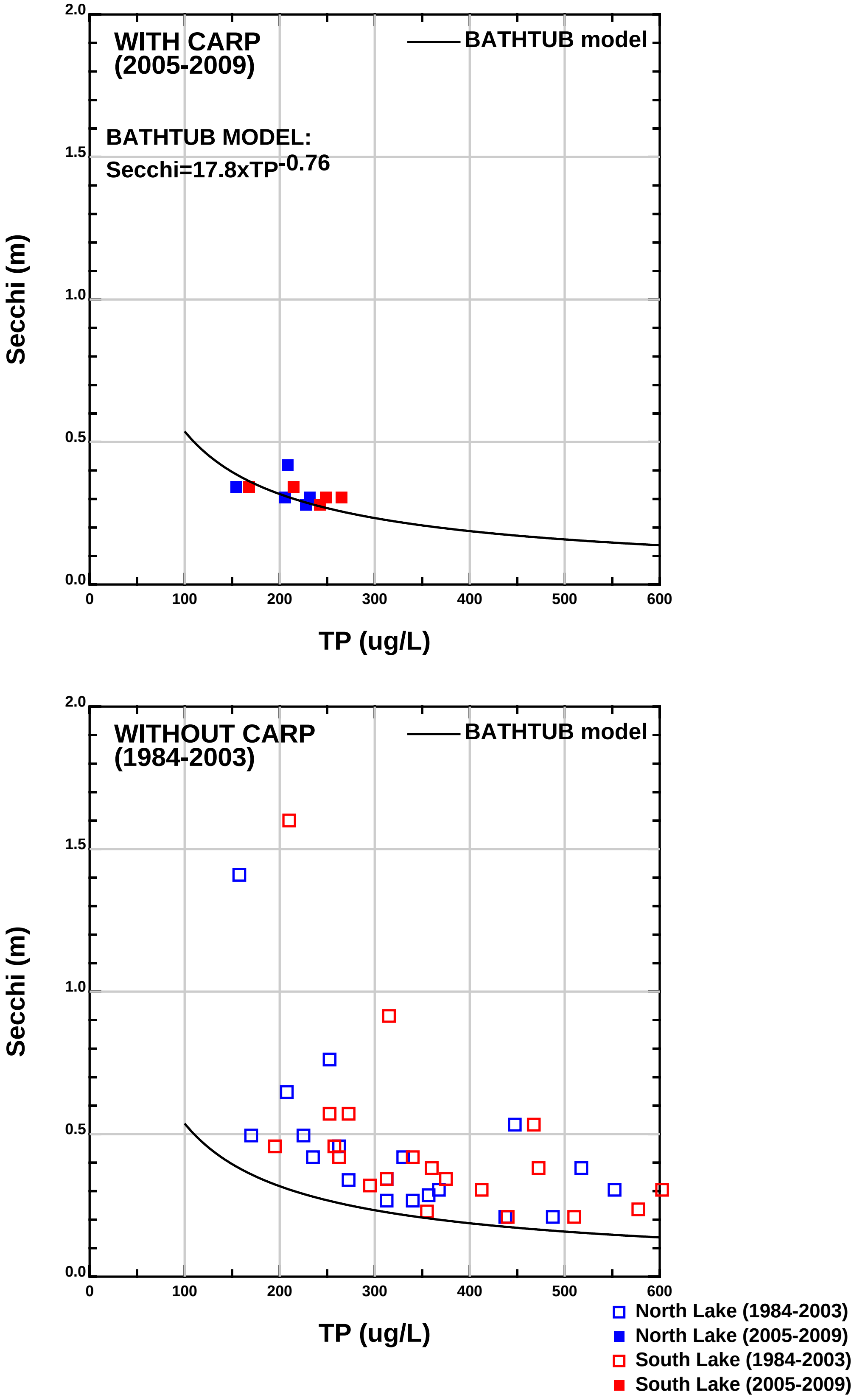

Figure 4. Lake Winona Total Phosphorus and Secchi Disk Data (1984-2009)

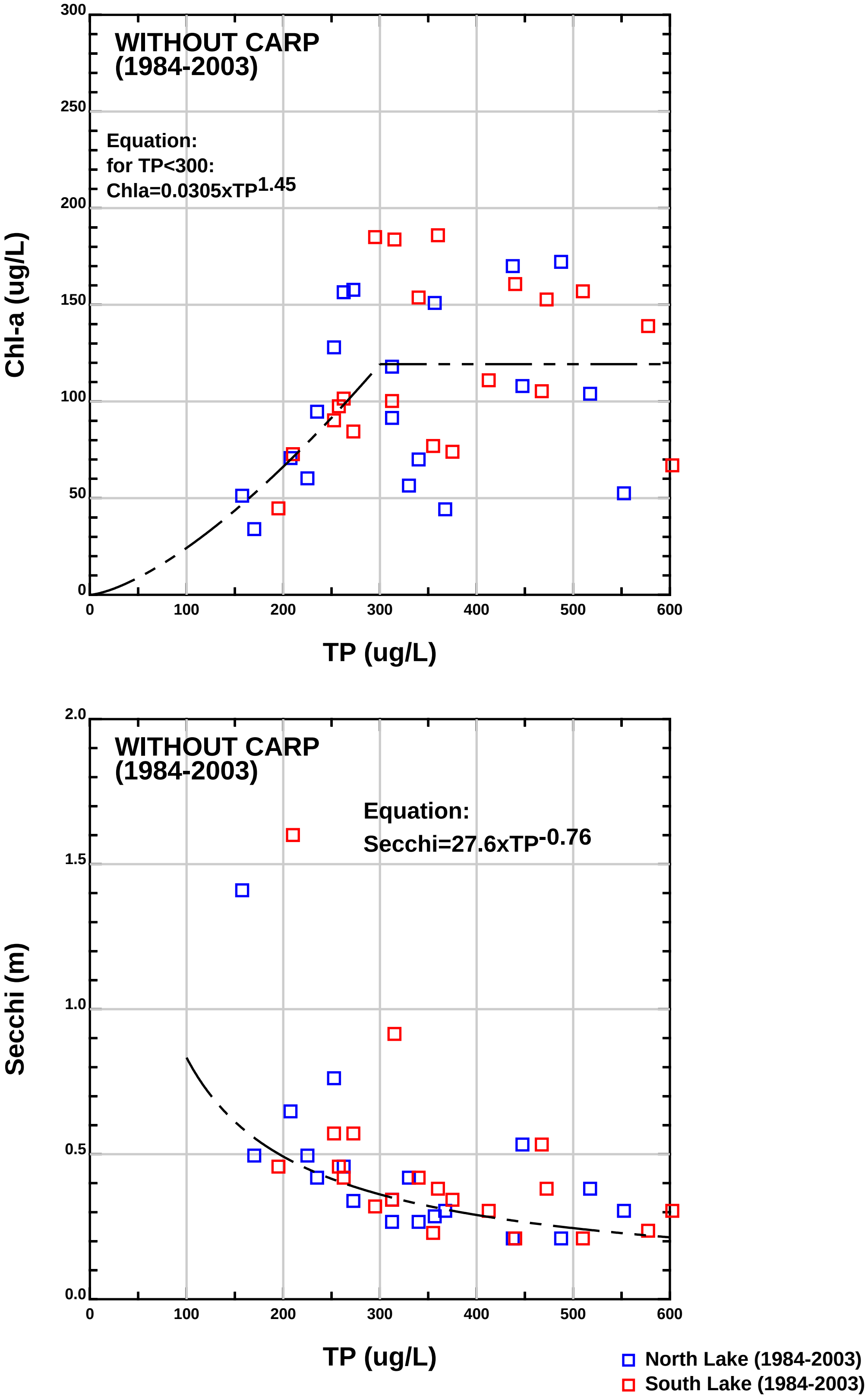

Figure 5. Lake Winona Chlorophyll-a and Total Phosphorus Data (1984-2003)

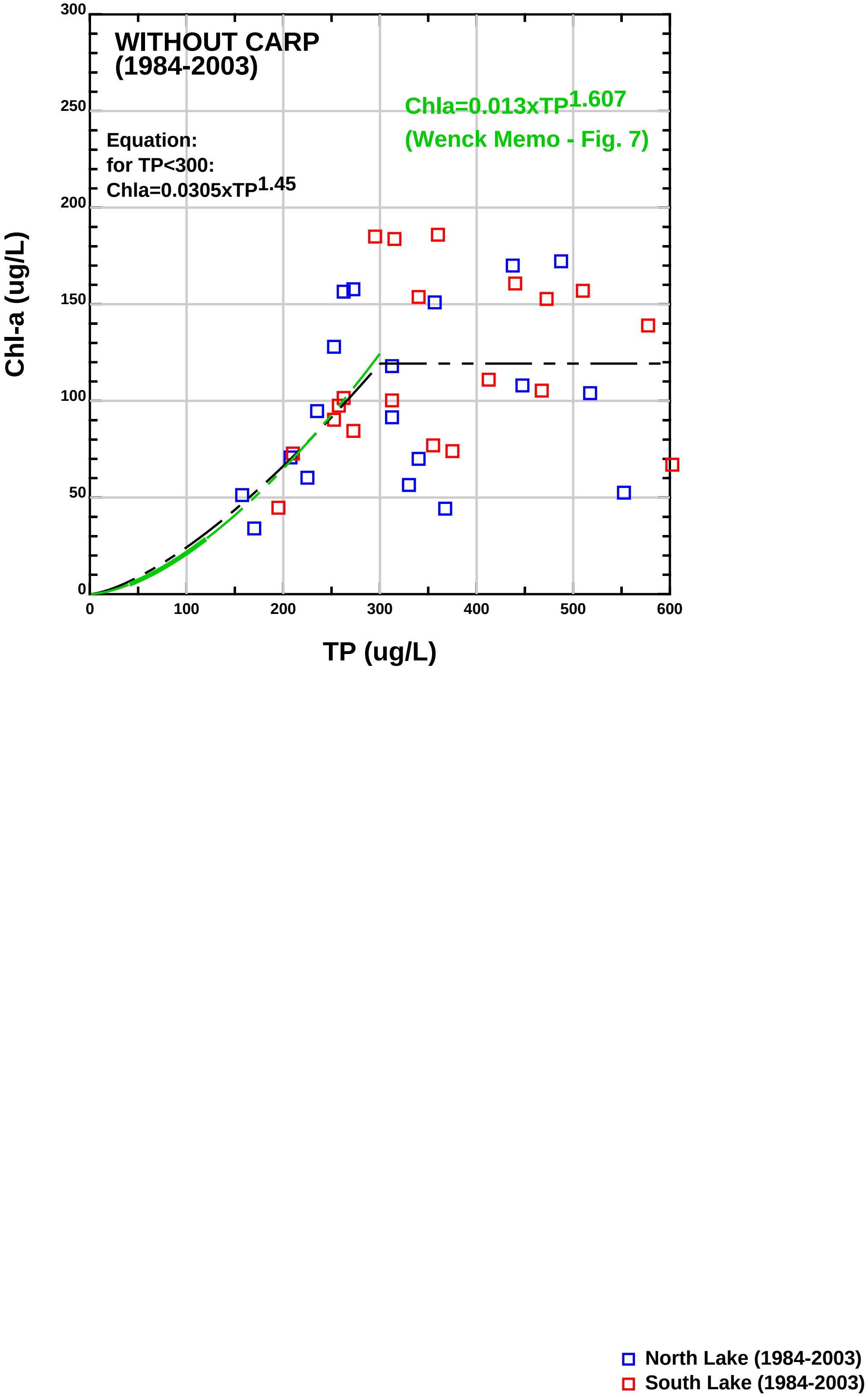

Figure 6. Lake Winona Chlorophyll-a and Total Phosphorus Data (1984-2003)