APPENDIX H

Lakes Analyses Using the BATHTUB Model

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B.1 Description of Target Endpoint

A frequently used biomass-related trophic state index is that of Carlson (1977). It is relatively simple to use, requires a minimum of data, and is generally easy to understand, both in theory and use. Carlson's trophic state index (TSI) uses algal biomass as the basis for trophic state classification. Three variables, chlorophyll pigments, Secchi depth, and total phosphorus, independently estimate algal biomass. The trophic continuum is divided into units based on a base-2 logarithmic transformation of Secchi depth; each 10-unit division of the index represents a halving or doubling of Secchi depth. Because total phosphorus often correlates with transparency, a doubling of the total phosphorus often corresponds to a halving of Secchi depth. Chlorophyll pigments double every 7 units rather than every 10 units (Carlson 1980).

The relationship between Carlson's TSI and relative algal abundance is given in Table B.1. For the Lake Logan and Oakthorpe Lake TMDLs, the target TSI was set at 60.

Table B.1. Carlson Trophic State Index (TSI)

TSI	Chl *a* (µg/L)	SD (m)	TP (µg/L)	Attributes	Water Supply	Fisheries & Recreation
<30	<0.95	>8	<6	**Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion	Water may be suitable for an unfiltered water supply	Salmonid fisheries dominate
30-40	0.95-2.6	8-4	6-12	Hypolimnia of shallower lakes may become anoxic		Salmonid fisheries in deep lakes only
40-50	2.6-7.3	4-2	12-24	**Mesotrophy:** Water moderately clear; increasing probability of hypolimnetic anoxia during summer	Iron, manganese, taste, and odor problems worsen. Raw water turbidity requires filtration	Hypolimnetic anoxia results in loss of salmonids. Walleye may predominate
50-60	7.3-20	2-1	24-48	**Eutrophy:** Anoxic hypolimnia, macrophyte problems possible		Warm-water fisheries only. Bass may dominate

Table B.1. Carlson Trophic State Index (TSI) (con't)

TSI	Chl *a* (µg/L)	SD (m)	TP (µg/L)	Attributes	Water Supply	Fisheries & Recreation
60-70	20-56	1-0.5	48-96	Blue-green algae dominate, algal scums and macrophyte problems	Episodes of severe taste and odor possible	Nuisance macrophytes, algal scums, and low transparency may discourage swimming and boating
70-80	56-155	0.5-0.25	96-192	**Hypereutrophy:** (light limited productivity). Dense algae and macrophytes		
>80	>155	<0.25	192-384	Algal scums, few macrophytes		Rough fish dominate; summer fish kills possible

B.2 Description of the BATHTUB Lake Model

BATHTUB is a U. S. Army Corps of Engineers steady-state model (W. W. Walker, 1999; 2004). The model incorporates several empirical equations of nutrient settling and algal growth to predict steady-state nutrient and chlorophyll *a* concentrations based on waterbody characteristics, hydraulic characteristics, and nutrient loadings.

BATHTUB has three primary input interfaces: global inputs, lake morphology, and watershed loading. Compared to other reservoir models, the BATHTUB model requires a moderate amount of site-specific data to configure and calibrate. Input data includes atmospheric loads of nutrients, tributary flows and concentrations, and global parameters such as evaporation rates and annual average precipitation. For lakes with low phosphorus residence times, the recommended critical condition is the period of increased sunlight, temperature and algal growth from May through September.

A phosphorus TMDL was completed for Oakthorpe Lake and Lake Logan, using GWLF and BATHTUB as a watershed/receiving water model combination. The non-point source model, GWLF, was used to predict phosphorus loads and flows

from the watersheds. These loads were then input into the BATHTUB lake model to assess resulting chlorophyll *a* concentrations. The BATHTUB model was selected because it does not have extensive data requirements and can therefore be applied with the GWLF data.

For both lake watersheds, the single basins modeled in GWLF represented the tributary inputs. The monthly loads were summed over the May to September period, and average flow was also take from the GWLF output for this time period. Phosphorus concentrations were determined by dividing nutrient mass by the volume of flow. Table B.2 shows the selected BATHTUB options.

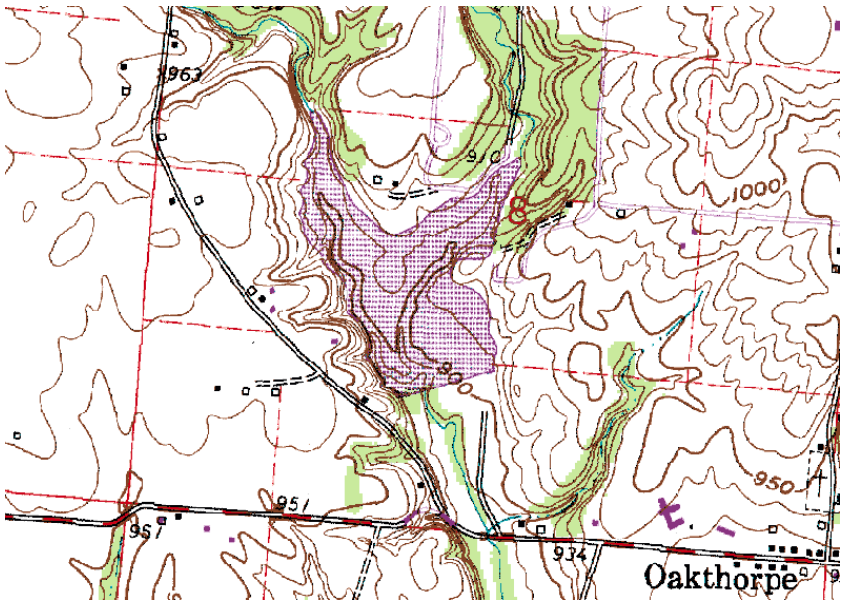
The results of the GWLF model for each May to September period from 1995 to 2004 were applied to BATHTUB to evaluate water quality/trophic conditions. The BATHTUB model was then used as a "diagnostic" tool in order to estimate the phosphorus load reductions required to achieve a chlorophyll *a* target of about 20 µg/L (equivalent to a Carlson's TSI of 60). The allowable pounds per year resulting from the modeling show the effects of varying climatic conditions observed during these years. Therefore, an average value of these years was set as the target loading to meet the in-lake water quality standards of about 20 µg/L chlorophyll *a*.

Table B.2. Algorithms used within BATHTUB to simulate water quality in Oakthorpe Lake and Lake Logan

Process	Algorithm number	Algorithm description
Phosphorus balance	1	Second order, available phosphorus
Nitrogen balance	0	Not computed
Chlorophyll *a* concentration	4	Linear function of phosphorus
Secchi depth	3	Function of total phosphorus
Phosphorus calibration	1	Decay rates
Nitrogen calibration	0	None

B.3 Global and Morphometric Model Inputs for Oakthorpe Lake

Global inputs represent atmospheric contributions of precipitation, evaporation, and atmospheric phosphorus. Rainfall data was obtained from stations in Lancaster and Enterprise. Seasonal lake evaporation was calculated using



Penman's equation with a pan coefficient of 0.78, in conjunction with OARDC data from the Delaware station. The default atmospheric phosphorus deposition rate suggested in the BATHTUB model (30 kg/km^2/yr) was used in the absence of site-specific data.

The BATHTUB model requires basic lake morphometric data to assess residence time, net flow rate, and potential euphotic depth. Design data were provided by the ODNR Division of Water. The model was run assuming normal pool elevation. Table B.3 shows lake morphometry data for Oakthorpe Lake. Because the lake is fairly uniform, segmentation is not required.

Table B.3. Oakthorpe Lake morphometry data

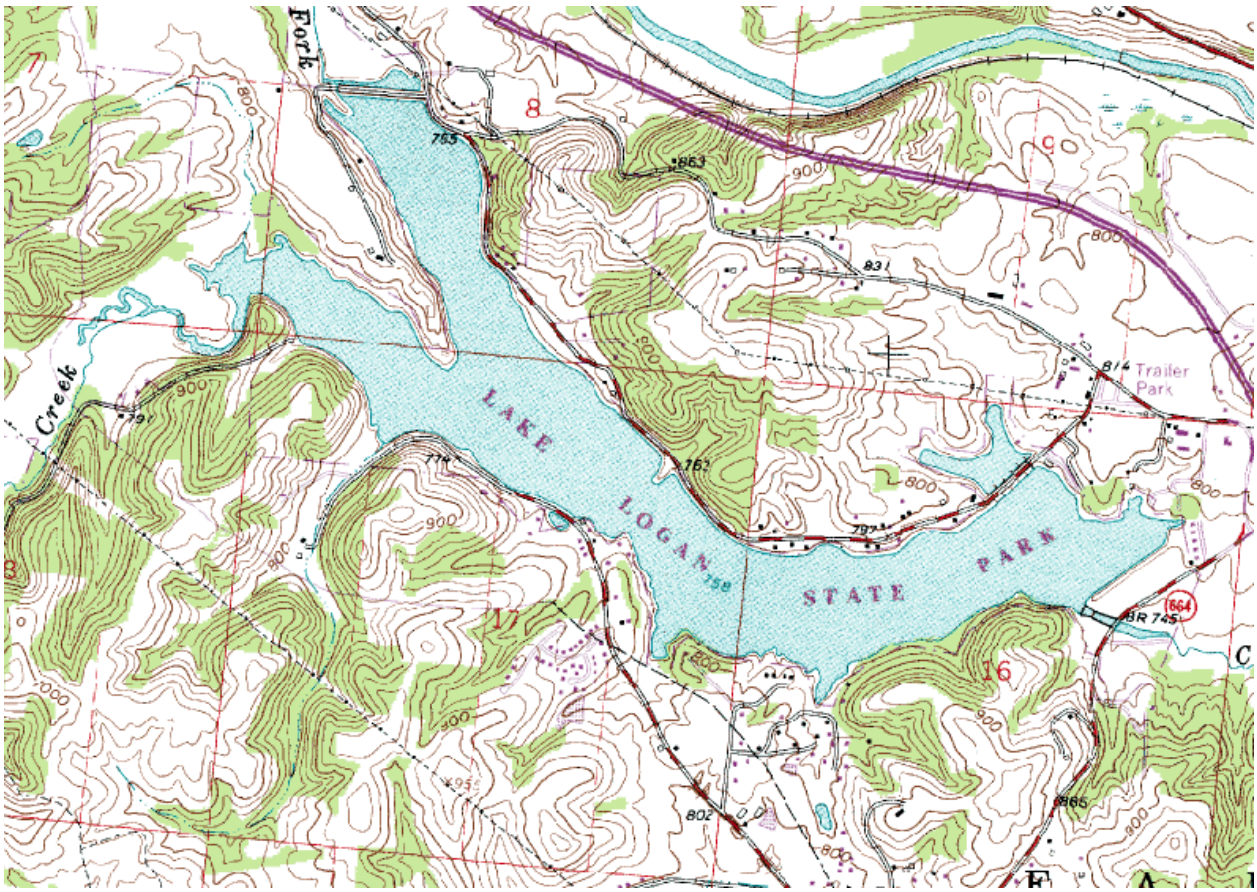
Drainage Area	7.32	square miles[1]
Lake Area	41.8	acres[2,3]
Volume	377	acre-feet[2,3]
Maximum Depth	28.8	feet[2,3]
Average Depth	9.0	feet
Relative Depth*	0.019	dimensionless
Development of Volume	0.94	dimensionless
Lake Length	2330	feet[4]

Table B.3. Oakthorpe Lake morphometry data (con't)

Fetch	2200	feet[4]
Maximum Width, Perpendicular to Fetch	1810	feet[4]
Shoreline Length	7999	feet[5]
Development of Shoreline	1.70	dimensionless[5]
May to September Average Flow	6.29	hm^3/year[6]
	7.04	cfs
May to September Average Hydraulic Detention Time	27	days[3,6]
May to September Average Surface Overflow Rate	122	feet/year[3,6]
	37.2	m/year

* max depth / lake diameter, if the lake area was a circle. Most lakes < 0.02.

[1] ArcGIS result
[2] ODNR Inventory Sheets
[3] Normal pool (principal spillway)
[4] ArcGIS using USGS 1:24000 topographic map
[5] ArcGIS NHD values
[6] GWLF results



B.4 Global and Morphometric Model Inputs for Lake Logan

Rainfall data was obtained mainly from Enterprise, with precipitation data from Laurelville used to fill in any gaps. Seasonal lake evaporation was calculated using Penman's equation with a pan coefficient of 0.78, in conjunction with OARDC data from the Jackson station. The default atmospheric phosphorus deposition rate suggested in the BATHTUB model (30 kg/km^2/yr) was used in the absence of site-specific data.

Morphometric design data were provided by the ODNR Division of Water. The model was run assuming normal pool elevation. Table B.3 shows lake morphometry data for Lake Logan. Because the lake is fairly uniform, segmentation is not required.

Table B.4. Lake Logan morphometry data

Drainage Area	14.72	square miles[1]
Lake Area	340	acres[2,3]
Volume	3000	acre-feet[2,3]
Maximum Depth	29	feet[2,3]
Average Depth	8.8	feet
Relative Depth*	0.0067	dimensionless
Development of Volume	0.91	dimensionless
Lake Length	10800	feet[4]
Fetch	7800	feet[4]
Maximum Width, Perpendicular to Fetch	1650	feet[4]
Shoreline Length	49390	feet[5]
Development of Shoreline	3.73	dimensionless[5]
May to September Average Flow	10.9	hm^3/year[6]
	12.2	cfs
May to September Average Hydraulic Detention Time	124	days[3,6]
May to September Average Surface Overflow Rate	26	feet/year[3,6]
	7.9	m/year

* max depth / lake diameter, if the lake area was a circle. Most lakes < 0.02.

[1] ArcGIS result
[2] ODNR Inventory Sheets
[3] Normal pool (principal spillway)
[4] ArcGIS using USGS 1:24000 topographic map
[5] ArcGIS NHD values
[6] GWLF results

B.5 BATHTUB Model Results for Oakthorpe Lake

For Oakthorpe Lake, the existing average seasonal (May-September) loading for total phosphorus was calculated at 3064 lbs (Table B.5). Almost all of the loading is from runoff, with small fractions from atmospheric deposition and septic

systems. BATHTUB predicted an average seasonal in-lake chlorophyll *a* concentration of about 50 µg/L, well above the target of 20 µg/L, with a corresponding Carlson's TSI of 69 (Figures B.1-B.4).

The total phosphorus loading was adjusted and the BATHTUB model was run until the seasonal chlorophyll *a* averaged about 20 µg/L. Reductions were allocated equally between septic systems and runoff. The average dissolved/total phosphorus ratio was assumed constant (BATHTUB is relatively insensitive to this ratio.)

The total phosphorus loading to meet the target values is about 747 lbs/season. With a 10% margin of safety (MOS), the phosphorus loadings from septic systems and runoff would need to be reduced by about 78%. The resulting calculated seasonal values of chlorophyll *a*, Secchi depth, in-lake phosphorus, and Carlson's TSI for chlorophyll are given in Figures B.5-B.8. The TMDL allocations are in Table B.6.

B.6 BATHTUB Model Results for Lake Logan

For Lake Logan, the existing average seasonal (May-September) loading for total phosphorus was calculated at 2766 lbs (Table B.5). Almost all of the loading is again from runoff. Small fractions come from atmospheric deposition and septic systems. There is also a small point source, Lake Moor Estates Subdivision, which discharges directly to Lake Logan about midway down the lake. Based on historical monitoring data, Lake Moor Estates has discharged an average of about 24 kg/season. BATHTUB predicted an average seasonal in-lake chlorophyll *a* concentration of about 24 µg/L, with a corresponding Carlson's TSI of 62 (Figures B.9-B.12). This is only slightly above the targets of 20 µg/L/60 TSI.

The total phosphorus loading was adjusted and the BATHTUB model was run until the seasonal chlorophyll *a* averaged about 20 µg/L. The contribution from Lake Moor Estates was actually increased, to allow its effluent permit concentration of 1 mg/L at the facility design flow of 0.03 mgd. Reductions between septic systems and runoff were allocated equally. The average dissolved/total phosphorus ratio was assumed constant (BATHTUB is relatively insensitive to this ratio.)

The total phosphorus loading to meet the target values would be about 1949 lbs/season. With a 10% margin of safety (MOS), the phosphorus loadings from septic systems and runoff would need to be reduced by about 38%. The resulting calculated seasonal values of chlorophyll *a*, Secchi depth, in-lake phosphorus, and Carlson's TSI for chlorophyll are given in Figures B.13-B.16. The TMDL allocations are in Table B.6.

Table B.5. Existing total phosphorus loads.

Lake	**14-Digit HUC[1]**	**Sub-Watershed**	**Sub-Watershed Extent** (RM)	**Parameter** (units)	**Existing Point and Non-Point Source Loads**				
					Atmospheric	Point	Septic	Runoff	Total
Oakthorpe Lake	030-020	Indian Creek	the basin upstream of the lake, starting at RM 0.82	TP (lbs • season^{-1})	3.9	0	184	2876	**3064**
Lake Logan	050-030	Clear Fork	the basin upstream of the lake, starting at RM 2.07	TP (lbs • season^{-1})	32	24	185	2525	**2766**

Table B.6. TMDL total phosphorus loads.

Lake	**14-Digit HUC[1]**	**Sub-Watershed**	**Sub-Watershed Extent** (RM)	**Parameter** (units)		**Point and Non-Point Source Loads**					
						Atmospheric	Point	Septic	Runoff	MOS	**Total**
Oakthorpe Lake	030-020	Indian Creek	the basin upstream of the lake, starting at RM 0.82	TP (lbs • season^{-1})	Allocation	3.9	—	40	629	75	747
					% Reduction	0%	—	78%	78%	—	76%
Lake Logan	050-030	Clear Fork	the basin upstream of the lake, starting at RM 2.07	TP (lbs • season^{-1})	Allocation	32	38	115	1569	195	1949
					% Reduction	0%	-62%	38%	38%	—	30%

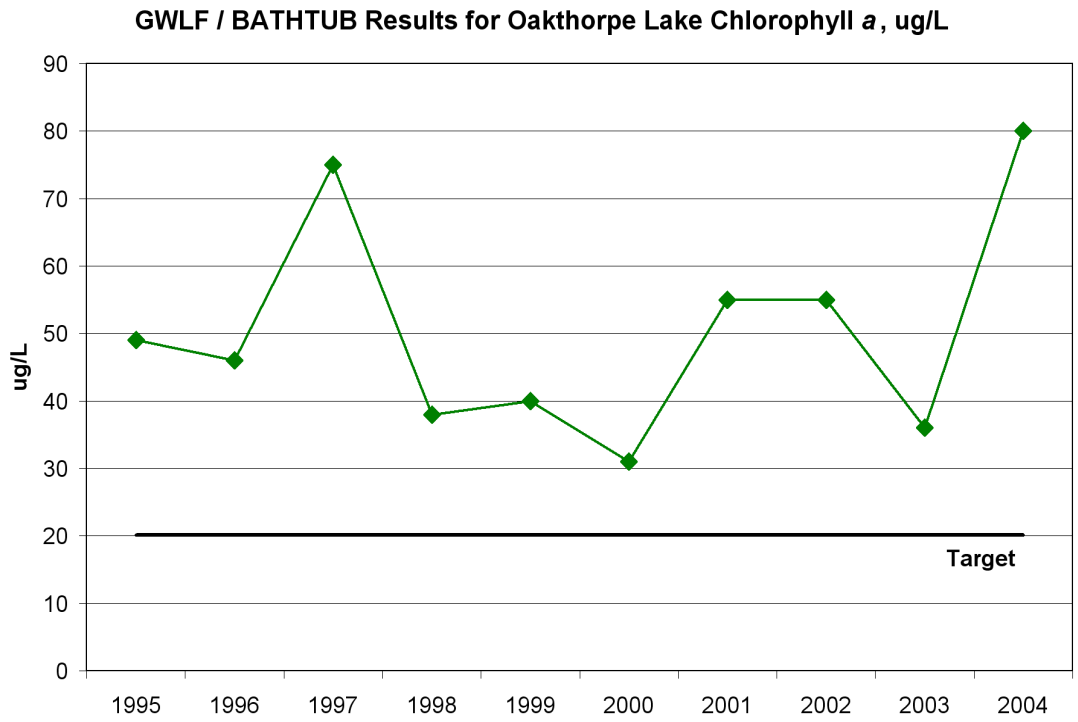


Figure B.1 BATHTUB / GWLF chlorophyll *a* in Oakthorpe Lake, calculated from current loads, 1995-2004.

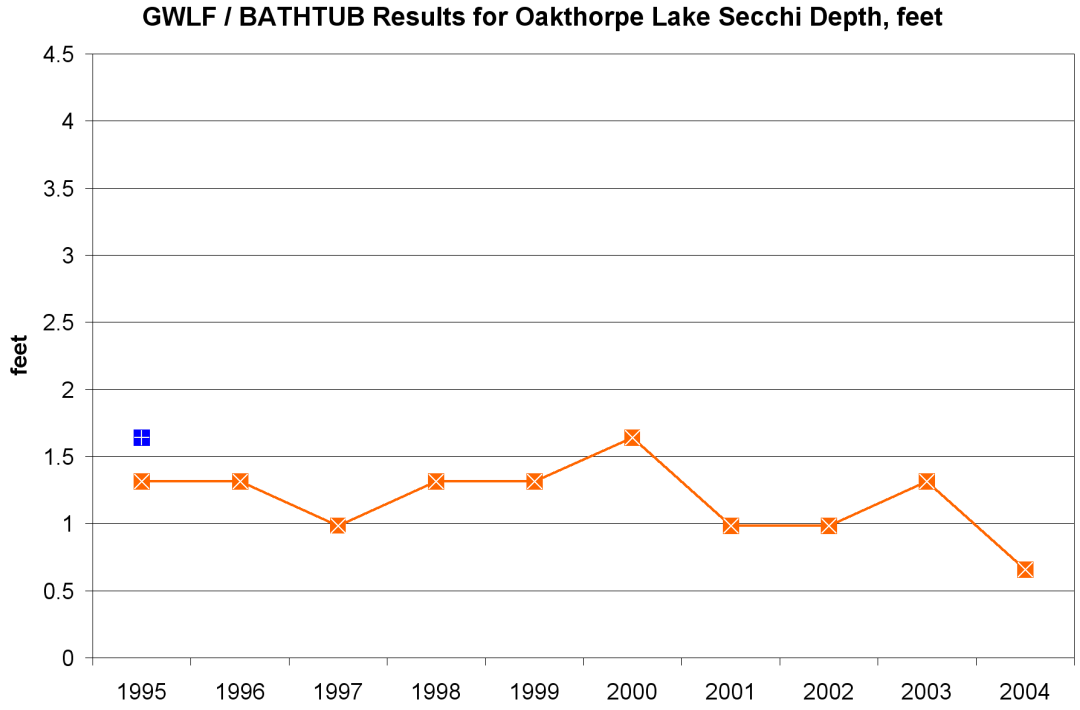


Figure B.2 BATHTUB / GWLF Secchi depth in Oakthorpe Lake, calculated from current loads, 1995-2004. (The blue square is a 1995 Secchi depth measurement.)

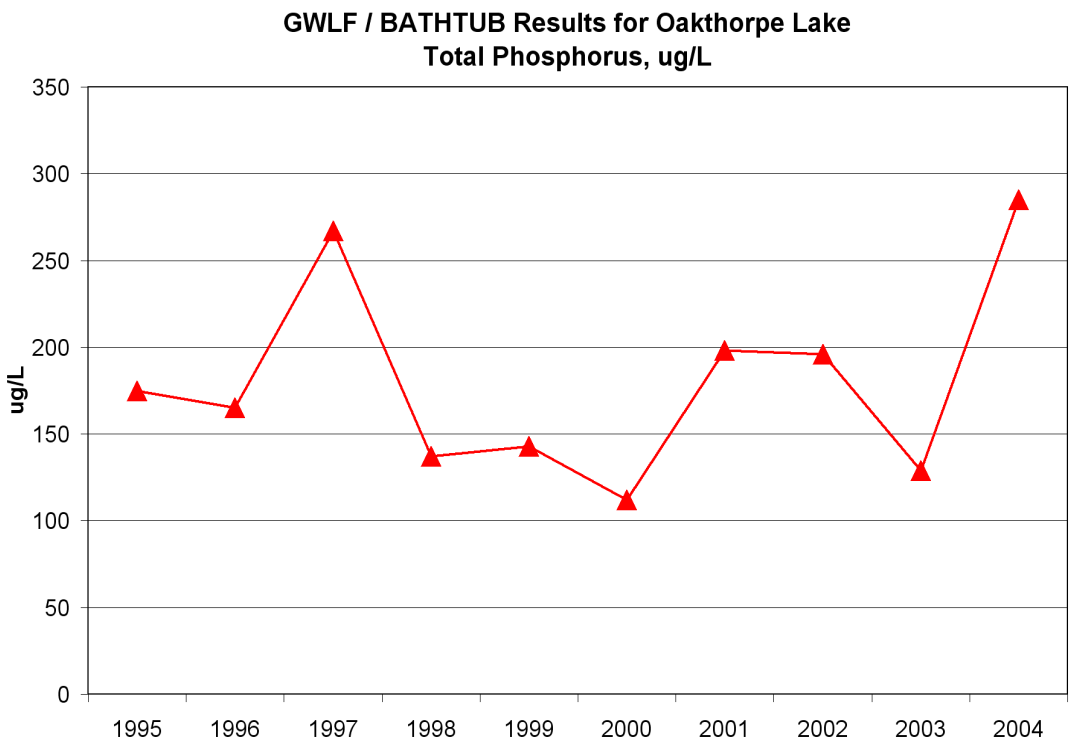


Figure B.3 BATHTUB / GWLF total phosphorus concentrations in Oakthorpe Lake, calculated from current loads, 1995-2004.

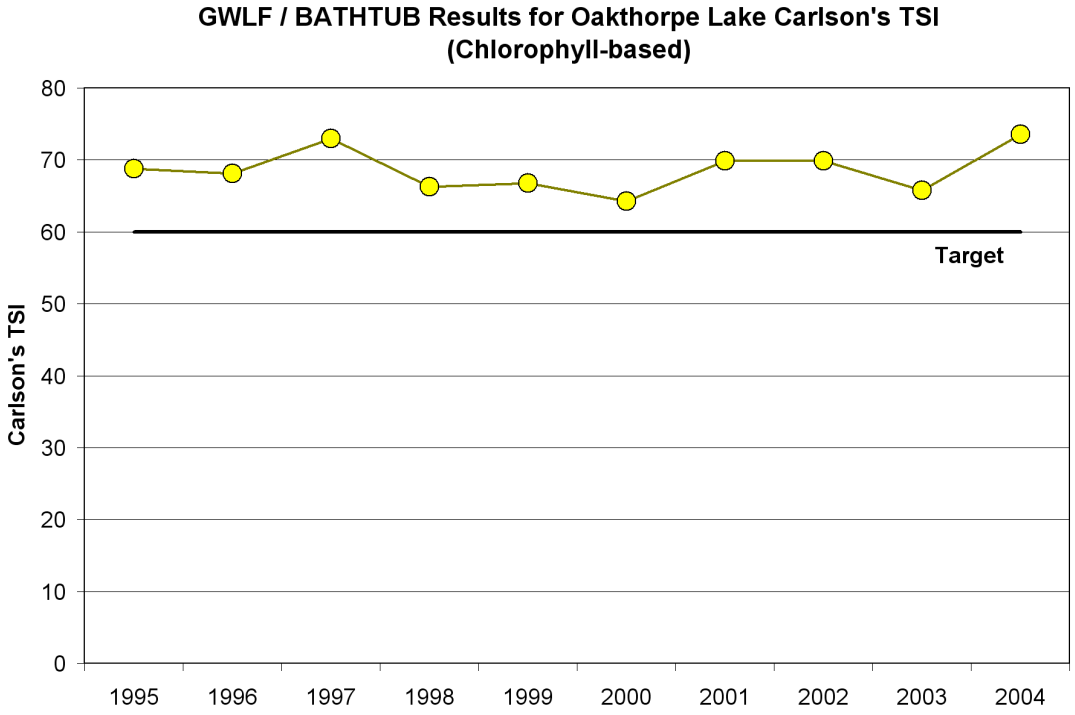


Figure B.4 BATHTUB / GWLF Carlson's TSI (chlorophyll-based) for Oakthorpe Lake, calculated from current loads, 1995-2004.

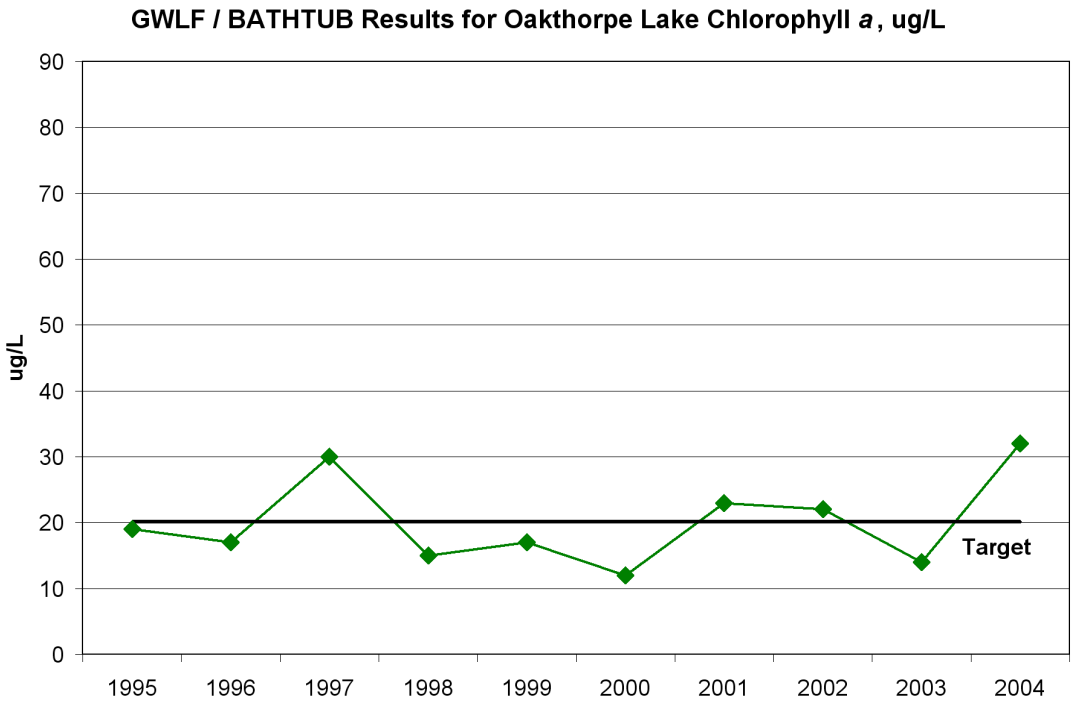


Figure B.5 BATHTUB / GWLF chlorophyll *a* in Oakthorpe Lake, calculated from TMDL-reduced loads, 1995-2004.

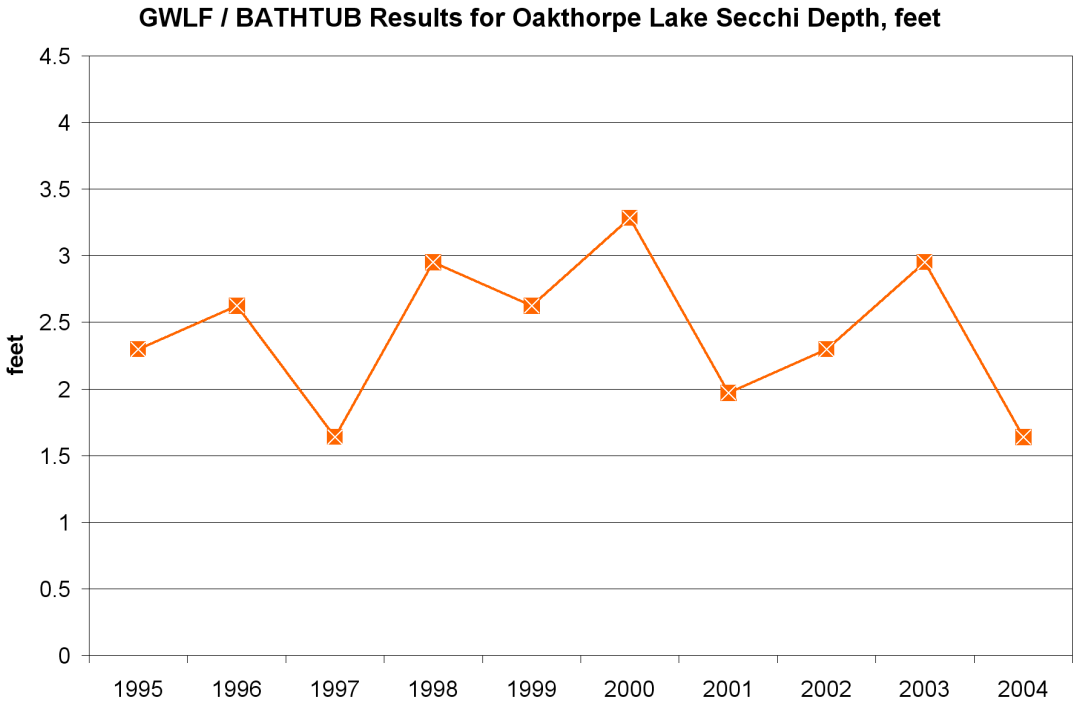


Figure B.6 BATHTUB / GWLF Secchi depth in Oakthorpe Lake, calculated from TMDL-reduced loads, 1995-2004.

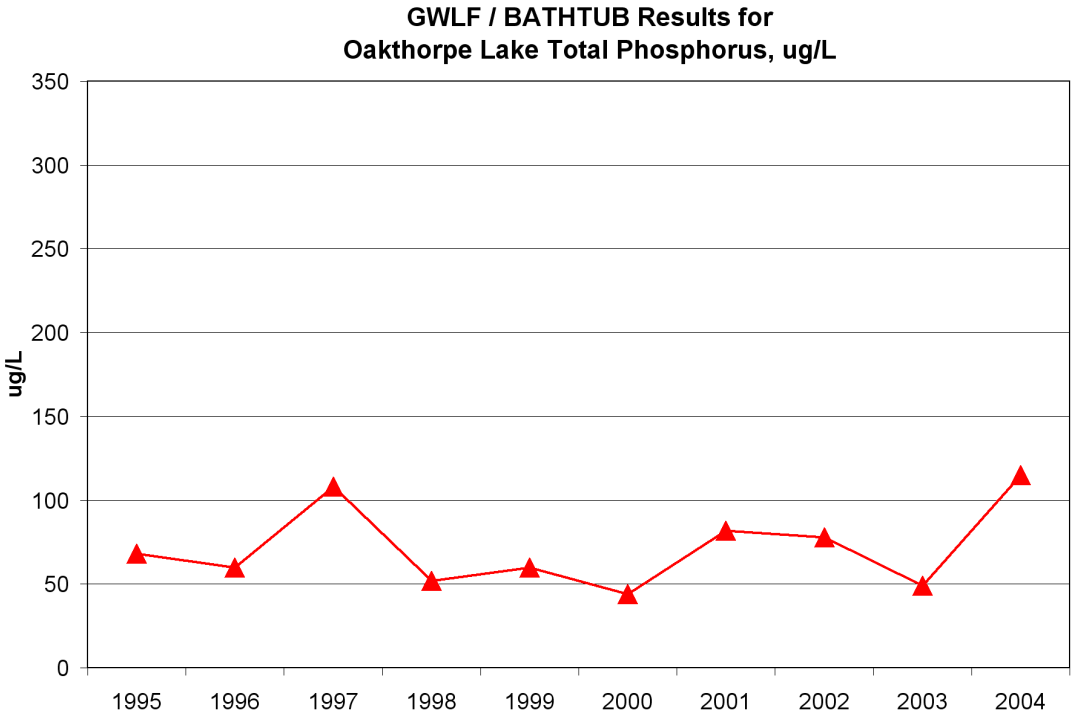


Figure B.7 BATHTUB / GWLF total phosphorus concentrations in Oakthorpe Lake, calculated from TMDL-reduced loads, 1995-2004.

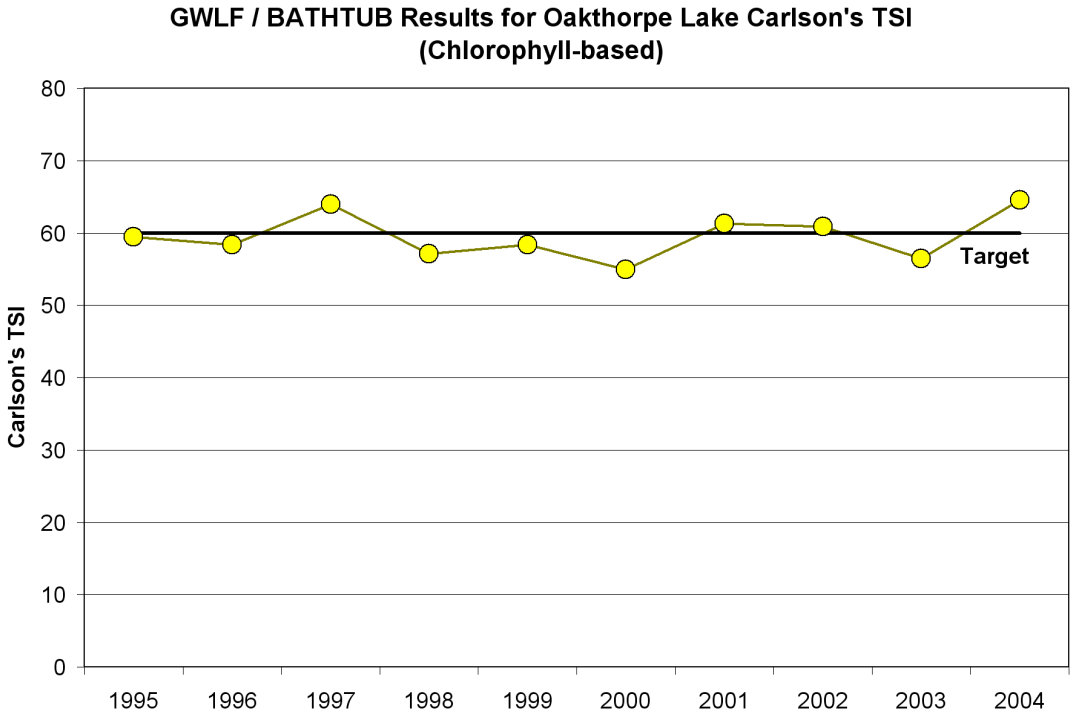


Figure B.8 BATHTUB / GWLF Carlson's TSI (chlorophyll-based) for Oakthorpe Lake, calculated from TMDL-reduced loads, 1995-2004.

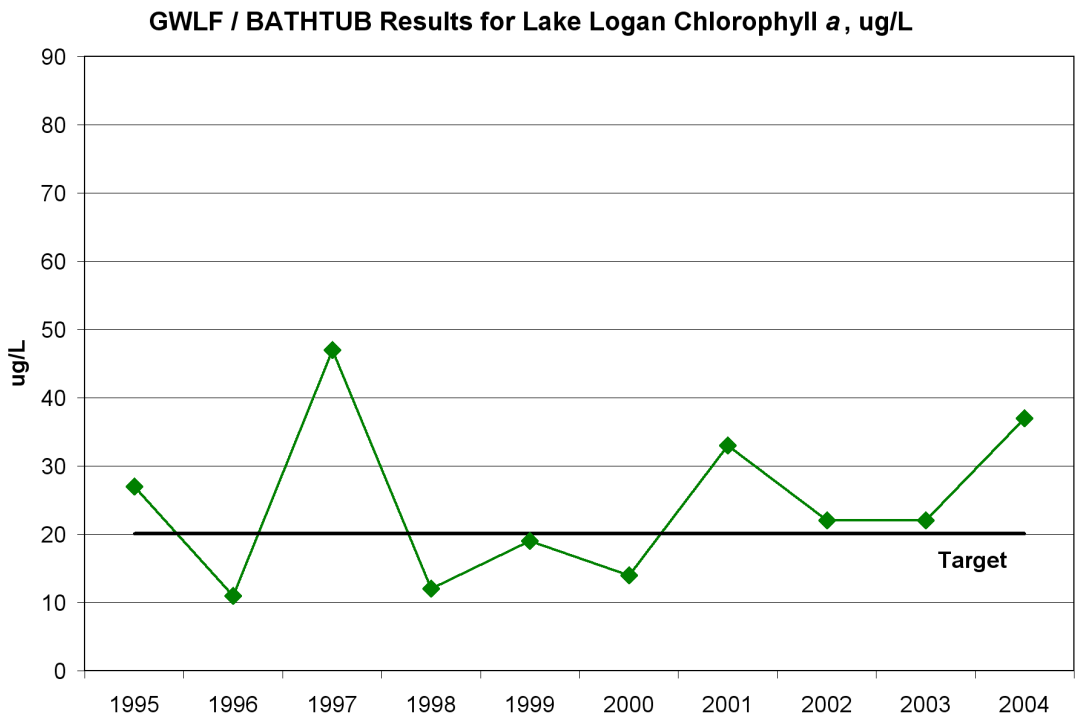


Figure B.9 BATHTUB / GWLF chlorophyll *a* in Lake Logan, calculated from current loads, 1995-2004.

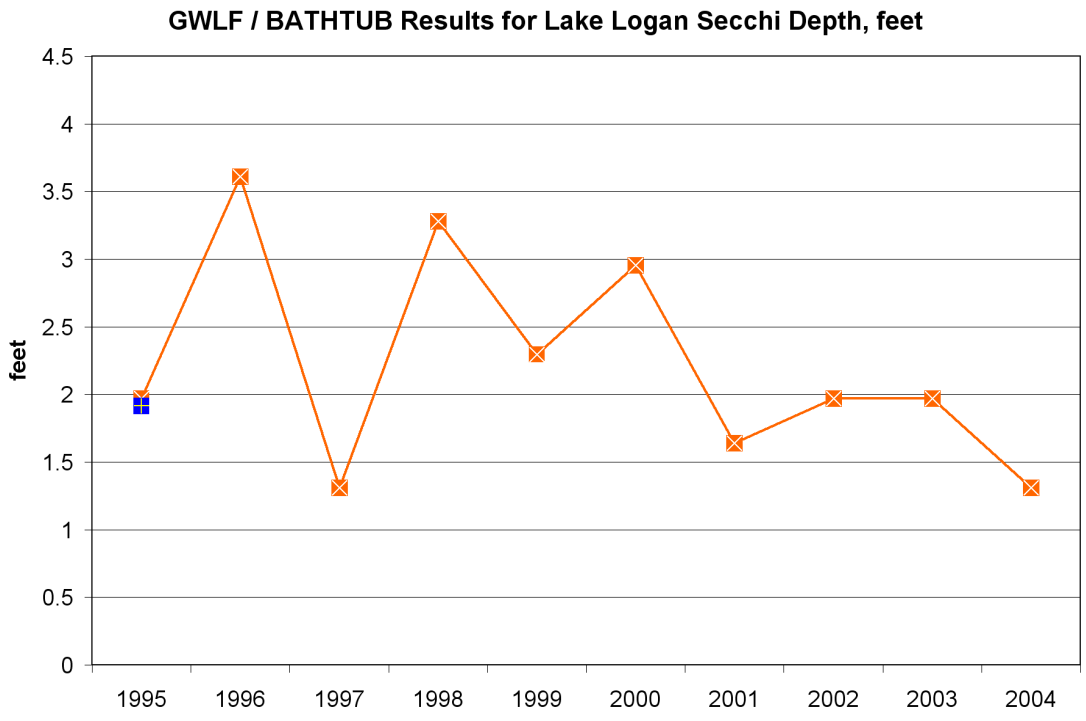


Figure B.10 BATHTUB / GWLF Secchi depth in Lake Logan, calculated from current loads, 1995-2004. (The blue square is a 1995 Secchi depth measurement.)

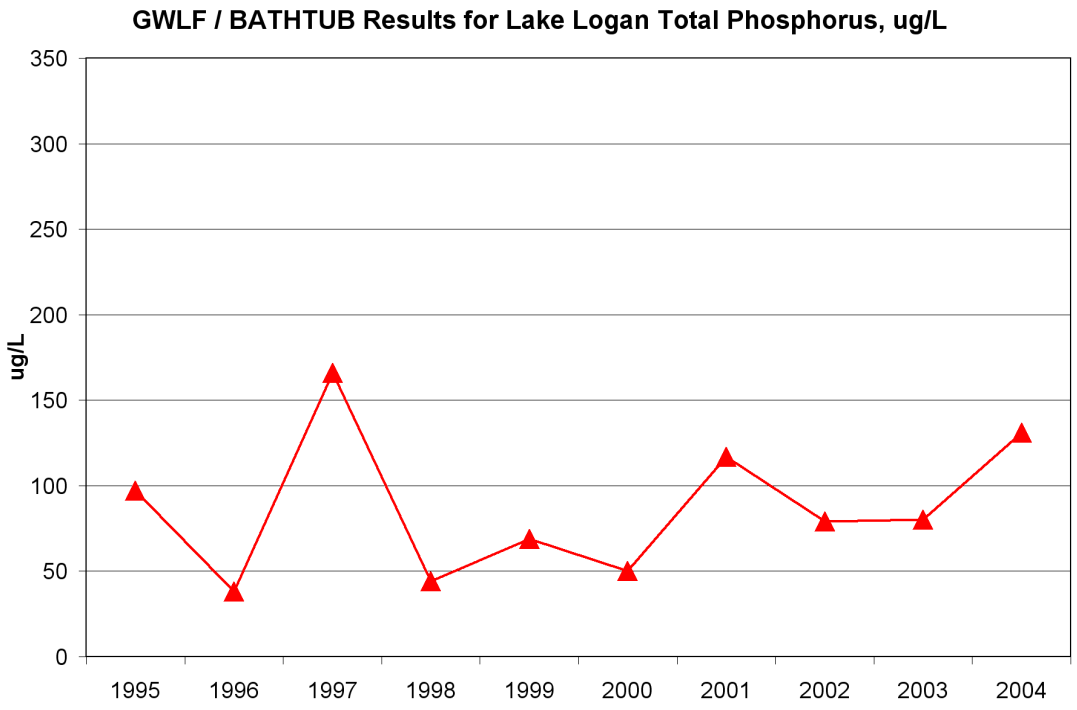


Figure B.11 BATHTUB / GWLF total phosphorus concentrations in Lake Logan, calculated from current loads, 1995-2004.

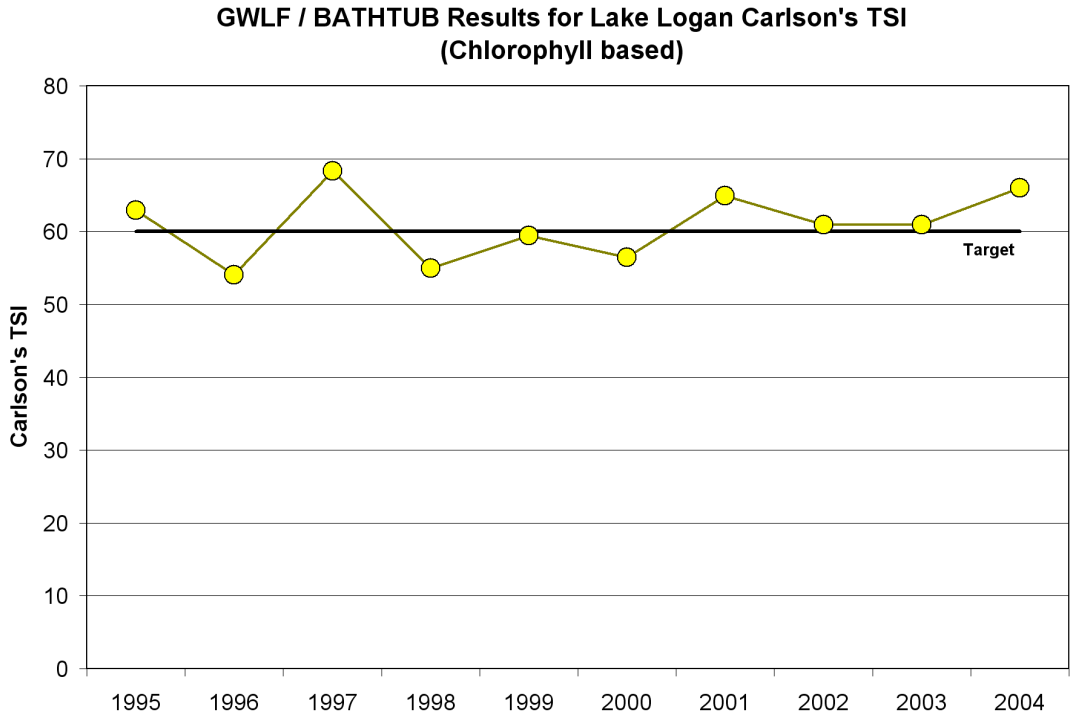


Figure B.12 BATHTUB / GWLF Carlson's TSI (chlorophyll-based) for Lake Logan, calculated from current loads, 1995-2004.

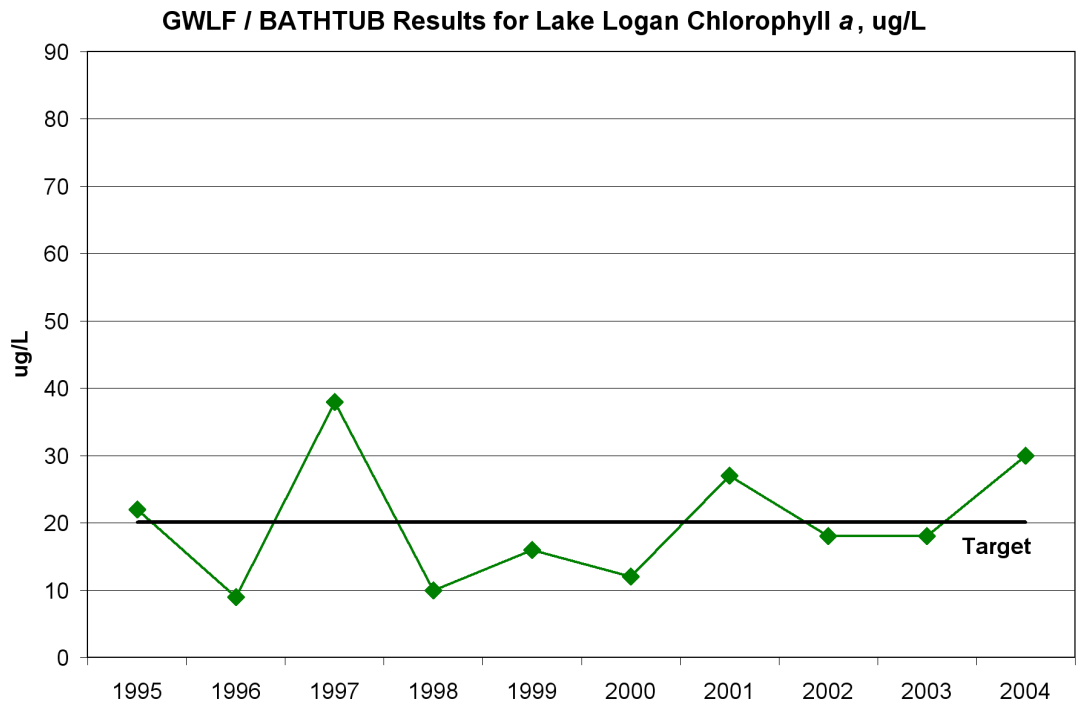


Figure B.13 BATHTUB / GWLF chlorophyll *a* in Lake Logan, calculated from TMDL-reduced loads, 1995-2004.

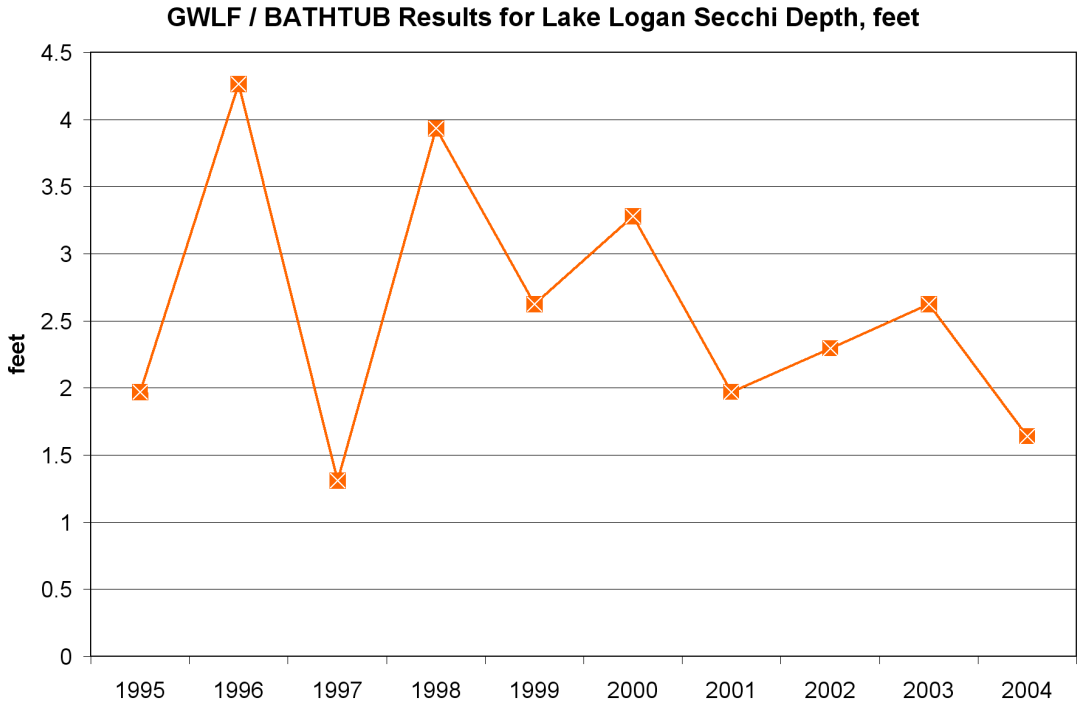


Figure B.14 BATHTUB / GWLF Secchi depth in Lake Logan, calculated from TMDL-reduced loads, 1995-2004.

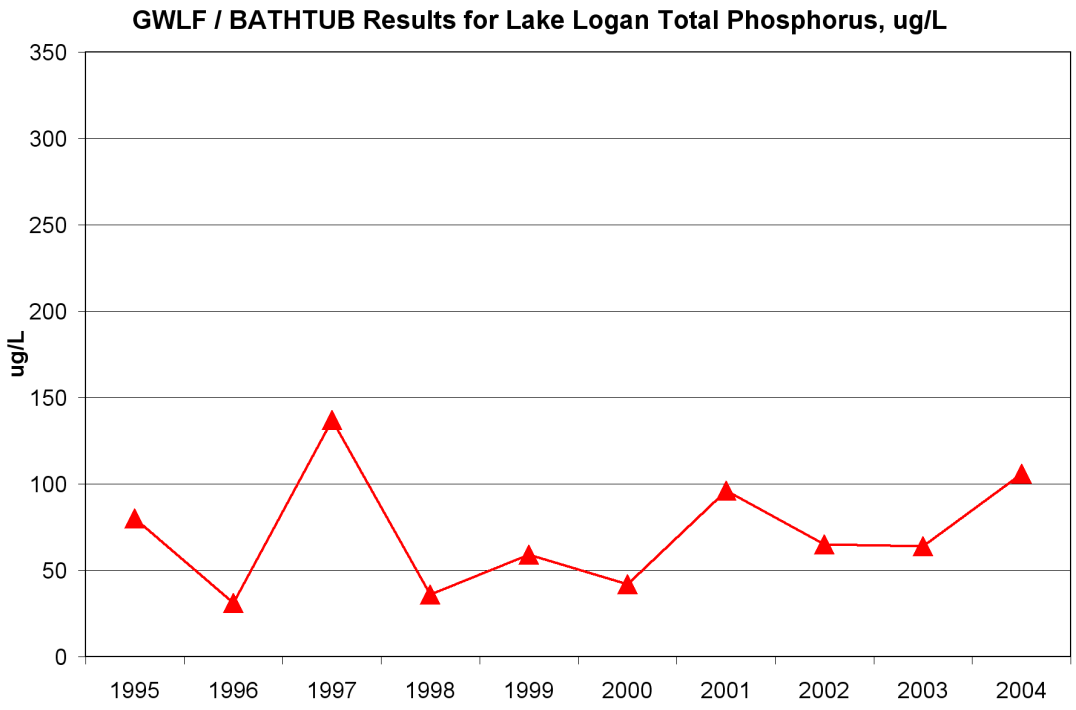


Figure B.15 BATHTUB / GWLF total phosphorus concentrations in Lake Logan, calculated from TMDL-reduced loads, 1995-2004.

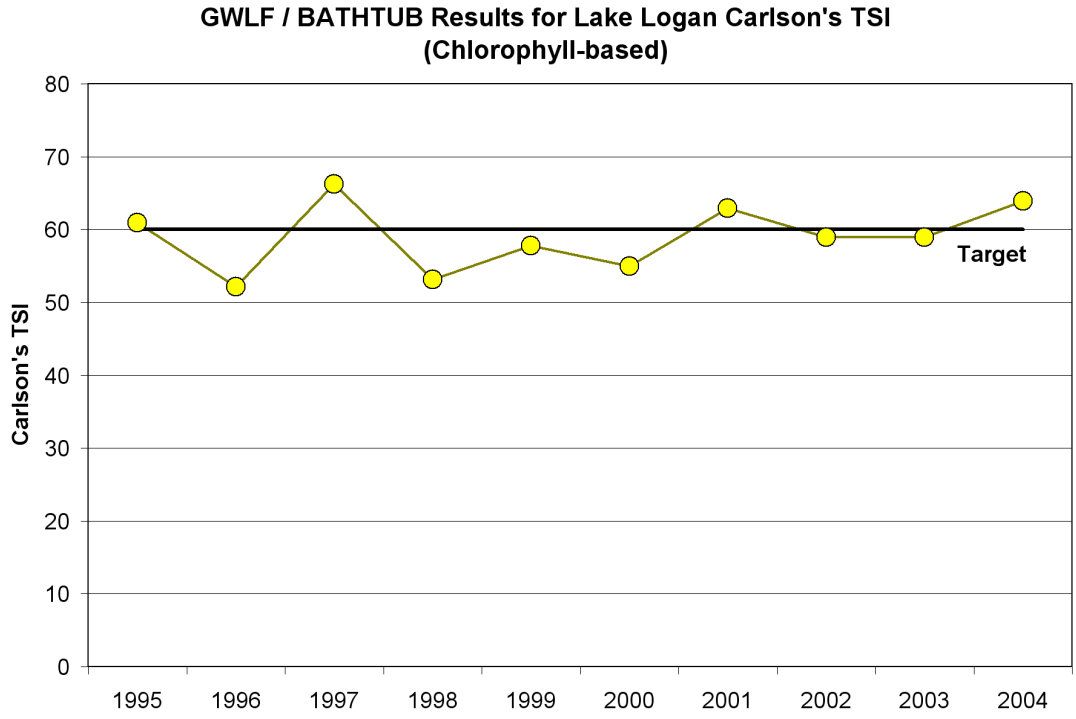


Figure B.16 BATHTUB / GWLF Carlson's TSI (chlorophyll-based) for Lake Logan, calculated from TMDL-reduced loads, 1995-2004.