Water Quality Modeling Report

Armstrong Lake, Markgrafs Lake, and Wilmes Lake

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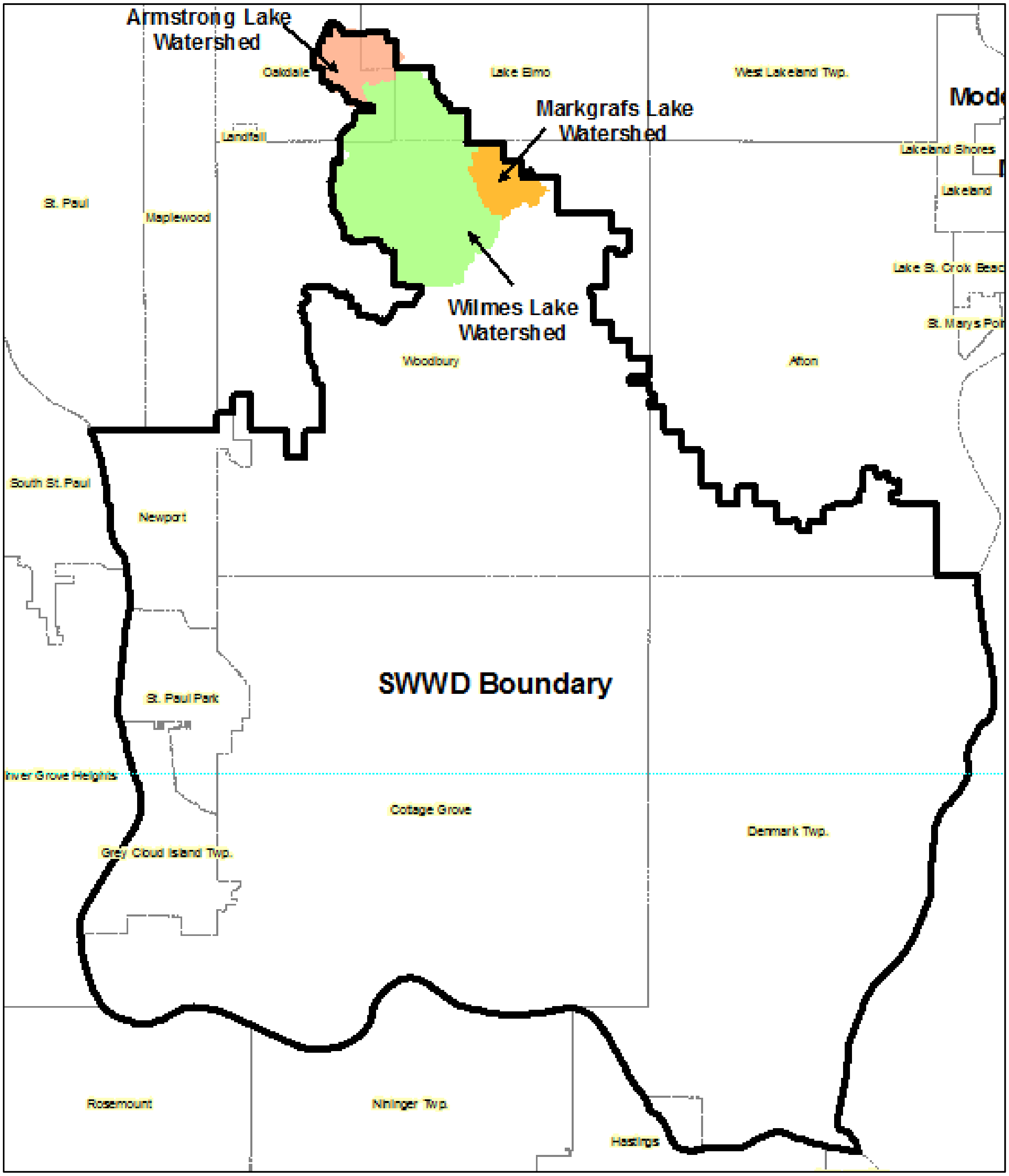
1.0 INTRODUCTION

Armstrong, Markgrafs, and Wilmes lakes form part of a multi-lake system located within southern Washington County in the Minneapolis-St. Paul metropolitan area of eastern Minnesota (see **Figure 1**). The three lakes are managed by the South Washington Watershed District (SWWD).

In 2006, Markgrafs Lake and Wilmes Lake were placed on the Minnesota Pollution Control Agency's (MPCAs) List of Impaired Waters (i.e., 303(d) list) for Nutrient Eutrophication/Biological Indicators. Both are currently listed in Category 5 with no Total Maximum Daily Load (TMDL) plan having been approved. As of the 2012 draft 303(d) list, Armstrong Lake is not currently listed as impaired. In an effort to prevent continued degradation of these three lakes, the SWWD requested the assistance of Houston Engineering, Inc. (HEI) to evaluate existing data and develop models to describe the stresses imposed upon the three lakes. The analyses are necessary to establish the load capacity of the lakes and allocate the loads, thereby establishing a basis to manage the lakes.

This report presents an assessment of the water quality for Armstrong, Markgrafs, and Wilmes lakes, including the estimated water budgets and total phosphorus mass balances for three years of monitoring data, 2009-2011. Watershed loading and in-lake eutrophication response models were created for each of the watersheds and lakes for the summer growing season (June 1 through September 30) using monitoring data for model calibration and validation. Once the models were calibrated and validated, a long-term precipitation record was used within the watershed model to simulate 50-years of runoff volume and load. These loads along with other external sources were then used as input to the receiving water model to develop the phosphorus loading capacities for the three lakes. Multiple model runs for various loading reduction scenarios were completed to identify the loading capacity necessary to achieve both the State numeric water quality standard and the SWWD's water quality goal for total phosphorus concentrations of each lake. Finally, the report presents implementation strategies to achieve the loading capacity by allocating the loads amongst the various sources in the watershed.

Figure 1. Armstrong Lake, Markgrafs Lake, and Wilmes Lake Watersheds.

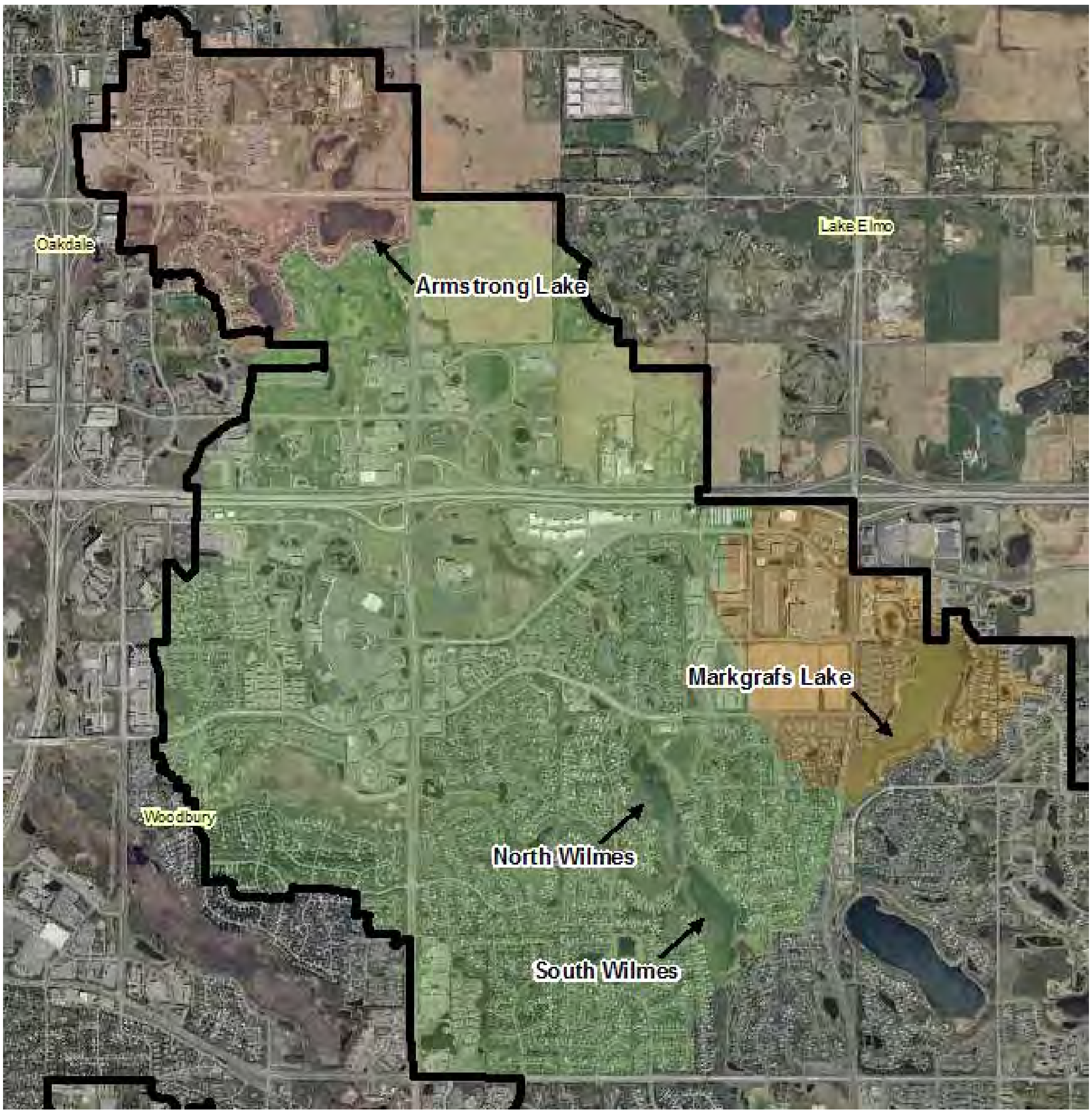


HoustonEngineering Inc.

2.0 LAKE INFORMATION

All three of the lakes included in this study are located in the North Central Hardwood Forests ecoregion at the eastern edge of the Minneapolis-St. Paul metropolitan area in southern Washington County. Armstrong Lake and Markgrafs Lake both lie upstream of Wilmes Lake (see Figure 2). The contributing drainage area to the lakes is highly urbanized.

Figure 2. Armstrong Lake, Markgrafs Lake, and Wilmes Lake and their contributing drainage areas.



2.1 Lake Descriptions

2.1.1 Armstrong Lake

Armstrong Lake is a 28.7-acre lake located within the cities of Lake Elmo and Oakdale. The lake and its watershed form the headwaters of a multi-lake system, contributing water downstream to multiple smaller wetlands and eventually to the northern basin of Wilmes Lake. Armstrong Lake is divided into a north and south basin by Washington County Road (CR) 10. A 36-inch reinforced concrete pipe (RCP) culvert exists under the road, hydraulically connecting the two basins. The northern basin is located within the City of Lake Elmo and has a maximum depth of 3 feet. The southern basin is located within the City of Oakdale and has a maximum depth of 5 feet. Armstrong Lake has a contributing watershed of 487 acres with inflows coming predominantly from storage areas to the west, consisting of stormwater ponds and wetlands associated with commercial and residential development. The majority of the watershed is developed, comprised mostly of low density residential land use with some farm areas. There is no public access to Armstrong Lake. The lake is used for wildlife viewing and aesthetics. Non-motorized boating is possible.

Armstrong Lake is identified by the Minnesota Department of Natural Resources (MnDNR) as Public Water No. 82-0116-00. The water levels on Armstrong Lake are controlled by two 18-inch pipes in the southern basin set at upstream invert elevations of 1017.35 and 1017.49 (NAVD 1988). The Ordinary High Water Level (OHWL) for Armstrong Lake is at an elevation of 1019.25 (NAVD 1988). The lake shows no overall trend in water level since 2000. The maximum water level fluctuation for Armstrong Lake over this period is slightly less than 3 feet. Water quality samples are collected from the southern basin because of its greater depth. At the request of the South Washington Watershed District (SWWD), this study focuses on the southern basin of Armstrong Lake. With a maximum depth of 5 feet, Armstrong Lake is entirely littoral. According to modeling completed in this study, Armstrong Lake has an average hydraulic residence time of 13 months. Because of the shallow nature of the lake, it does not thermally stratify for any extended period of time.

2.1.2 Markgrafs Lake

Markgrafs Lake is a 40.5-acre lake located in the City of Woodbury. This lake and its watershed contribute water downstream to multiple smaller wetlands and eventually to the south basin of

Wilmes Lake or, at times of high flow, to Powers Lake via a channel and/or a pump. High flow conditions occur when the water in Markgrafs Lake rises greater than 4.12 feet. This does not occur in a 2-year storm event. The City of Woodbury confirmed that flow has been directed to Wilmes Lake with the exception of a 100-year storm event, occurring in 2005. The lake has a maximum depth of 8 feet. Markgrafs Lake has a contributing watershed of 413 acres with inflows coming from storage areas to the west, consisting of commercial and residential stormwater ponds. The watershed is almost fully developed. Commercial land use dominates the upper part of the watershed. Dense residential units surround the lake but the shoreline remains wooded. Stormwater treatment ponds receive runoff from the development prior to flowing into Markgrafs Lake.

Markgrafs Lake is identified by the MnDNR as Public Water No. 82-0089-00. The water levels on Markgrafs Lake are controlled by a 12-inch pipe with the upstream invert elevation set at 924.94 feet (NAVD 1988). A valve device exists downstream from the outlet so that discharge can be split to Powers or Wilmes Lakes. The OHWL for Markgrafs Lake is at an elevation of 925.44 feet (NAVD 1988). The lake shows no overall trend in water level since 2000. The maximum water level fluctuation for Markgrafs Lake over this period is slightly less than 2 feet. According to modeling completed in this study, Markgrafs Lake has an average hydraulic residence time of 2.2 years. The lake does not thermally stratify for any extended period of time.

2.1.3 Wilmes Lake

Wilmes Lake is a 34.2-acre lake located within the City of Woodbury. Wilmes Lake receives water from multiple surrounding waterbodies, including Armstrong Lake, Markgrafs Lake, and during high flows when a lift station is operating, Powers Lake. Wilmes Lake contributes water downstream to Colby Lake. Wilmes Lake is divided into a north and south basin by a recreational trail. A 48-inch RCP culvert exists under a trail, hydraulically connecting the two basins during low flows. During times of high flow, water can pass from the north basin to the south by overtopping the trail. The north basin has a maximum depth of 7 feet. The south basin has a maximum depth of 18 feet. For the purposes of this study, the two portions of the Wilmes Lake are referred to as, North Wilmes Lake and South Wilmes Lake. Including drainage from Armstrong and Markgrafs lakes, Wilmes Lake has a contributing watershed of approximately

1,000 acres. The watershed surrounding Wilmes Lake is entirely developed and comprised of low density residential development.

Wilmes Lake is identified by the MnDNR as Public Water No. 82-0090-00. The water levels on Wilmes Lake are controlled by at 7-foot weir on the southern basin, with a crest elevation of 902.6 feet (NAVD 1988). The OHWL for Wilmes Lake is 902.75 feet (NAVD 1988). The lake shows no overall trend in water level since 2000. However, Wilmes Lake levels show the largest fluctuation in any given year (3.57 feet in 2009) compared to the other lakes in this study with long-term lake level data (collected in the north basin). Water quality samples were collected from the northern basin in 1994-1995, and in the southern basin from 1996 to the present. In this study, the two basins (north and south) are modeled separately. According to modeling completed in this study, North Wilmes Lake has an average hydraulic residence time of 3.1 months, and South Wilmes has an average hydraulic residence time of 0.6 months.

2.2 Classification

According to the SWWD Watershed Management Plan (WMP), Armstrong Lake and Wilmes Lake are managed as Class B waters, while Markgrafs Lake is managed as a Class C water.

Class B waters generally demonstrate a reasonable chance of attaining the in-lake phosphorus goal established by the SWWD and of meeting the designated uses. Class B lakes are defined as generally exhibiting long term phosphorus concentrations between 60 and 100 ppb for the growing season. The natural lake ecosystem of Class B lakes may be considered as moderately disturbed. Lakes classified as Class B are those that may support some fishery, but are also well suited for supporting wildlife, aesthetic enjoyment, and boating or other special purposes.

Class C waters, without considerable measures, lack a reasonable potential to attain the in-lake phosphorus goal established by the SWWD for meeting designated use. Class C lakes exhibit exceptionally high nutrient enrichment and long-term monitoring data generally reflect phosphorus concentrations greater than 100 ppb as an average growing season concentration. The natural ecosystem is severely disturbed and considered out of balance. Due to their physical and nutrient characteristics, these lakes are limited in their recreational role and are best suited for flood control, landscape aesthetics, and wildlife habitat.

According to the SWWD WMP, all three of the lakes in this study are classified as Class 2B waters by the Minnesota Pollution Control Agency. Minnesota Rules (MR) 7050.0222 state that Class 2B surface waters shall be such as to permit the propagation and maintenance of a healthy community of cool or warm water sport or commercial fish and associated aquatic life, and their habitats. These waters shall be suitable for aquatic recreation of all kinds, including bathing, for which the waters may be usable. This class of surface water is not protected as a source of drinking water.

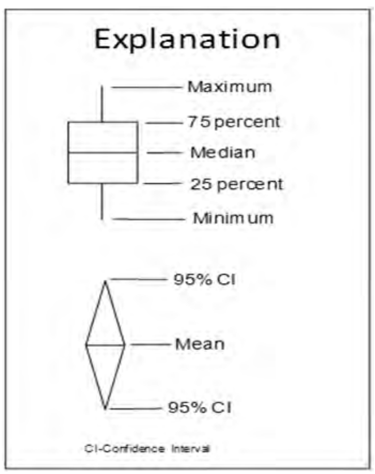
With maximum depths of 5 feet, 8 feet, and 18 feet, respectively, Armstrong, Markgrafs, and Wilmes are all considered littoral shallow lakes. Applicable state Class 2B conventional water quality standards for shallow lakes in the North Central Hardwood Forest Ecoregion include dissolved oxygen (DO), pH, temperature, and eutrophication (total phosphorus [TP], chlorophyll-*a* [chl-*a*], and Secchi depth [SD]). TP is the primary stressor causing the use impairment. The applicable MPCA eutrophication numeric standards expressed as the June 1 through September 30 average value for a near-surface (epilimnetic) samples are: 1) TP should not exceed 60 micrograms per liter (µg/L); 2) chl-*a* should not exceed 20 µg/L; and 3) SD should not be less than 1.0 meter. Eutrophication standards are compared to data averaged over the summer season (June through September). Exceedance of the TP and either the chl-a or SD standard is required to indicate a polluted condition. Based on the causal relationship between these three parameters, exemplified in the Carlson Trophic State Index (TSI), by meeting the TP water quality standard, all other standards can likewise be assumed to be met. This report shows analyses for all three parameters. However, the focus of the loading capacity calculations is solely based on TP concentrations in each of the lakes.

2.3 Existing Water Quality

The water quality of the three lakes has been assessed through monitoring by various agencies and volunteers since 1998 for Armstrong Lake, 1994 for Markgrafs Lake, and 1994 for Wilmes Lake. All samples were collected in the upper three feet of each lake. Water quality samples were collected in Wilmes Lake from the north basin in 1994-1996, and from the south basin in 1996-2011. Monitoring of the three lakes continues through support from the SWWD. For the purposes of this study, water quality and surface water flow data were needed to simulate conditions within the watersheds and the individual lakes. The time period used for model development, calibration, and validation includes data from June 1 through September 30 (summer season) from 2009 through 2011 (study period). The summer season is used to be consistent with the averaging period for the numeric standards.

This section summarizes the available water quality data for each of the three lakes. For each lake, a table is included, which presents the mean and median TP, chl-*a*, and SD for each of the three lakes, calculated for the summer season of the study period. Also included in the table are the respective TSIs, computed using the mean summer season value for each parameter (Carlson 1977). Finally, graphs are presented to illustrate the monitoring data statistically. All data are summarized using box and whisker plots. **Figure 3** shows how to interpret these plots. The top of the box represents the value that 75 percent of observations are at or below, while the bottom of the box represents the value that 25 percent of all observations are at or below. The line through the middle is the median value and the minimum and maximum values are represented by the lower and upper ends of the stem in the box. The diamond shape represents the data using parametric statistics (i.e., the mean value and upper and lower values of the 95 percent confidence interval).

Figure 3. Interpretation of box and whisker plots.



Graphs are provided for TP concentration, chl-*a* concentration, and SD data collected during the summer season throughout the past 12 years (2000-2011).

2.3.1 Armstrong Lake

The following section summarizes water quality data for Armstrong Lake.

Table 1. Water quality statistics for Armstrong Lake.

Year	n	Total Phosphorus (ug/L)		Chlorophyll-a (ug/L)		Secchi Disk Transparency (meters)	
		Mean	Median	Mean	Median	Mean	Median
Concentrations							
2009	8	63.3	57.5	11.9	9.9	1.1	1.1
2010	4	55.8	44.5	8.5	8.5	0.9	1.2
2011	4	37.3	37.0	6.2	5.4	1.1	1.1
Trophic State Index Computed from Mean Concentrations							
2009	8	64		55		59	
2010	4	62		52		62	
2011	4	56		48		59	

Figure 4. Armstrong Lake historic TP concentrations.

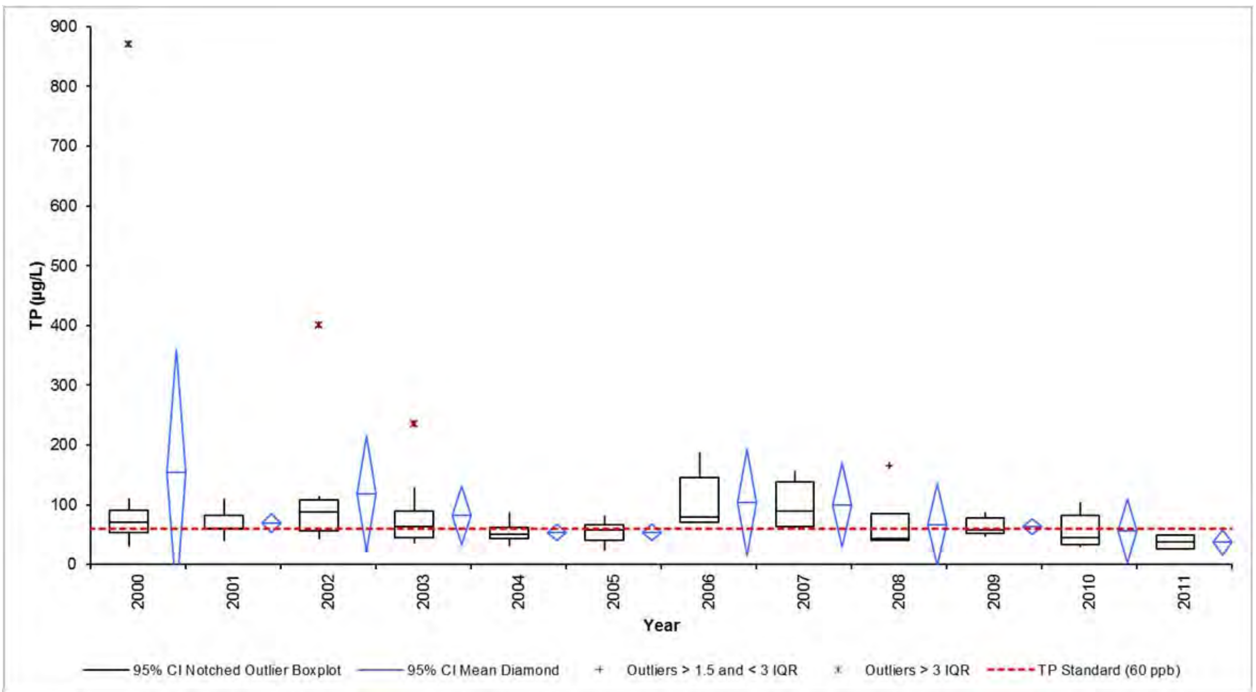


Figure 5. Armstrong Lake historic chl-a concentrations.

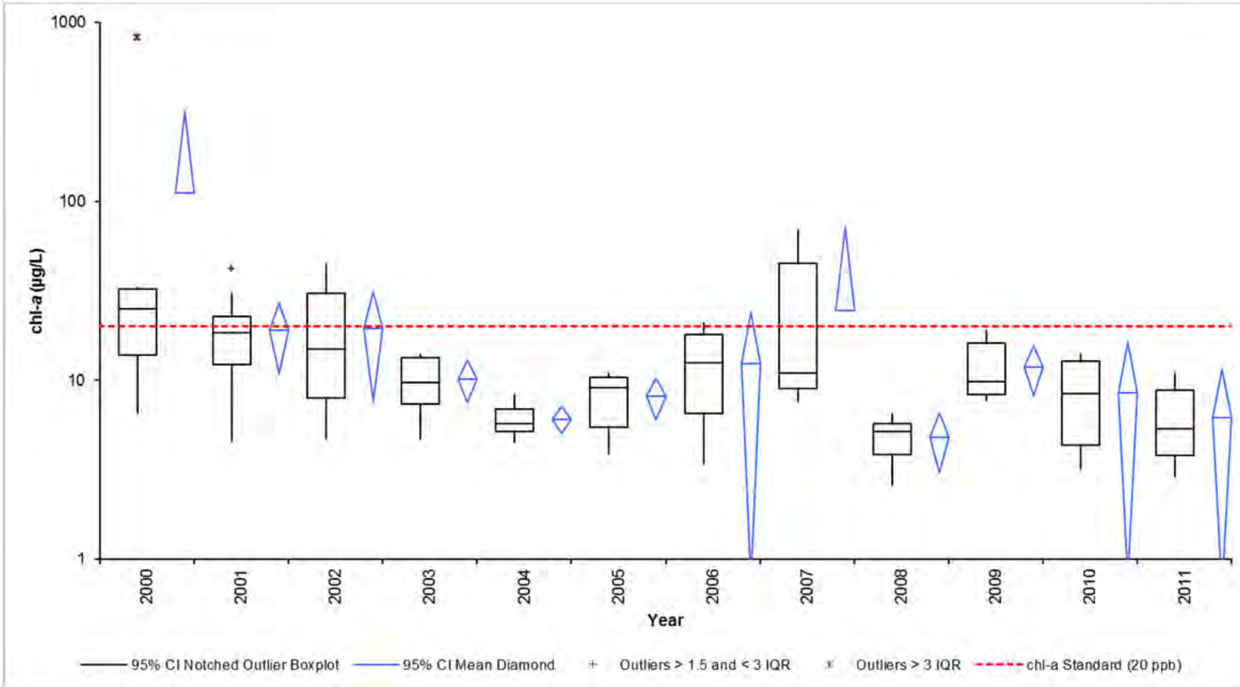
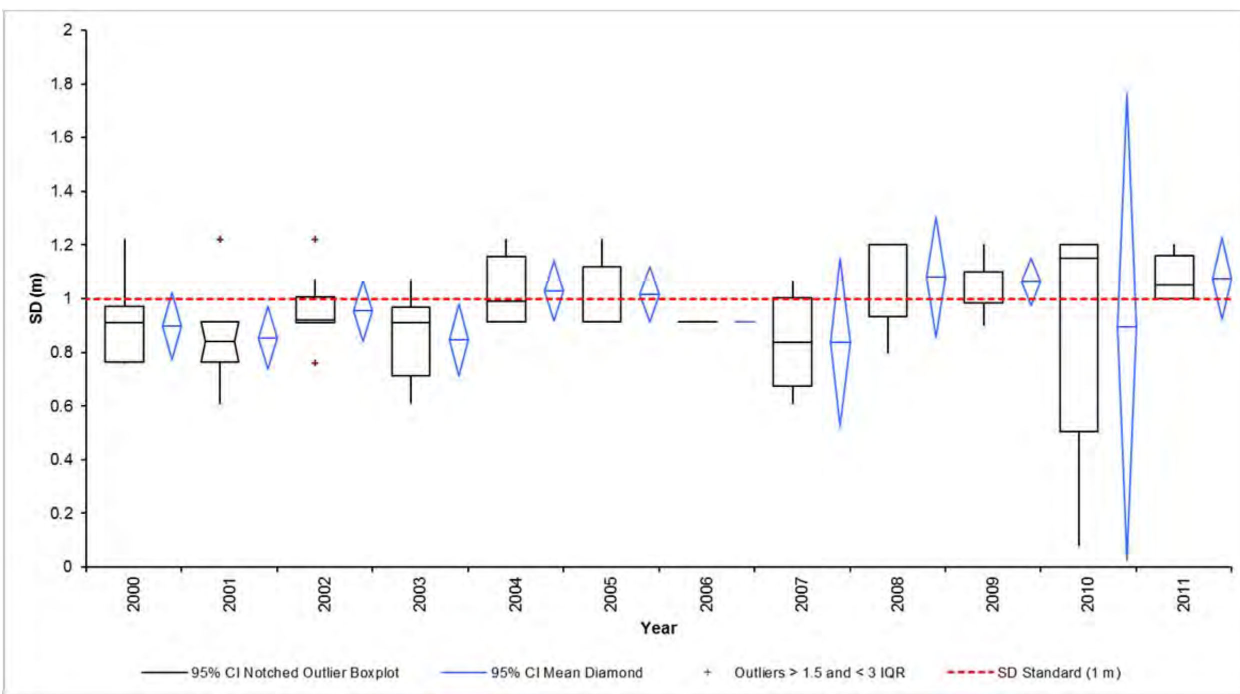


Figure 6. Armstrong Lake historic SD concentrations.



Although there is variability from season to season, **Figure 4** indicates that phosphorus concentrations for Armstrong Lake have remained relatively constant and fluctuate above and below the state water quality standard. **Figure 5** indicates chl-*a* concentrations have typically been below the water quality standard since about 2003. Similar to TP concentrations, **Figure 6** shows that SD values have fluctuated above and below the state water quality standards.

2.3.2 Markgrafs Lake

The following section summarizes water quality data for Markgrafs Lake.

Table 2. Water quality statistics for Markgrafs Lake.

Year	n	Total Phosphorus (ug/L)		Chlorophyll-a (ug/L)		Secchi Disk Transparency (meters)	
		Mean	Median	Mean	Median	Mean	Median
Concentrations							
2009	8	240.9	226.0	79.5	86.5	0.4	0.4
2010	9	223.1	227.0	172.9	140.0	0.3	0.3
2011	8	135.5	131.0	58.1	53.0	0.5	0.5
Trophic State Index Computed from Mean Concentrations							
2009	8	83		74		75	
2010	9	82		81		79	
2011	8	75		70		71	

Figure 7. Markgrafs Lake historic TP concentrations.

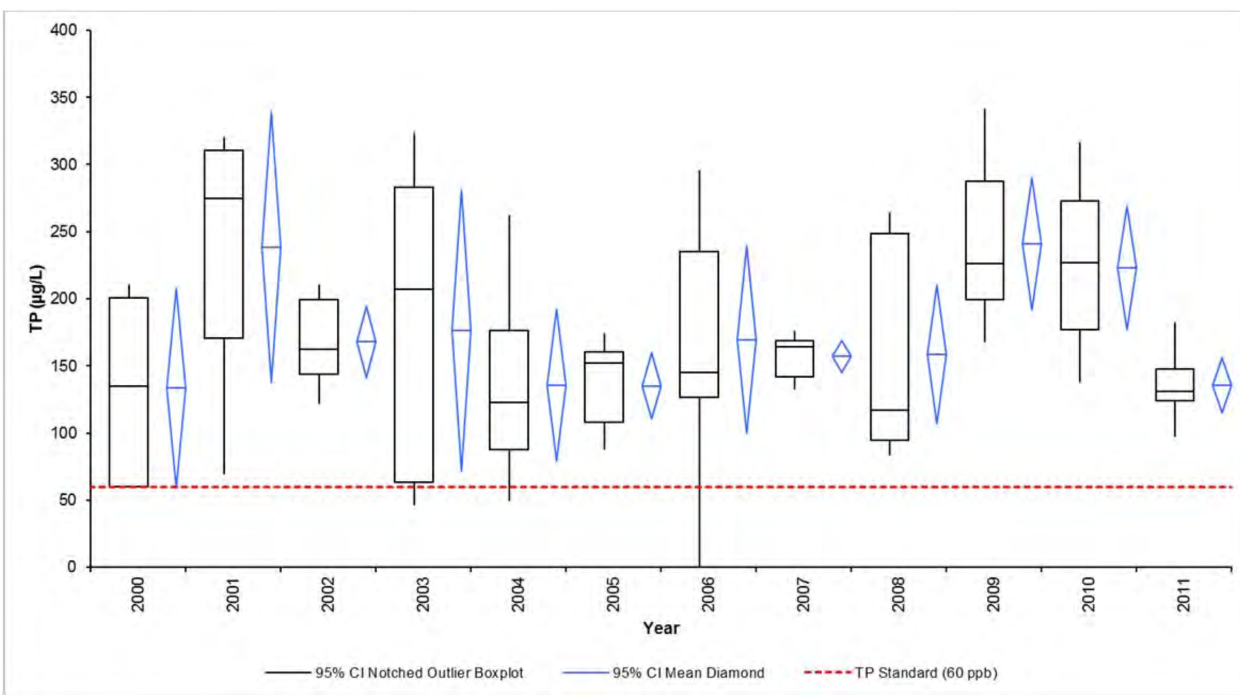


Figure 8. Markgrafs Lake historic chl-a concentrations.

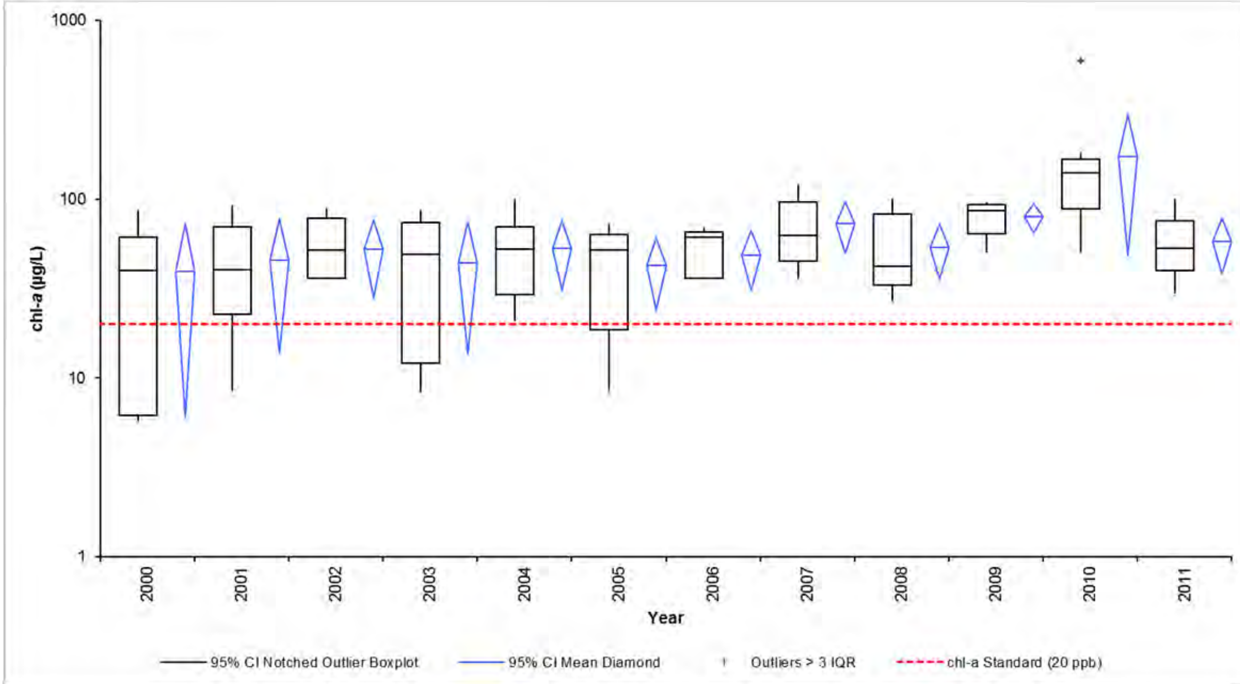
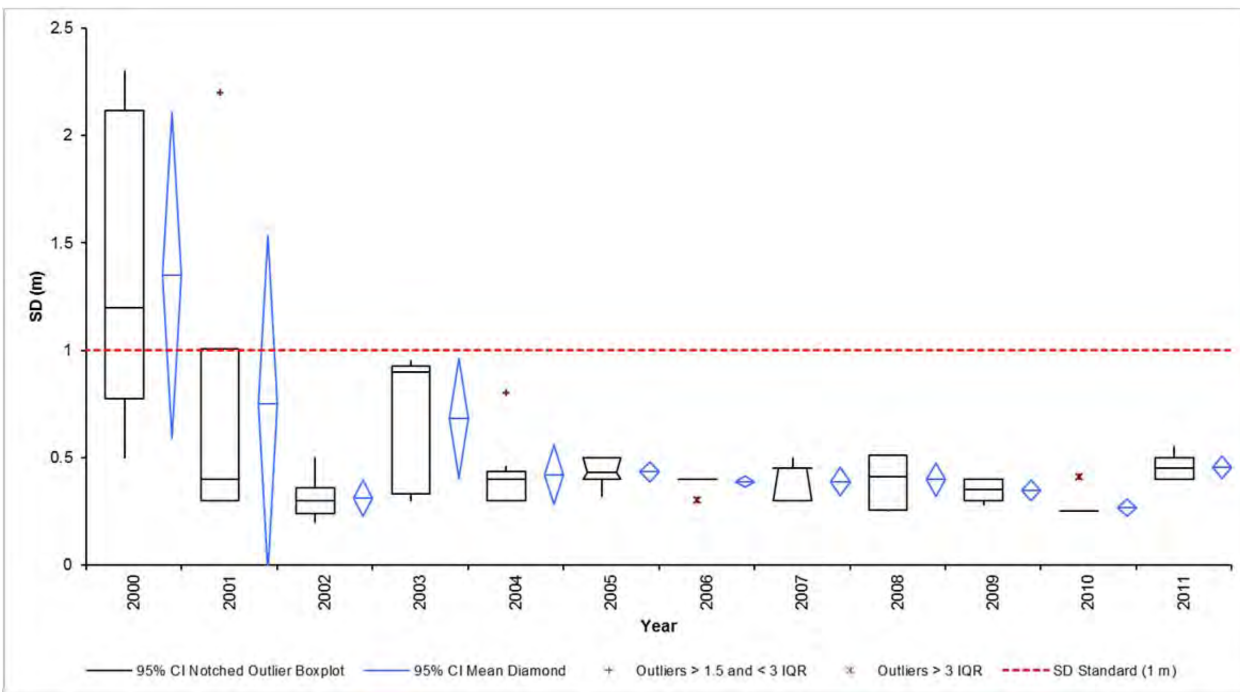


Figure 9. Markgrafs Lake historic SD concentrations.



Despite variability from season to season, **Figure 7** indicates that phosphorus concentrations have remained well above and the state water quality standard. **Figure 8** and **Figure 9** indicate that chl-*a* concentrations and SD values have both consistently failed to meet the state water quality standards since at least 2000.

2.3.3 Wilmes Lake

Because all of the water quality data collected in Wilmes since 2000 has been in the south basin, the data presented in this section represents the south basin. For modeling purposes in this study, it is assumed that the in-lake water quality is similar for both the north and south basin.

Table 3. Water quality statistics for Wilmes Lake.

Year	n	Total Phosphorus (ug/L)		Chlorophyll-a (ug/L)		Secchi Disk Transparency (meters)	
		Mean	Median	Mean	Median	Mean	Median
Concentrations							
2009	7	62.7	58.0	19.5	21.0	1.6	1.4
2010	6	95.5	107.5	39.7	27.0	1.4	1.3
2011	8	63.3	53.0	16.2	17.0	1.8	1.7
Trophic State Index Computed from Mean Concentrations							
2009	7	64		60		53	
2010	6	70		67		55	
2011	8	64		58		52	

Figure 10. Wilmes Lake historic TP concentrations.

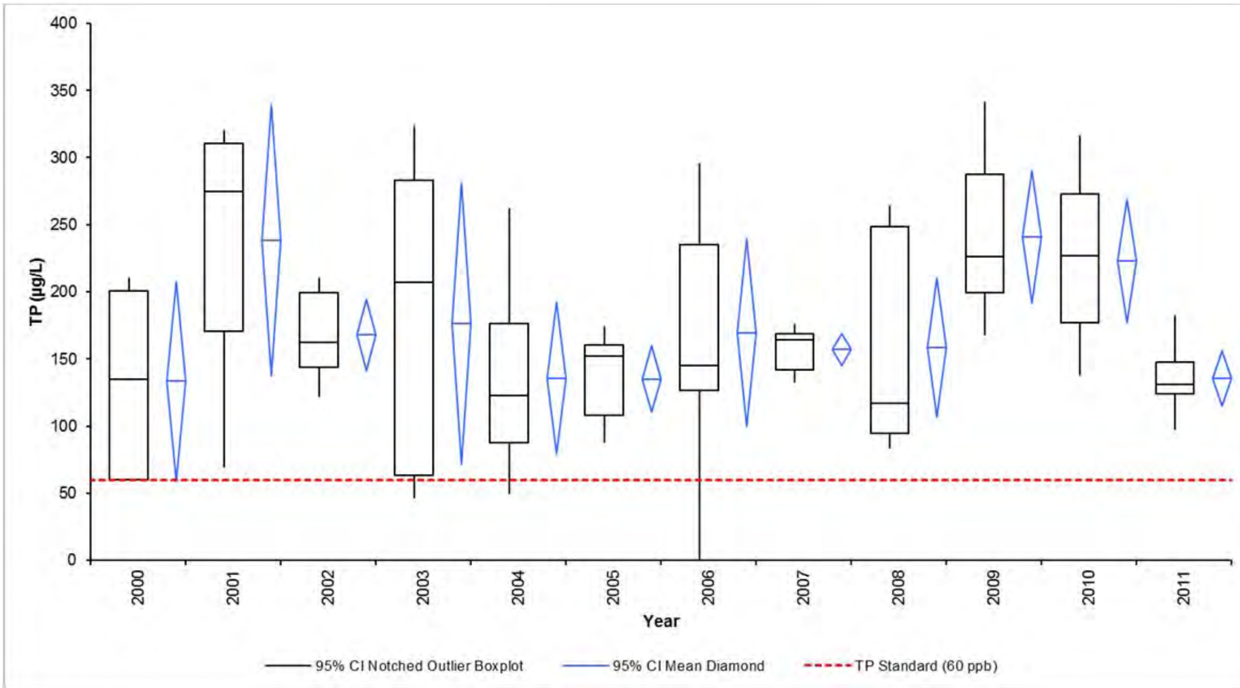


Figure 11. Wilmes Lake historic chl-a concentrations.

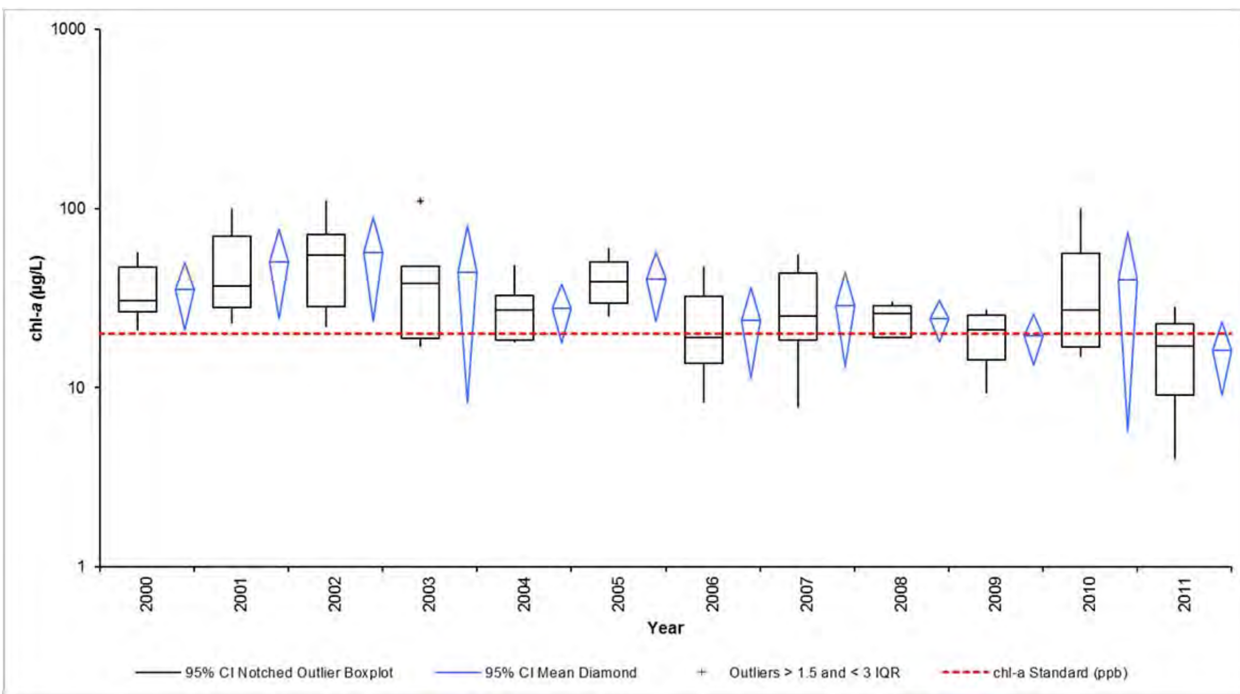
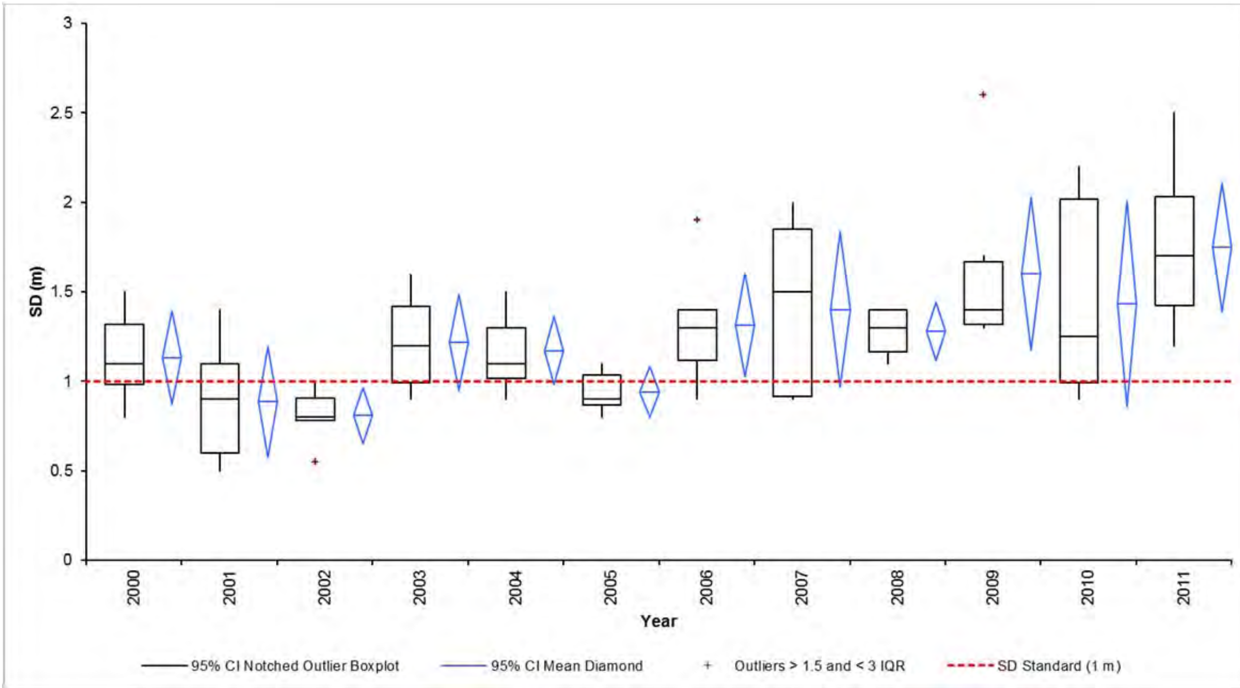


Figure 12. Wilmes Lake historic SD concentrations.



Similar to Markgrafs Lake, **Figure 10** indicates that phosphorus concentrations in Wilmes Lake have remained well above the state water quality standard. **Figure 11** indicates that chl-*a* concentrations have consistently been above or near the water quality standard, whereas **Figure 12** shows SD values have been improving, starting in 2005.

2.4 Water Budget

A water budget is an accounting of the amount of water entering and leaving a lake over a given time period. The time period used to develop the water budget in this study is the summer seasons of the study period, to correspond with the averaging period of the numeric standards. The amount of water moving in and out of a system varies from year-to-year, dictated primarily by the seasonal precipitation occurring in the area. The water budget is important to quantify because different sources of water can contain different quantities of pollutants and the amount of water entering and leaving the lake determines the hydraulic residence time. The water budget is also important because it is used during hydrologic and water quality modeling for model calibration and validation purposes.

A water budget accounts for "gains" in water to the lake (*i.e.*, precipitation, runoff and groundwater inflow) as well as "losses" (*i.e.*, evaporation, surface outflow, and groundwater outflow). Each of these affects the volume of water in the lake (storage). This section describes how the various terms of the water budget were computed for the three lakes in this study, identifying any specific variations for each of the lakes. The water budget for each of the lakes is presented in **Section 2.4.8**.

2.4.1 Tributary Inflow

For Armstrong Lake where the focus of the study is on the south basin, the north basin (which was not modeled), was treated as direct runoff to the south basin, rather than a tributary inflow (see **Section 2.4.2**). Therefore, Armstrong Lake does not have any tributaries flowing into it.

Markgrafs Lake does not have any tributaries flowing into it.

Each individual basin within Wilmes Lake (North Wilmes and South Wilmes) receives tributary inflows from other upstream modeled waterbodies. The amount of tributary inflow entering these basins during the summer season of the study period was estimated using a P8 model previously developed and calibrated for a similar study of Colby Lake. Colby Lake is located downstream of all of the lakes modeled in this study, and therefore the P8 model contains individually modeled areas of the watershed, portions of which contain each of the lakes within this study. The P8 model was run from 1962 through 2011 and tributary inflow volumes entering the respective lake models were extracted and compiled to determine the total tributary inflow to each lake.

For the North Wilmes basin the outflow of the upstream watershed (including Armstrong Lake) was treated as a tributary inflow. The outflow from the North Wilmes basin was used as a tributary inflow into the South Wilmes basin. Additionally, the Markgrafs outflow, combined with direct runoff along the channel between Markgrafs and the South Wilmes basin, were used as a tributary inflow to the South Wilmes basin.

The applicable tributary inflow volumes are shown in **Table 4**.

Table 4. Tributary inflow volumes (acre-feet) estimated by the P8 for the summer seasons.

	Tributary inflow volumes (acre-feet)		
	2009	**2010**	**2011**
Armstrong	0	0	0
Markgrafs	0	0	0
North Wilmes	231	474	315
South Wilmes	408	422	629

2.4.2 Direct Runoff

The amount of direct runoff entering each of the lakes during the summer season of the study period was also estimated using the P8 model described above in **Section 2.4.1**. Direct runoff refers to surface water entering the lake via overland flow. The P8 model was run from 1962 through 2011 and direct runoff inflow volumes to each of the lakes were extracted and compiled to determine the total direct runoff inflow volume to each lake. The direct runoff inflow volumes for the study period are shown in **Table 5**

Table 5. Direct runoff average inflow volumes (acre-feet) for the summer seasons.

	Direct runoff inflow volumes (acre-feet)		
	2009	**2010**	**2011**
Armstrong	56	124	84
Markgrafs	68	140	96
North Wilmes	140	284	191
South Wilmes	66	141	94

2.4.3 Precipitation

Long-term precipitation records (1962-2011) from the first order weather monitoring station located at the Minneapolis St-Paul airport (MSP) were used as forcing data in the P8 watershed model developed under this study and to estimate the amount of water falling on the surface of each of the lakes as precipitation during the study period. The mean summer season precipitation observed at MSP during this 50-year period (i.e., the time period used in setting the loading capacity of the lakes, discussed in **Section 3.4**) is 14.7 inches. By comparison, a summer season total of 11.9 inches was observed in 2009, 19.7 inches in 2010, and 13.9 inches in 2011. When these rainfall depths are applied to the areas of the three lakes, the seasonal precipitation volumes associated with these rainfall depths are determined and shown in **Table 6**.

Table 6. Precipitation volumes (acre-feet) for each of the models the summer seasons.

	Precipitation volumes (acre-feet)		
	2009	**2010**	**2011**
Armstrong	29	47	33
Markgrafs	40	66	47
North Wilmes	16	27	19
South Wilmes	17	29	20

2.4.4 Evaporation

Evaporation is an important component of the water budget, particularly for shallow lakes with small subwatersheds. Evaporation volumes were estimated using the combined aerodynamic and energy balance method. The method is derived from both physical and empirical relationships and accounts for many of the influencing meteorological parameters. Three methods were analyzed, including the Lake Hefner #1 and #2 and the Meyer methods. The results of these methods were averaged to determine the yearly evaporation during the study period.

Each method requires the following meteorological data: air temperature, wind speed, and water vapor pressure (expressed as dew point). Daily meteorological data from the MSP station was used. The methods also require daily water temperature data, which was estimated by forming a linear regression between known lake water temperature data and corresponding air temperature data, then applying a regression to create a daily water temperature dataset. Evaporation was calculated on a daily time step and summed over the summer season. Summer season evaporation totals were calculated for each of the years in the study period. The estimated evaporation totals (inches per summer season) for each year of the study period were determined and applied to each lake area to determine a summer season evaporation volume (acre-feet) for each year of the study period. The results are shown in the **Table 7.**

Table 7. Evaporation totals (inches per summer season) and volumes (acre-feet) for each lake.

	2009	2010	2011
	Evaporation (inches per summer season)		
Armstrong	21	21	22
Markgrafs	26	27	27
North Wilmes	24	24	25
South Wilmes	24	24	25
	Evaporation volumes (acre-feet)		
Armstrong	50	50	52
Markgrafs	88	89	92
North Wilmes	33	33	34
South Wilmes	35	35	36

2.4.5 Change in Storage

Change in storage (increase or decrease) was estimated using measured lake levels obtained from the MnDNR LakeFinder website (http://www.dnr.state.mn.us/lakefind/index.html, accessed April 2012) and the lake surface areas used in the P8 modeling. Observed water level values were linearly interpolated between measurements to estimate daily values. The changes in storage were estimated from the difference in lake level between June 1 and September 30 during each year. An increase in water level over the season is interpreted as a positive change in storage value. The change in storage volumes are shown in **Table 8**.

Table 8. Change in storage volumes (acre-feet) for each lake during the summer seasons.

	Change in storage volumes (acre-feet)		
	2009	2010	2011
Armstrong	3	0	0
Markgrafs	11	8	-20
North Wilmes	-1	4	-28
South Wilmes	-1	5	-29

For Armstrong Lake, no summer season lake level data exists for 2010 and 2011. Because lake levels in Armstrong Lake have historically been consistent (approximately 1 foot maximum variation throughout 2008 and 2009) and because the change in storage volume is shown to make up a small percentage (~4%) of the overall water budget, the storage change for 2010 and 2011 was assumed to be negligible and therefore set to 0. The lake level data that exists for Wilmes Lake applies to the levels in North Wilmes basin. One data point exists to compare the lake levels, which shows that South Wilmes basin is 1.38 feet below the North Wilmes basin. Because the two basins are hydraulically connected and their watersheds are similar, for the purpose of this study, the south basin was assumed to have the same water level fluctuations as the north basin. Therefore the summer season changes in the north levels were used to estimate the storage volume changes in the south basin.

2.4.6 Surface Outflow

With the exception of the South Wilmes basin, surface outflow volumes were estimated using the P8 model. In the case of the South Wilmes basin, measured discharge collected at the outlet was used to determine summer season outflow volumes throughout the study period. Discharge monitoring at the Wilmes Lake outlet location began in 2009. The surface outflow volumes for each of the water budgets are shown in **Table 9**.

Table 9. Surface outflow volumes (acre-feet) for each of the lakes during the summer seasons.

	Surface outflow volumes (acre-feet)		
	2009	**2010**	**2011**
Armstrong	43	121	84
Markgrafs	24	63	51
North Wilmes	355	748	519
South Wilmes	292	2006	1459

2.4.7 Net Groundwater & Error

Information about groundwater interaction within the overall watershed containing the three lakes is limited. A large-scale assessment of groundwater resources in Washington County determined that all three of the lakes in this study are considered “perched” waterbodies with respect to groundwater interaction. This indicates that the lake bottom is at an elevation above the regional water table. These types of lakes may be connected to local perched water table conditions but they do not receive inflows of regional groundwater (Barr, 2005). Given the qualitative nature of this information and the lack of more detailed data on groundwater interactions for each of the lakes, the net groundwater term for each water budget was combined with the error term. In general, this value was determined using the remaining terms in the balance equations (i.e. net groundwater + error = inputs - outputs). The exception to this applies to Wilmes Lake. Due to the lack of data for each individual basin, the groundwater & error term in the North Wilmes basin water budget was set to 0, and the remaining balance was used to determine the outflow into the South Wilmes basin. The net groundwater & error volumes for each of the hydrologic balances are shown in **Table 10**.

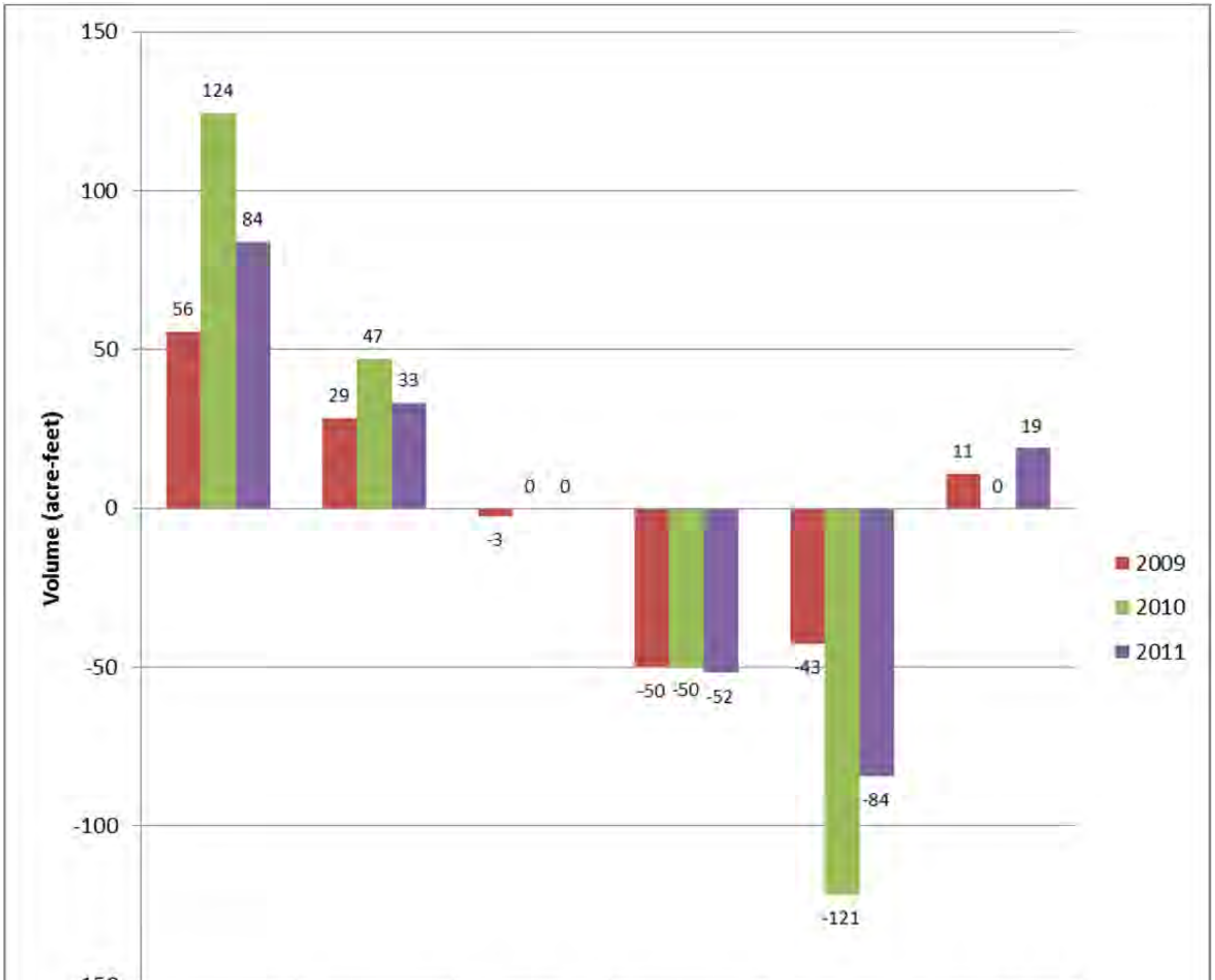
Table 10. Net groundwater & error volumes (acre-feet) for each lake during the summer seasons.

	Groundwater/Error (acre-feet)		
	2009	**2010**	**2011**
Armstrong	11	0	19
Markgrafs	15	-46	-20
North Wilmes *	0	0	0
South Wilmes	-166	1454	723

2.4.8 Estimated Water Budgets

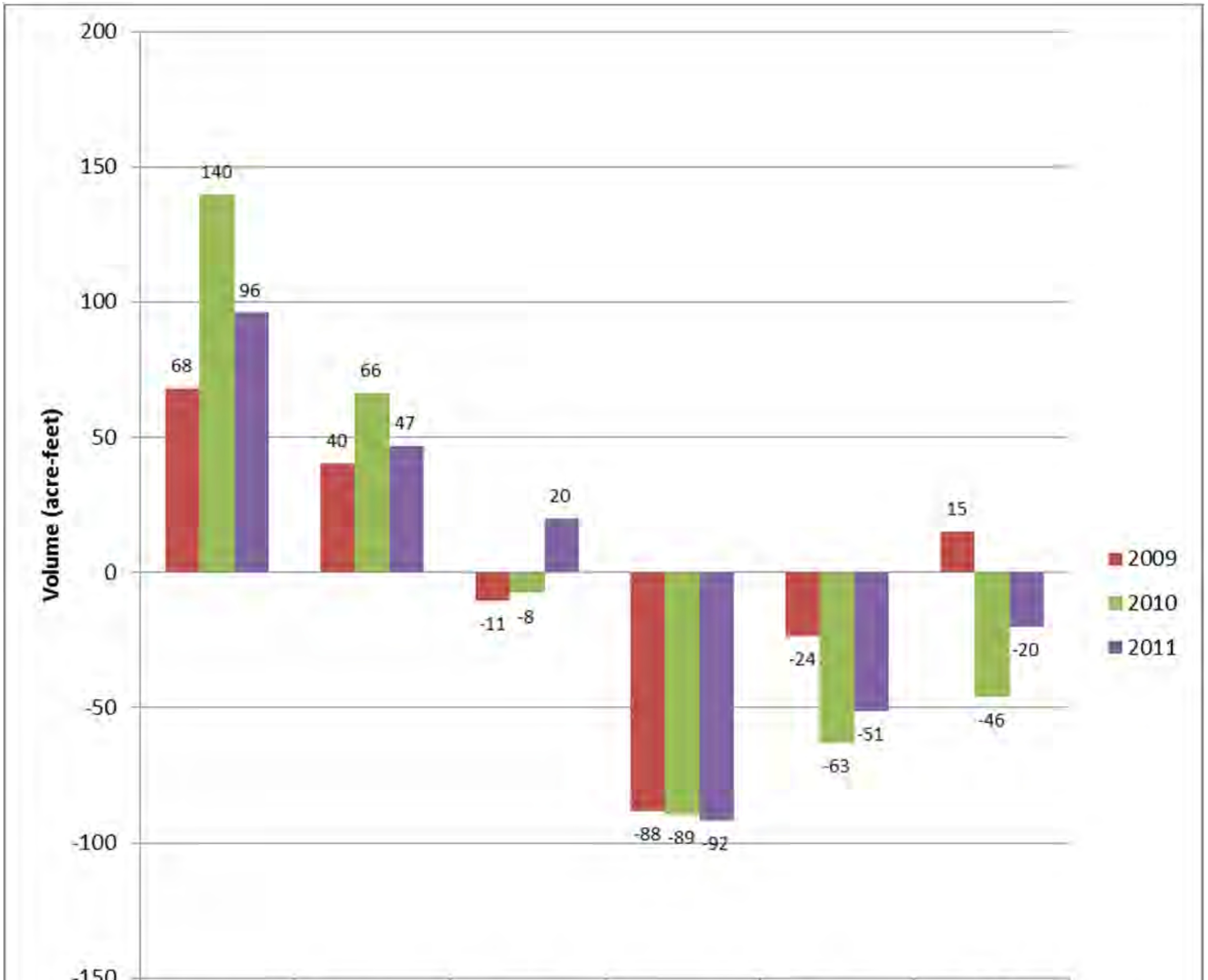
The water budgets for each of the lakes in the study are shown in the **Figure 13** through **Figure 16**. The budgets represent the summer season. Each budget was estimated as described in the sections above.

Figure 13. Water budget for Armstrong Lake during the summer seasons.



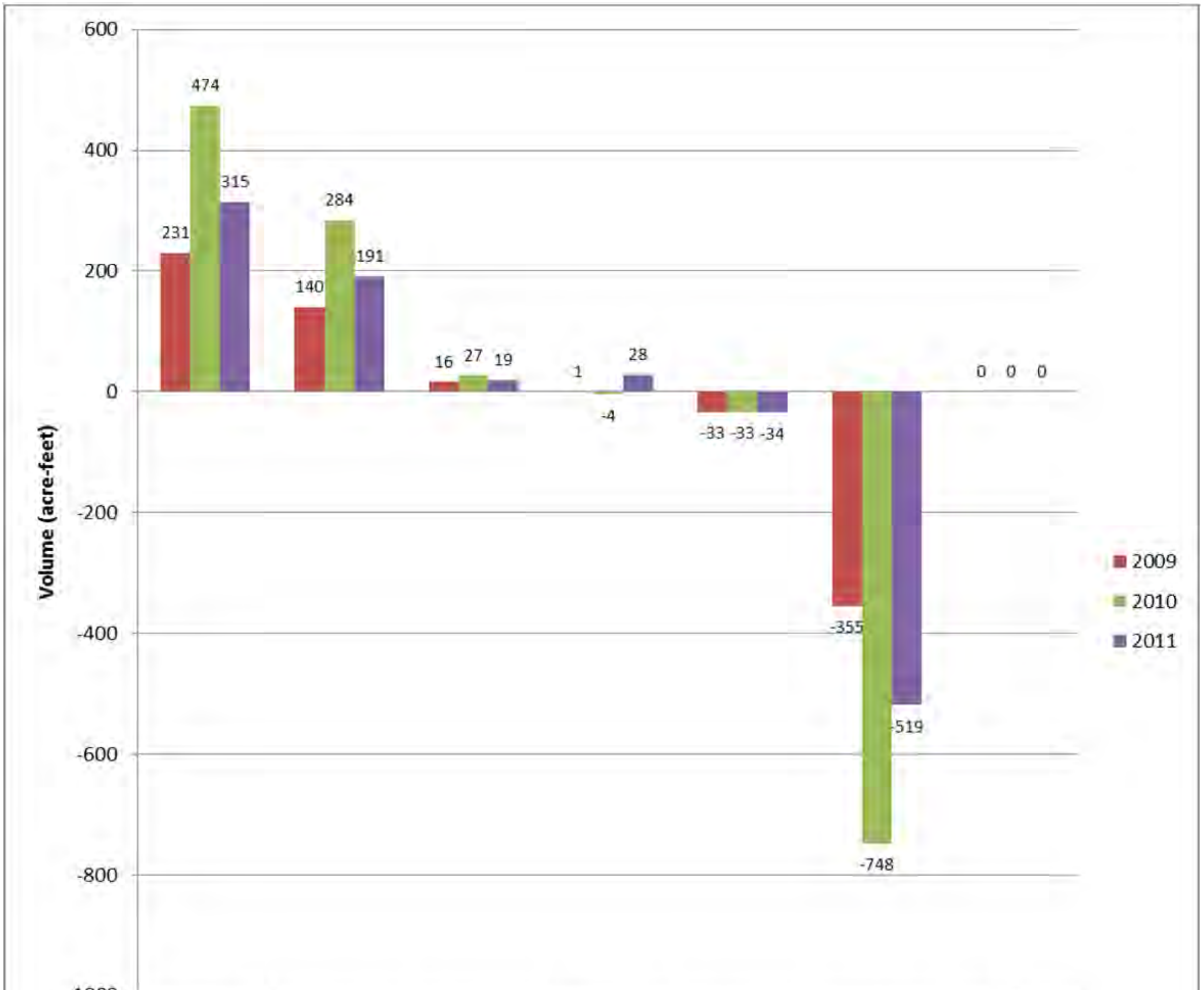
	Direct Runoff	Precipitation	Change In Storage	Evaporation	Surface Outflow	Net Groundwater & Error
2009	56	29	-3	-50	-43	11
2010	124	47	0	-50	-121	0
2011	84	33	0	-52	-84	19

Figure 14. Water budget for Markgrafs Lake during the summer seasons.



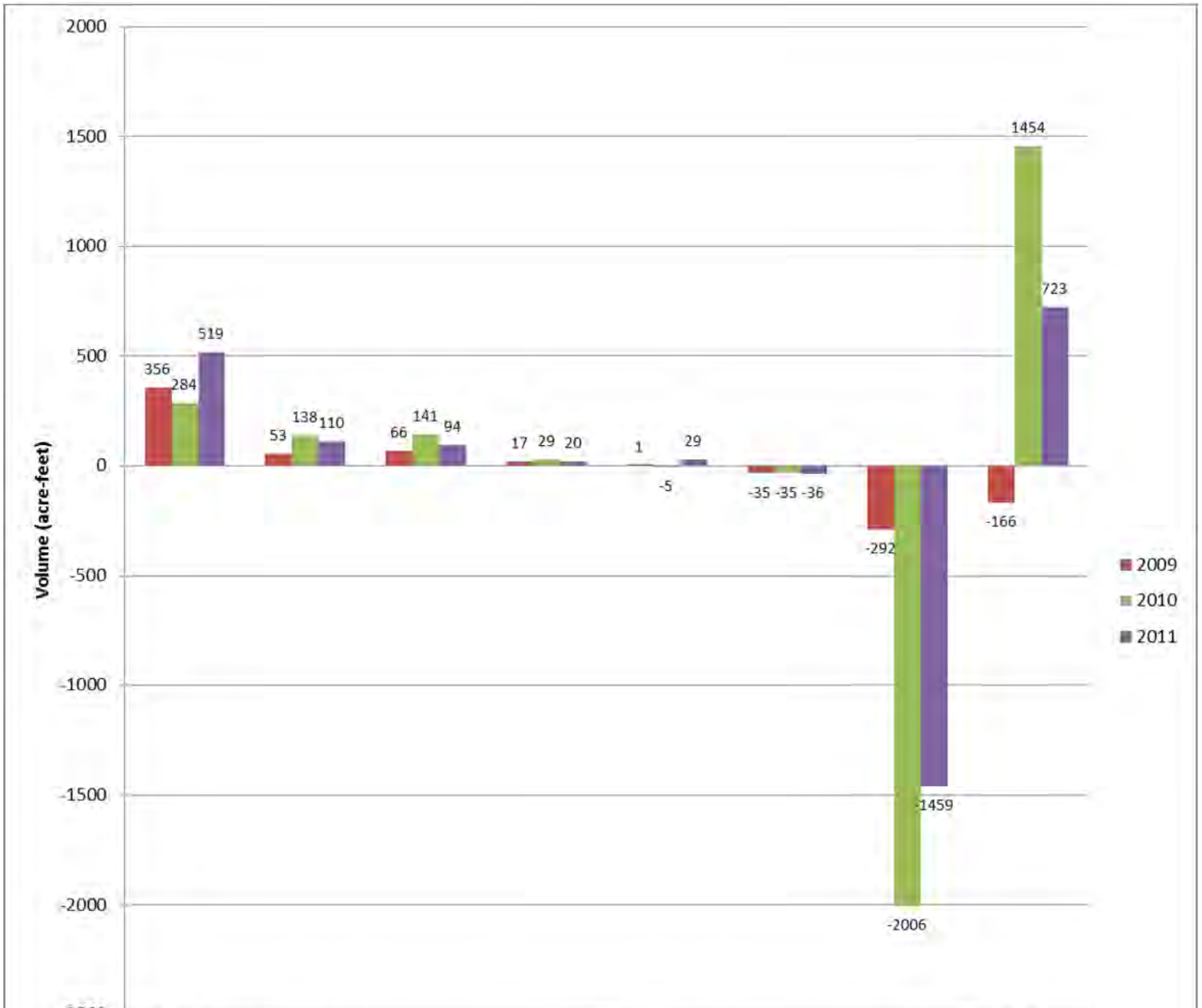
	Direct Runoff	Precipitation	Change In Storage	Evaporation	Surface Outflow	Net Groundwater & Error
2009	68	40	-11	-88	-24	15
2010	140	66	-8	-89	-63	-46
2011	96	47	20	-92	-51	-20

Figure 15. Water budget for North Wilmes Lake during the summer seasons.



	Tributary Inflow	Direct Runoff	Precipitation	Change In Storage	Evaporation	Surface Outflow	Net Groundwater & Error
2009	231	140	16	1	-33	-355	0
2010	474	284	27	-4	-33	-748	0
2011	315	191	19	28	-34	-519	0

Figure 16. Water budget for South Wilmes Lake during the summer seasons.



	North Wilmes Inflow	Markgrafs Inflow	Direct Runoff	Precipitation	Change In Storage	Evaporation	Surface Outflow	Net Groundwater & Error
2009	356	53	66	17	1	-35	-292	-166
2010	284	138	141	29	-5	-35	-2006	1454
2011	519	110	94	20	29	-36	-1459	723

2.5 Total Phosphorus Nutrient Budget

Along with accounting for the amount of water it is necessary to account for the amount of nutrients by developing a total phosphorus budget (mass balance) for nutrient loads entering and leaving the lakes throughout the study period. Loads are expressed in units of mass per time (e.g. kg/year or lb/year) and are estimated by considering the concentration of a substance in the water and the amount of that water entering and exiting the waterbody over a time period. In the case of this study, the substance/nutrient considered is phosphorus. This section describes how the various components of the phosphorus budgets for each lake were estimated. In the case of this study, monitoring data collected by the SWWD was used whenever available to estimate loads. The overall budget results are presented in **Section 2.5.6**.

2.5.1 Tributary and Direct Runoff Loading

Loading includes nutrients entering the lakes through tributary inflows as well as direct runoff. With the exception of the tributary loading to the South Wilmes basin via the North Wilmes basin and Markgrafs Lake, all tributary and direct runoff loading to the three lakes for the summer seasons of the study period were estimated using the P8 model. In the case of the South Wilmes basin, tributary loading from the North Wilmes basin was estimated by assuming that both basins maintain similar average annual TP concentrations and applying the summer season annual average concentration assumed for both basins to the inflow from the north basin. Tributary inflow loading from Markgrafs Lake to the South Wilmes basin was estimated in a similar way, by applying the summer seasonal annual average TP concentration in Markgrafs Lake to the tributary inflow from Markgrafs Lake. The resulting tributary and direct runoff loading for all three lakes is summarized in **Table 11** and **Table 12**.

Table 11. Tributary TP loading (kg) for each of the lakes during the summer seasons.

	Tributary TP Loading (kg)		
	2009	2010	2011
Armstrong	0	0	0
Markgrafs	0	0	0
North Wilmes	22	50	32
South Wilmes	43	126	59

Table 12. Direct runoff TP loading (kg) for each of the lakes during the summer seasons.

	Local Runoff TP Loading (kg)		
	2009	**2010**	**2011**
Armstrong	10	22	14
Markgrafs	17	33	21
North Wilmes	26	52	33
South Wilmes	12	25	16

2.5.2 Atmospheric Deposition

The annual atmospheric deposition rate for the watershed encompassing the three lakes was determined to be 0.29 kg/hectare/yr (Barr 2007). In order to estimate atmospheric deposition during the summer seasons of the study period, it was assumed that the amount of TP from atmospheric deposition is driven solely by precipitation and that the TP concentration of precipitation remains constant throughout the year. Using the 50-year precipitation data from hydrologic budget, a long-term average annual precipitation was calculated to be 28.55 inches. A ratio of summer season precipitation to long-term average annual precipitation was calculated for each year in the study period. For example, in 2009 the summer season total precipitation was 11.92 inches; therefore the ratio for 2009 is 0.42. Summer season atmospheric loadings for the study period were computed by applying the respective ratios to the annual atmosphere deposition rate of 0.29 kg/hectare/yr. The seasonal TP atmospheric loading to each of the three lakes is summarized in **Table 13**.

Table 13. Atmospheric TP loading (kg) for each of the models during the summer seasons.

	Atmospheric Deposition TP Loading (kg)		
	2009	**2010**	**2011**
Armstrong	1	2	2
Markgrafs	2	3	2
North Wilmes	1	1	1
South Wilmes	1	1	1

2.5.3 Internal Loading

Internal TP loads to the three lakes were estimated using information developed by the Rice Creek Watershed District (RCWD), also in the Twin Cities Metropolitan area. The RCWD retained the U.S. Army Corps of Engineer's Eau Galle Lab to measure the sediment phosphorus release rates in 30 of their lakes, in the laboratory, under oxic and anoxic conditions. Phosphorus release rates in the three lakes were estimated assuming a long-term average summer season internal release rate of 1.62 milligrams per square meter per day. This internal release rate was estimated and used in the previous Colby Lake study. The value is the median rate observed in 23 lakes in the RCWD, characterized as both shallow and urban, similar to the lakes in this study. The release rate was applied over an area equal to the surface area of each lake. A constant internal loading was assumed for the entire study period; therefore the internal loading of each individual lake was assumed to remain constant for that lake during each summer season throughout the study period. The resulting internal phosphorus loading is summarized in **Table 14**.

Table 14. Internal TP loading (kg) for each of the lakes during the summer seasons.

	Internal TP Loading (kg)		
	2009	**2010**	**2011**
Armstrong	23	23	23
Markgrafs	32	32	32
North Wilmes	13	13	13
South Wilmes	14	14	14

2.5.4 Retained Mass & Error

Other in-lake processes (sedimentation, groundwater loading, nutrient uptake, etc.) were not explicitly accounted for in the TP nutrient balances of the three lakes in the study, but rather estimated with the retained mass & error term in the nutrient balance equations (i.e. retained mass + error = TP inputs – TP outputs). However, the CNET in-lake response model does account for the sedimentation term in its simulations. The retained mass & error TP loading is shown in **Table 15.**

Table 15. Retained mass & error TP loading (kg) for each of the lakes during the summer seasons.

	Retained Mass & Error TP Loading (kg)		
	2009	**2010**	**2011**
Armstrong	31	39	35
Markgrafs	44	51	46
North Wilmes	34	28	39
South Wilmes	48	-70	-25

2.5.5 Surface Outflow

The TP load exiting each of the lakes was estimated by applying the mean summer season TP concentration for each lake to the summer season outflow for that lake. In the case of the North Wilmes basin, where no in-lake data was available, the mean summer season TP concentration was assumed to be the same as the South Wilmes basin and this value was applied to the North Wilmes basin outflow. The surface outflow loads are shown in **Table 16**.

Table 16. Surface outflow TP loading (kg) for each of the lakes during the summer seasons.

	Surface Outflow (kg)		
	2009	**2010**	**2011**
Armstrong	3	8	4
Markgrafs	7	17	9
N. Wilmes	28	88	40
S. Wilmes	23	236	114

2.5.6 Estimated Total Phosphorus Nutrient Budget

Using the results of **Sections 2.5.1** through **2.5.5**, the summer season TP mass balances for the three lakes were estimated for the study period. The results are shown in **Figure 17** through **Figure 20**.

Figure 17. Armstrong Lake TP nutrient budget during the summer seasons.

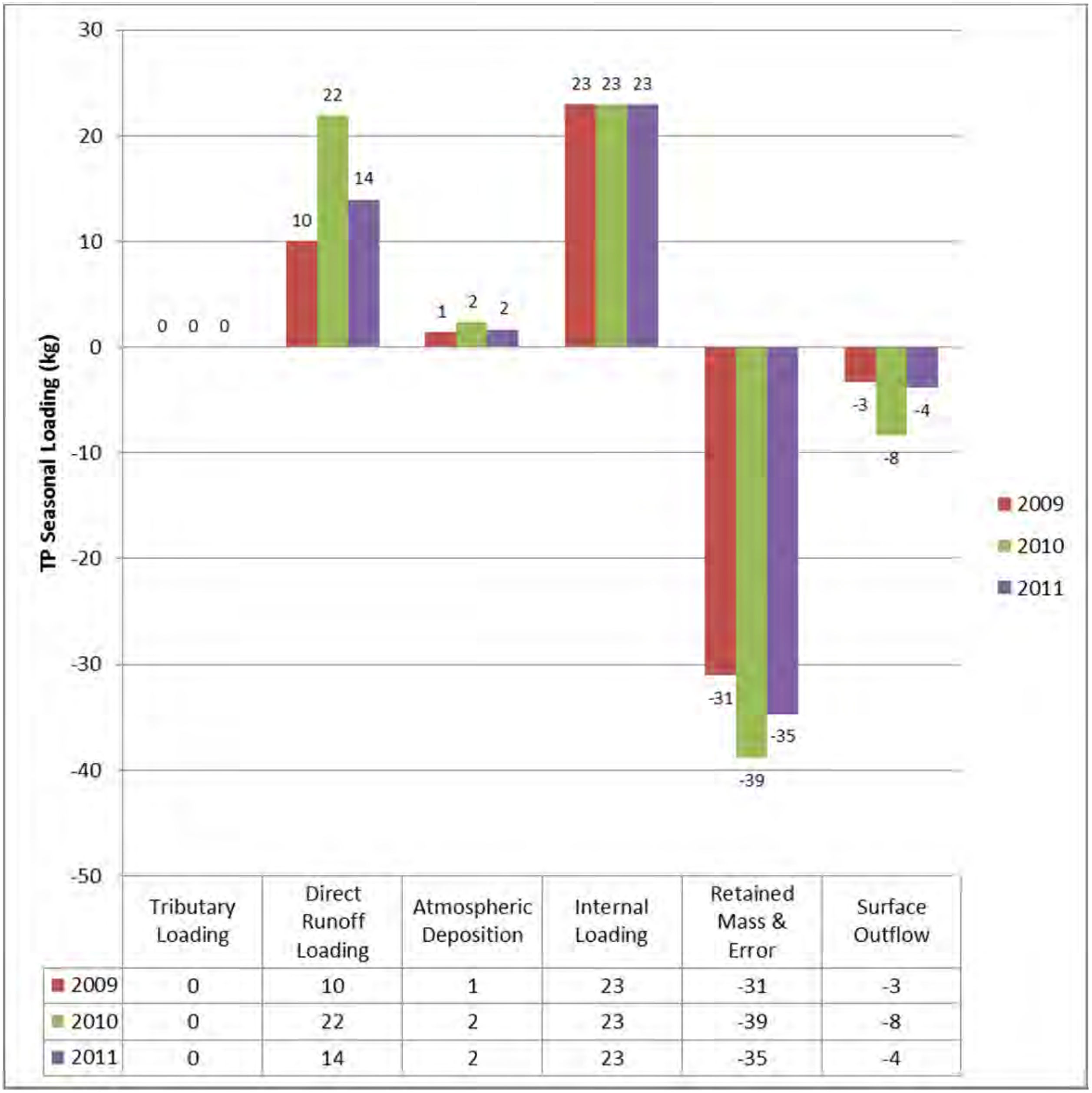
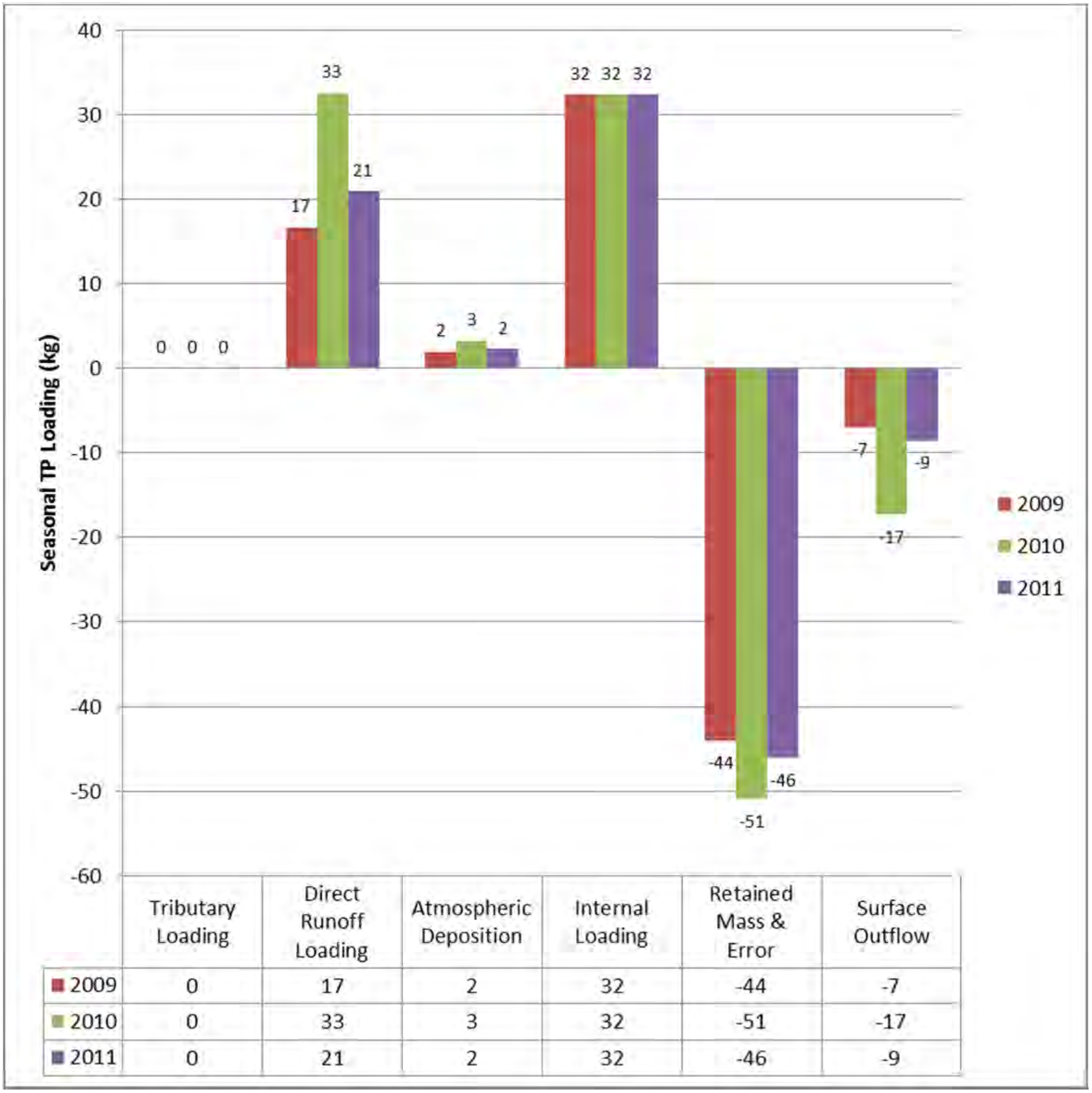
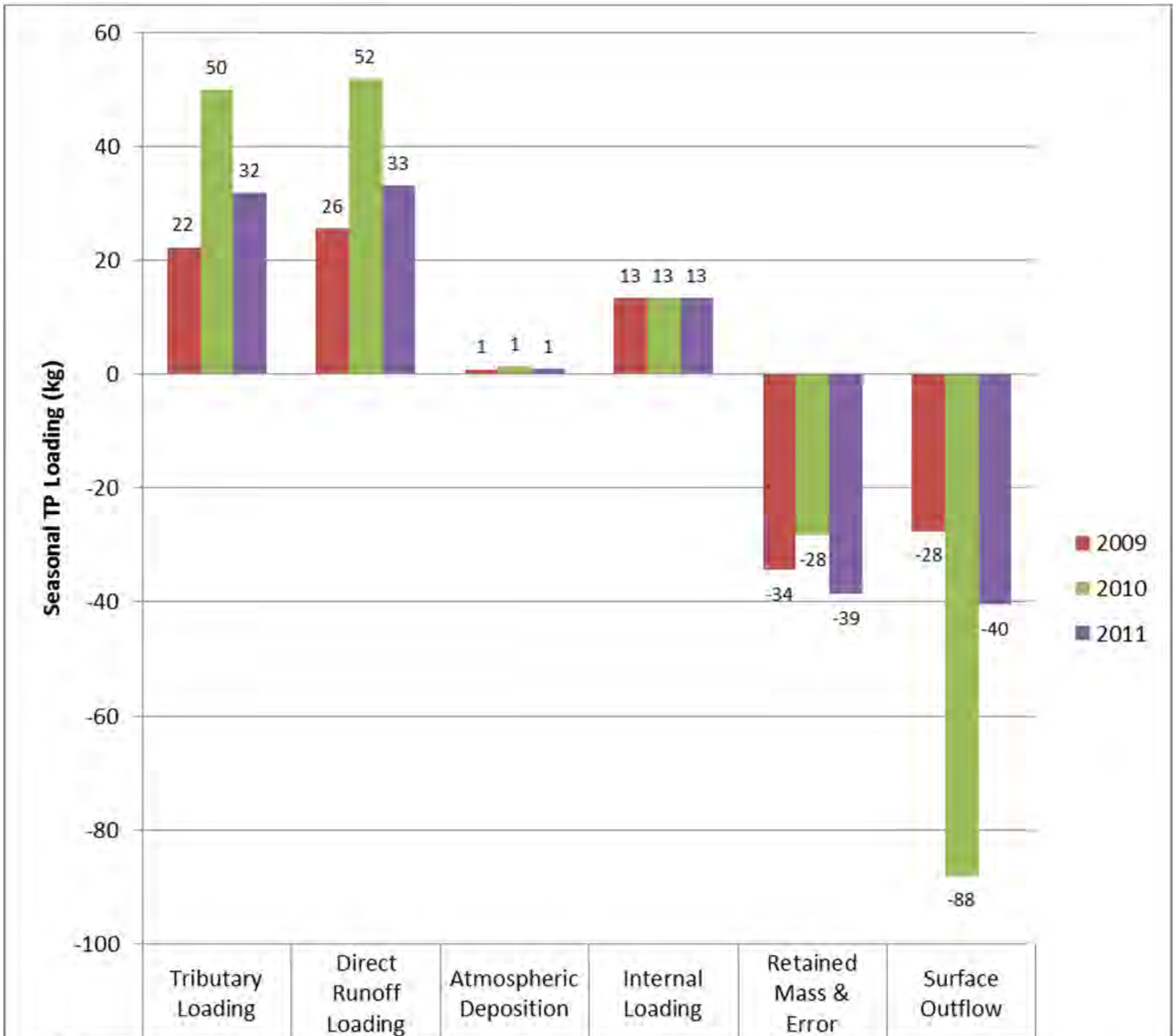


Figure 18. Markgrafs Lake TP nutrient budget during the summer seasons.



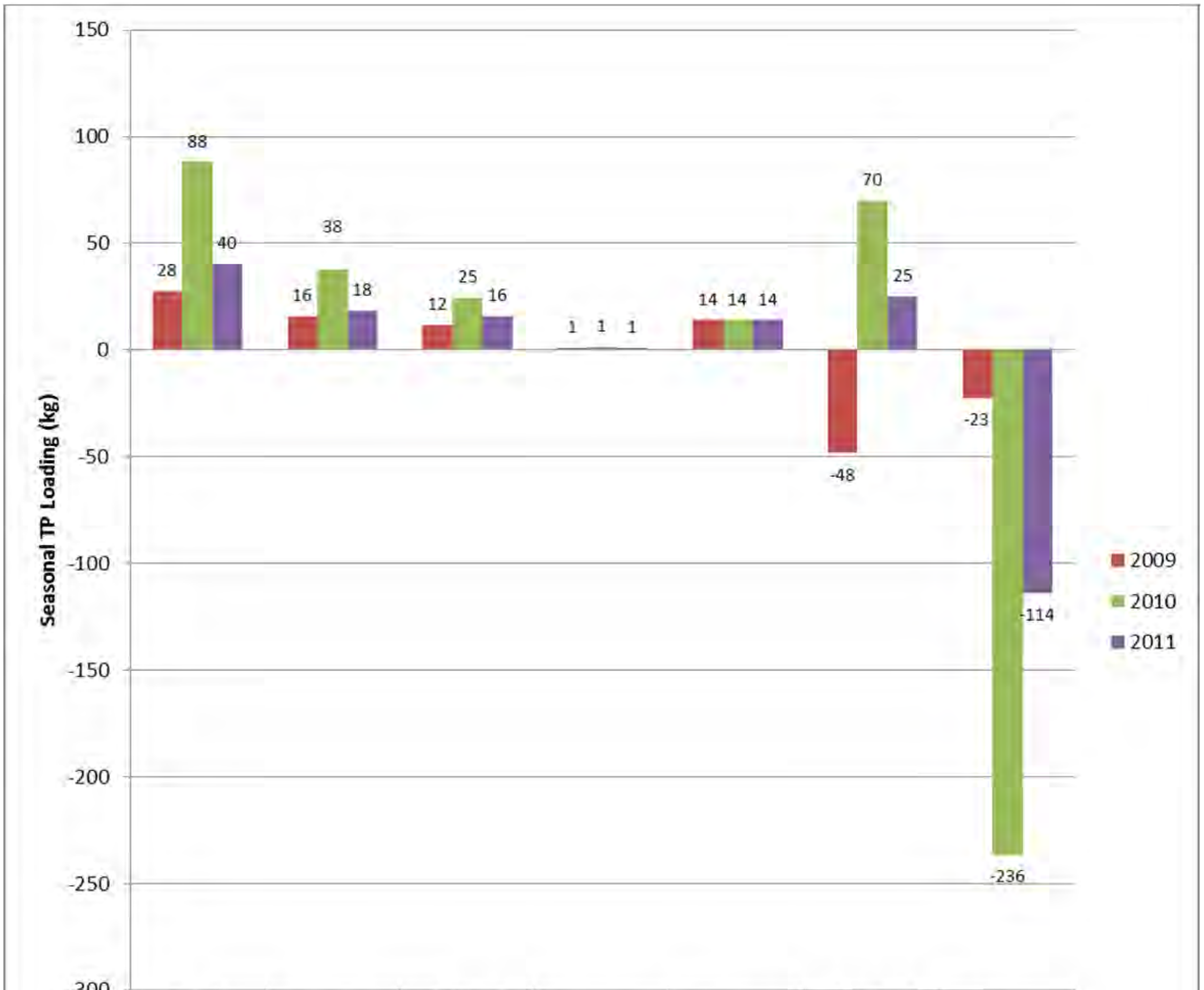
	Tributary Loading	Direct Runoff Loading	Atmospheric Deposition	Internal Loading	Retained Mass & Error	Surface Outflow
2009	0	17	2	32	-44	-7
2010	0	33	3	32	-51	-17
2011	0	21	2	32	-46	-9

Figure 19. North Wilmes Lake basin TP nutrient budget during the summer seasons.



	Tributary Loading	Direct Runoff Loading	Atmospheric Deposition	Internal Loading	Retained Mass & Error	Surface Outflow
2009	22	26	1	13	-34	-28
2010	50	52	1	13	-28	-88
2011	32	33	1	13	-39	-40

Figure 20. South Wilmes Lake basin TP nutrient budget during the summer seasons.



	North Wilmes Loading	Markgrafs Loading	Direct Runoff Loading	Atmospheric Deposition	Internal Loading	Retained Mass & Error	Surface Outflow
2009	28	16	12	1	14	-48	-23
2010	88	38	25	1	14	70	-236
2011	40	18	16	1	14	25	-114

3.0 MODEL DEVELOPMENT AND APPLICATION

3.1 Modeling Goals and Technical Objectives

Developing written modeling goals and technical objectives should be a component of all projects that include modeling. In order to conduct a successful modeling effort, the modeling goals and technical objectives must be clearly identified early in the process. These should be memorialized in writing and shared with those parties with an interest in the project to ensure the results generated address the water quality issues of concern. The modeling goals and technical objectives establish the anticipated uses, technical methods and outcomes (i.e., products) of the model.

Modeling goals are general statements reflecting the "big picture" expectations or outcomes from the model development and application process. Technical objectives are specific to the water quality problem being addressed and should incorporate the applicable temporal and spatial scales to be addressed by the model (e.g., whether they are caused by some short-term episodic event or long-term conditions). For instance, a modeling goal would be to establish nutrient loads and the load reductions needed to achieve water quality goals for a particular lake. The corresponding technical objectives may include assessing the eutrophication response of the lake at each lake inlet and outlet for the average monthly condition.

Water quality modeling goals should consist of a general statement, explicitly identifying and describing the problems and issues to be resolved through the application of the model. The specific parameters to be modeled, temporal (time) and spatial scales that need to be generated by the model for these parameters and any additional descriptive information needed from the model (*e.g.*, minimum values) should be described within the technical objectives.

Modeling goals and objectives likely differ depending upon the type of modeling being performed. The two primary types of water quality modeling for this project can be broadly categorized as watershed (*i.e.*, landscape) and receiving water modeling. The water quality goals and technical objectives for the Armstrong, Markgrafs, and Wilmes Lake Water Quality Modeling Project are the same as those presented for the Powers Lake Pilot Project, as described in Tables 1 and 2 of a Technical Memorandum to the SWWD dated January 28, 2010. These goals and objectives can be generally described as understanding the response of the lakes to excess nutrients, both in terms of the amount of algae and the clarity of the lake.

3.2 Watershed Modeling

The movement of water from the watershed into Armstrong, Markgrafs, and Wilmes Lakes was determined using version 3.4 of the P8 model (Program for Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds (http://wwwalker.net/p8/)). The P8 model incorporates a number of factors that encompass inflow, outflow, and the movement of sediment-related particles (including TP) through a watershed. The goal of the P8 watershed modeling was to estimate the June through September total volume and TP loading to Armstrong, Markgrafs, and Wilmes Lakes. Results of these simulations were then used as inputs to the receiving water model (see Section 3.3), which was developed to compute the loading capacity of each lake.

The P8 model used for this study was originally developed as part of the Colby Lake Water Quality Modeling Project (HEI, 2011). The routing information and most other required inputs for the P8 model were adopted from an existing SWWD hydrologic and hydraulic XPSWMM model. Rainfall data used to generate P8 runoff volumes were taken from the MSP weather station. The Colby Lake watershed P8 model was calibrated and validated to observed summer season surface water runoff volumes, TSS loads, and TP loads. Model calibration was performed using data from 2008 and 2009, and model validation was performed using data from 2010. Complete details on the development of the Colby Lake P8 model and the calibration/validation process is included in Appendix A of the Colby Lake Water Quality Modeling Project Report (HEI 2011).

Detailed information on how the Colby Lake P8 model was used in this study to estimate the June through September total volume and TP loading to Armstrong, Markgrafs, and Wilmes Lakes is included in **Appendix A** of this report.

3.3 Receiving Water Modeling

Based upon the stated modeling goals and objectives (discussed above), the CNET model was used to simulate the eutrophication response within Armstrong, Markgrafs, and Wilmes Lakes. CNET is a modified version of the receiving water model BATHTUB (http://wwwalker.net/bathtub/index.htm), which was created by the Army Corps of Engineers. CNET is a spreadsheet model currently available as a “beta” version from Dr. William W. Walker. The primary modifications to the CNET model implemented during this effort were: 1) to use empirically derived regression relationships specific to the lakes derived from monitoring data to estimate the response of chl-*a* and SD to TP (used primarily to double check/confirm the responses values predicted by the CNET equations); and 2) implementing a Monte Carlo approach which allowed selected modeling parameters and inputs to vary based upon known statistical distributions and be reflected in the forecast results. The Monte Carlo approach generates a distribution of the annual mean concentrations reflecting the uncertainty in the model parameters and normal variability in inputs (*e.g.*, seasonal TP load from surface runoff).

To complete the Monte Carlo modeling the CNET model was linked with a program called Crystal Ball. Crystal Ball is proprietary software developed by Oracle (http://www.oracle.com/us/products/applications/crystalball/index.html) and is applicable to Monte Carlo or stochastic simulation and analysis. Stochastic modeling is an approach where model parameters and input values (*e.g.*, precipitation) used in the equations to compute the annual mean concentration of TP, chl-*a*, and SD are allowed to vary according to their statistical distribution and therefore their probability of occurrence. This allows the effect of parameter uncertainty and normal variability in the inputs (*e.g.*, amount of surface runoff which varies annually depending upon the amount of precipitation) to be quantified when computing the summer season mean concentration of TP, chl-*a*, and SD.

The Crystal Ball software allows for multiple probabilistic simulations of the model computations. Many trial values (1,000 trials in this study case) were generated, with each trial representing a different permutation of model parameters and input values within the bounds established by the statistical distributions. The many trials resulted in a computed distribution of annual mean concentrations rather than a single, fixed output that was based upon only one possible combination of model parameters and inputs. The stochastic approach reflects the variability in model parameters and inputs, and allows explicit determination of their effect on the mean values and the expression of model results as risk. **Sections 3.3.1, 3.3.2, 3.3.3, and 3.3.4** describe the details of the CNET model development for Armstrong, Markgrafs, North Wilmes, and South Wilmes Lakes, respectively, including the variable values in the Monte Carlo simulation and the statistical distributions for each parameter allowed to vary within the model. The other necessary inputs to the CNET model (e.g., the internal loading and groundwater + error terms) were held constant throughout all model simulations.

3.3.1 Armstrong Lake CNET Model Development

Table 17 shows the model inputs used in the Armstrong Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 17. Model inputs used in the Monte Carlo Analysis for Armstrong Lake

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station	Yes	Yes	Surface runoff (0.84) Surface load (0.44) Atmospheric Load (1.0)
Evaporation	Beta	1962 – 2011 computed from regression with air temperature data	Yes	No	---
Atmospheric Load	Beta	Distribution Assumed Same as Precipitation	Yes	No	Precipitation (1)
Surface Water Runoff Volume	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.84) Surface Load (0.82)
Surface Runoff Load	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.44) Surface Runoff Volume (0.82)

Notes:
All distributions truncated at lowest and highest values in the 50-year period of record
Distributions generally were best fit for the 50-year period (1962-2011) of seasonal values.
Correlation coefficients were derived from actual data.
Atmospheric TP load distribution assumed to be the same as precipitation with equal coefficient of variation.
Value in parentheses is correlation coefficient.
See **Appendix B** for the statistical distribution parameters.
Statistical distributions were the “best fit” distribution, as determined by the Crystal Ball software.

Prior to completing the Monte Carlo modeling analysis, the Armstrong Lake CNET model was calibrated to 2009/2010 average summer season mean TP, chl-*a*, and SD and validated for summer season of 2011. The modeling used the seasonal water budget and TP mass balance around the Lake as described in **Sections 2.4.8 and 2.5.6**. The following CNET models were used in the simulations:

- Total phosphorus sedimentation model: Canfield & Bachman (1981), Reservoirs
- Chlorophyll-*a* response model: P, Linear
- Secchi-disk Transparency response model: Secchi vs. Chl-*a* and Turbidity.

The goal of the CNET model calibration was to adjust each sedimentation and response models' calibration coefficient to reduce the errors between observed and simulated values. All three years with available measured data were used in the calibration and validation process. The model was calibrated to the average water quality data from 2009 and 2010, and it was validated to the water quality data in the year 2011. This approach ensures an in-lake response model that best represents long-term average conditions in Armstrong Lake, which is appropriate for computing the loading capacity. **Table 18** shows the results of model calibration using the 2009/2010 average summer season mean data. **Table 19** shows the results of model validation using the 2011data.

Table 18. Armstrong Lake CNET Model calibration results for an average of the 2009/2010 summer seasons (June through September) mean concentrations.

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	1.4	59.5 ppb	60.7 ppb	1.2 ppb	2.0 %
Chlorophyll-a	0.6	10.2 ppb	10.2 ppb	0.0 ppb	-0.1 %
Secchi Disk	1.0	1.0 meters	1.0 meters	0.0 meters	0.0 %

Table 19. Armstrong Lake CNET Model validation results for 2011 summer season (June through September) mean concentrations.

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	37.3 ppb*	58.9 ppb	21.7 ppb	57.9 %
Chlorophyll-a	6.2 ppb	9.9 ppb	3.8 ppb	59.7 %
Secchi Disk	1.1 meters	1.0 meters	-0.1 meters	-7.4 %

* Measured TP appears inconsistent with Chl-a and Secchi

3.3.2 Markgrafs Lake CNET Model Development

Table 20 shows the model inputs used in the Markgrafs Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 20. Model inputs used in the Monte Carlo Analysis for Markgrafs Lake

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station	Yes	Yes	Surface Inflow (0.91) Surface load (0.50) Atmospheric Load (1.0)
Evaporation	Beta	1962 – 2011 computed from regression with air temperature data	Yes	No	---
Atmospheric Load	Beta	Distribution Assumed Same as Precipitation	Yes	Yes	Precipitation (1.0)
Surface Water Runoff Volume	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.91) Surface Load (0.78)
Surface Runoff Load	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.50) Surface Runoff Volume (0.78)

Notes:

All distributions truncated at lowest and highest values in 50-year period of record
Distributions generally were best fit for the 50-year period (1962-2011) of seasonal values.
Correlation coefficients were derived from actual data.
Atmospheric TP load distribution assumed to be the same as precipitation with equal coefficient of variation.
Value in parentheses is correlation coefficient.
See **Appendix B** for the statistical distribution parameters.
Statistical distributions were the "best fit" distribution, as determined by the Crystal Ball software.

Prior to completing the Monte Carlo modeling analysis, the Markgrafs Lake CNET model was calibrated to 2009/2010 average summer season mean TP, chl-*a*, and SD and validated for summer season of 2011. The modeling used the seasonal water budget and TP mass balance around the Lake as described in **Sections 2.4.8 and 2.5.6**. The following CNET models were used in the simulations:

- Total phosphorus sedimentation model: Simple First-Order.
- Chlorophyll-*a* response model: P, Exponential, Jones & Bachman.
- Secchi-disk Transparency response model: Secchi vs. Total P, CE Reservoirs.

The goal of the CNET model calibration was to adjust each sedimentation and response models' calibration coefficient to reduce the errors between measured and simulated values. As in the Armstrong Lake calibration, the Markgrafs Lake CNET model was also calibrated to the average water quality data from 2009 and 2010, and it was validated to the water quality data in the year 2011. **Table 21** shows the results of model calibration using the 2009/2010 average summer season mean data. **Table 22** shows the results of model validation using the 2011 data.

Table 21. Markgrafs Lake CNET Model calibration results for an average of the 2009/2010 summer seasons (June through September) mean concentrations

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	1.3	232.0 ppb	229.5 ppb	-2.5 ppb	-3.7%
Chlorophyll-a	0.6	126.2 ppb	135.9 ppb	9.7 ppb	7.7 %
Secchi Disk	1.1	0.3 meters	0.3 meters	0.0 meters	0.0 %

Table 22. Markgrafs Lake CNET Model validation results for 2011 summer season (June through September) mean concentrations

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	135.5 ppb	206.0 ppb	73.0 ppb	52.0 %
Chlorophyll-a	58.1 ppb	116.1 ppb	50.2 ppb	99.8 %
Secchi Disk	0.46 meters	0.34 meters	-0.1 meters	-26.1 %

3.3.3 North Wilmes Lake CNET Model Development

Table 23 shows the model inputs used in the North Wilmes Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 23. Model inputs used in the Monte Carlo Analysis for North Wilmes Lake

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station	Yes	Yes	Surface Inflow (0.84) Surface load (0.43) Atmospheric Load (1.0)
Evaporation	Beta	1962 – 2011 computed from regression with air temperature data	Yes	No	---
Atmospheric Load	Beta	Distribution Assumed Same as Precipitation	Yes	No	Precipitation (1)
Surface Water Runoff Volume	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.84) Surface Load (0.82)
Surface Runoff Load	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.43) Surface Runoff Volume (0.82)

Notes:

All distributions truncated at lowest and highest values in the 50-year period of record
Distributions generally were best fit for the 50-year period (1962-2011) of seasonal values.
Correlation coefficients were derived from actual data.
Atmospheric TP load distribution assumed to be the same as precipitation with equal coefficient of variation.
Value in parentheses is correlation coefficient.
See **Appendix B** for the statistical distribution parameters.
Statistical distributions were the “best fit” distribution, as determined by the Crystal Ball software.

Prior to completing the Monte Carlo modeling analysis, the North Wilmes Lake CNET model was calibrated to the 2009/2010 average summer season mean TP, chl-*a*, and SD and validated for summer season of 2011. The modeling used the seasonal water budget and TP mass balance around the Lake as described in **Sections 2.4.8 and 2.5.6**. The following CNET models were used in the simulations:

- Total phosphorus sedimentation model: Canfield & Bachman (1981), Natural Lakes
- Chlorophyll-*a* response model: P, Linear

- Secchi-disk Transparency response model: Secchi vs. Chl-*a* and Turbidity.

The goal of the CNET model calibration was to adjust each sedimentation and response models' calibration coefficient to reduce the errors between measured and simulated values. Following the calibration procedure of the other lakes, the North Wilmes Lake CNET model was also calibrated to the average water quality data from 2009 and 2010, and it was validated to the water quality data in the year 2011. **Table 24** shows the results of model calibration using the 2009/2010 average summer season mean data. **Table 25** shows the results of model validation using the 2011data.

Table 24. North Wilmes Lake CNET Model calibration results for an average of the 2009/2010 summer seasons (June through September) mean concentrations

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	0.9	79.1 ppb	79.0 ppb	-0.1 ppb	-0.1 %
Chlorophyll-a	1.2	29.6 ppb	26.5 ppb	-3.0 ppb	-10.5 %
Secchi Disk	1.7	1.5 meters	1.2 meters	-0.4 meters	-20.0 %*

* Suggests something other than chlorophyll-a could be a larger factor in the Secchi Disk depth, e.g. algae, turbitity, organic matter, etc.

Table 25. North Wilmes CNET Model validation results for 2011 summer season (June through September) mean concentrations

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	63.3 ppb	74.4ppb	11.2 ppb	17.5 %
Chlorophyll-a	16.2 ppb	25.0 ppb	8.8 ppb	54.3 %
Secchi Disk	1.8 meters	1.2 meters	-0.6 meters	-33.3 %

3.3.4 South Wilmes Lake CNET Model Development

Table 26 shows the model inputs used in the South Wilmes Lake Monte Carlo simulation and the statistical distributions for each parameter used.

Table 26. Model inputs used in the Monte Carlo Analysis for South Wilmes Lake

Model Input	Statistical Distribution	Basis for Distribution	Distribution Truncated at Extreme Values?	Correlation	
				Considered?	Input Correlated With
Precipitation	Beta	1962 – 2011 MSP National Weather Service Station	Yes	Yes	Local Surface Inflow (0.86) Markgrafs Trib Inflow (0.91) N. Wilmes Trib Inflow (0.86) Local Surface load (0.44) Markgrafs Trib :load (0.88) N. Wilmes Trib load (0.44) Atmospheric Load (1.0)
Evaporation	Beta	1962 – 2011 computed from regression with air temperature data	Yes	No	---
Atmospheric Load	Beta	Distribution Assumed Same as Precipitation	Yes	Yes	Precipitation (1)
Local Surface Water Runoff Volume	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.86) Local Surface Load (0.80)
Markgrafs Tributary Inflow Volume	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.91) Markgrafs Trib. Load (0.98)
North Wilmes Tributary Inflow Volume	Lognormal	Distribution Assumed Same as Local Runoff	Yes	Yes	Precipitation (0.86) Markgrafs Trib. Load (0.80)
Local Surface Water Load	Lognormal	1962 – 2011 calibrated P8 model	Yes	Yes	Precipitation (0.44) Surface Runoff Volume (0.80)
Markgrafs Tributary Inflow Load	Gamma	Measured 1994-2011in-lake concentration multiplied by volume from P8 model. 1962-1993 load estimated with regression relationship for1994-2011	Yes	Yes	Precipitation (0.89) Markgrafs Trib. Volume (0.98)
North Wilmes Tributary Inflow Load	Lognormal	Distribution Assumed Same as Load from Local Runoff	Yes	Yes	Precipitation (0.44) N. Wilmes Trib. Volume (0.80)

Notes:
All distributions truncated at lowest and highest values in the 50-year period of record
Distributions generally were best fit for the 50-year period (1962-2011) of seasonal values.
Correlation coefficients were derived from actual data.
Atmospheric TP load distribution assumed to be the same as precipitation with equal coefficient of variation.
Value in parentheses is correlation coefficient.
See **Appendix B** for the statistical distribution parameters.
Statistical distributions were the "best fit" distribution, as determined by the Crystal Ball software.

Prior to completing the Monte Carlo modeling analysis, the South Wilmes Lake CNET model was calibrated to 2009/2010 average summer season mean TP, chl-*a*, and SD and validated for summer season of 2011. The modeling used the seasonal water budget and TP mass balance around the Lake as described in **Sections 2.4.8 and 2.5.6**. The following CNET models were used in the simulations:

- Total phosphorus sedimentation model: Canfield & Bachman (1981), Natural Lakes
- Chlorophyll-*a* response model: P, Linear
- Secchi-disk Transparency response model: Secchi vs. Chl-*a* and Turbidity.

The goal of the CNET model calibration was to adjust each sedimentation and response models' calibration coefficient to reduce the errors between measured and simulated values. Following the calibration procedure of the other lakes, the North Wilmes Lake CNET model was also calibrated to the average water quality data from 2009 and 2010, and it was validated to the water quality data in the year 2011. **Table 27** shows the results of model calibration using the 2009/2010 average summer season mean data. **Table 28** shows the results of model validation using the 2011data.

Table 27. South Wilmes Lake CNET Model calibration results for an average of the 2009/2010 summer seasons (June through September) mean concentrations

	Calibration Coefficient	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	0.5	79.1 ppb	73.4 ppb	-5.7 ppb	-7.2 %
Chlorophyll-a	1.3	29.6 ppb	26.7 ppb	-2.9 ppb	-9.7 %
Secchi Disk	1.7	1.5 meters	1.2 meters	-0.3 meters	-20.8 %*

* Suggests something other than chlorophyll-a could be a larger factor in the Secchi Disk depth, e.g. algae, turbitity, organic matter, etc.

Table 28. South Wilmes Lake CNET Model validation results for 2011 summer season (June through September) mean concentrations

	Measured	Modeled	Absolute Difference	Percent Difference
Total Phosphorus	63.3 ppb	46.6ppb	-16.7 ppb	-26.4 %
Chlorophyll-a	16.2 ppb	16.9 ppb	0.7 ppb	4.3 %
Secchi Disk	1.8 meters	1.4 meters	-0.4 meters	-22.2 %

3.4 Modeling the Loading Capacity

The water budget and TP mass balance used to develop the loading capacities and TMDL equations for Armstrong, Markgrafs, and Wilmes Lakes used the average values and statistical distributions for a 50-year period of record to represent the long-term condition. Fifty-years of precipitation data was used as input to the watershed model to compute long-term summer season surface water runoff and TP load. Additional methods were used to estimate the long-term evaporation and atmospheric loading, as shown in **Tables 17, 20, 23, and 26 in Section 3.3**. Long-term average internal TP loading rates were simulated as 23 kg/season, 32 kg/season, and 13 kg/season, and 14 kg/season as discussed in **Section 2.5.3,** for Armstrong, Markgrafs, North Wilmes, and South Lakes, respectively. The long-term average change in storage was assumed to be zero, and the groundwater + error term was assumed to be an average of values computed during the hydrologic budget in **Section 2.5.4**. The surface water outflow from the lake was computed by the CNET model. The long-term average hydrologic budgets for the four lakes are shown in **Figure 21** through **Figure 24**. Results of the modeling and the impacts of various load reductions are discussed below.

Figure 21. Long-term average Armstrong Lake summer season (June through September) water budget.

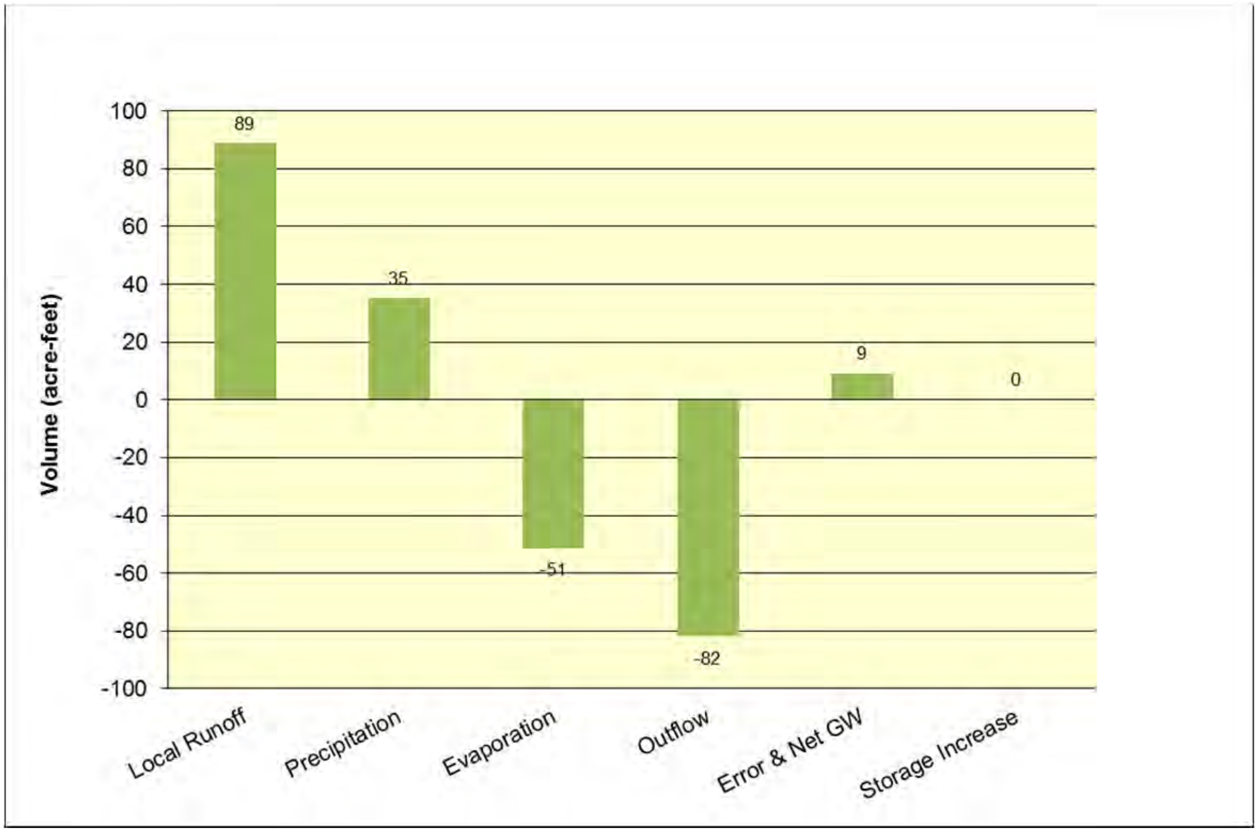


Figure 22. Long-term average Markgrafs Lake summer season (June through September) water budget.

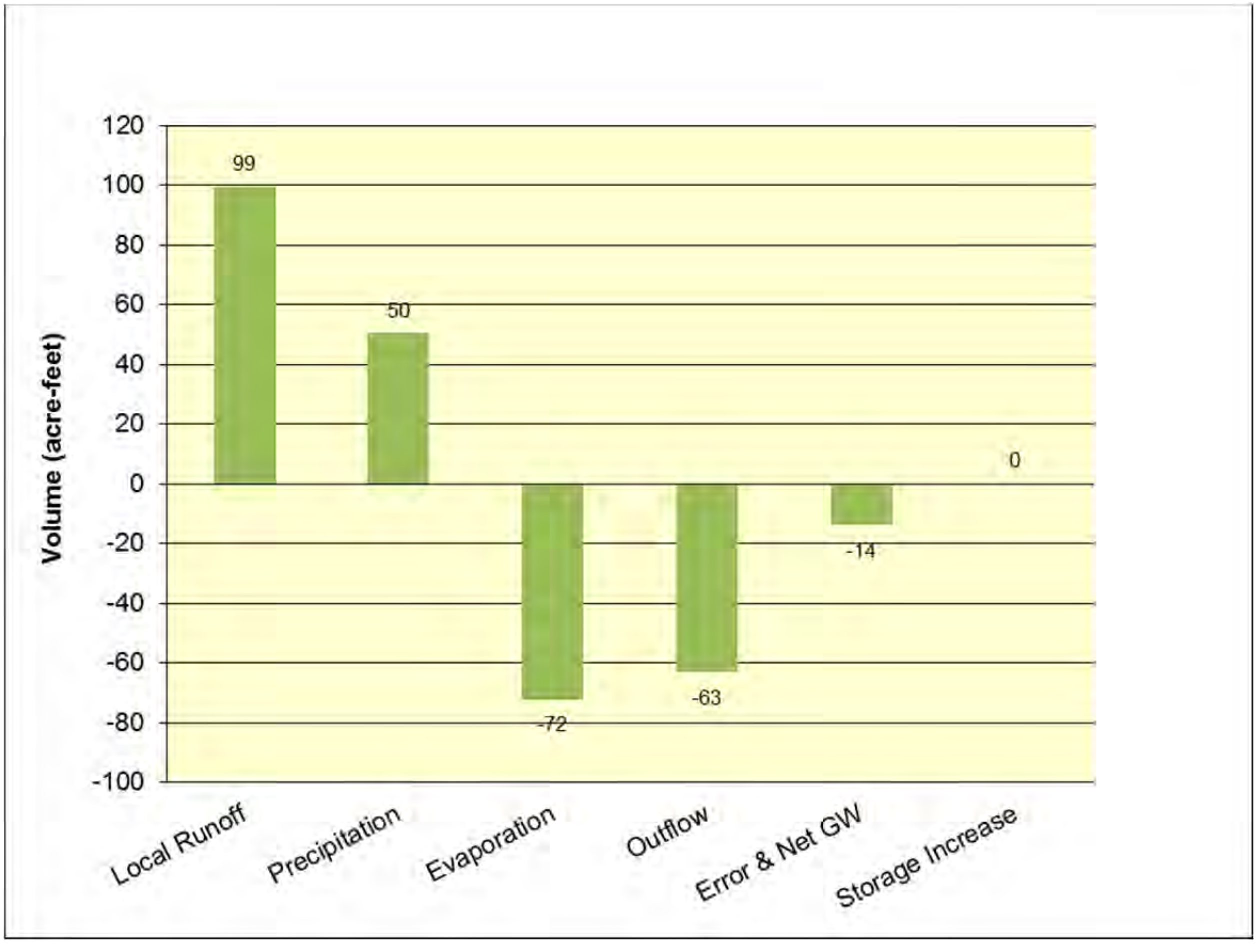


Figure 23. Long-term average North Wilmes Lake summer season (June through September) water budget.

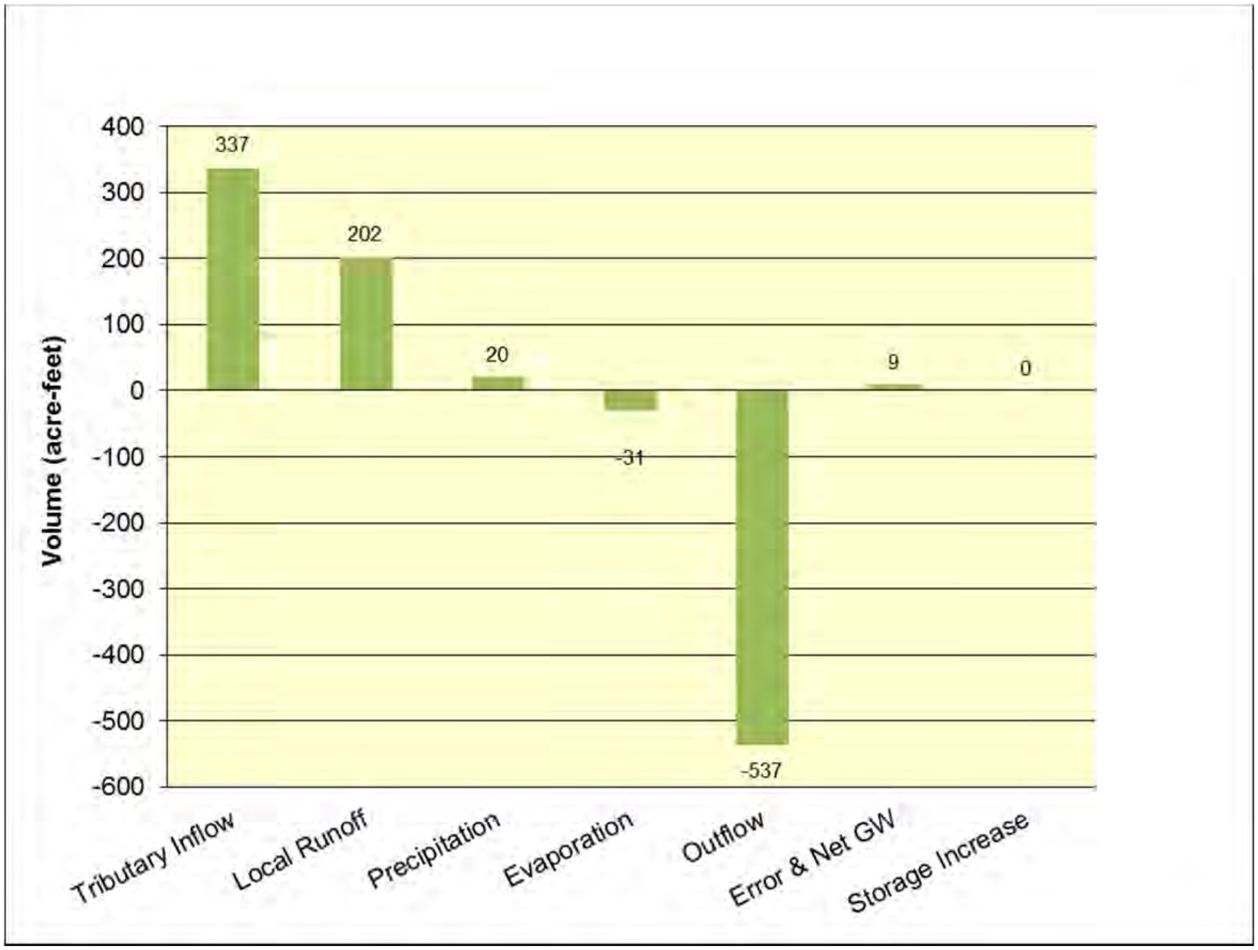
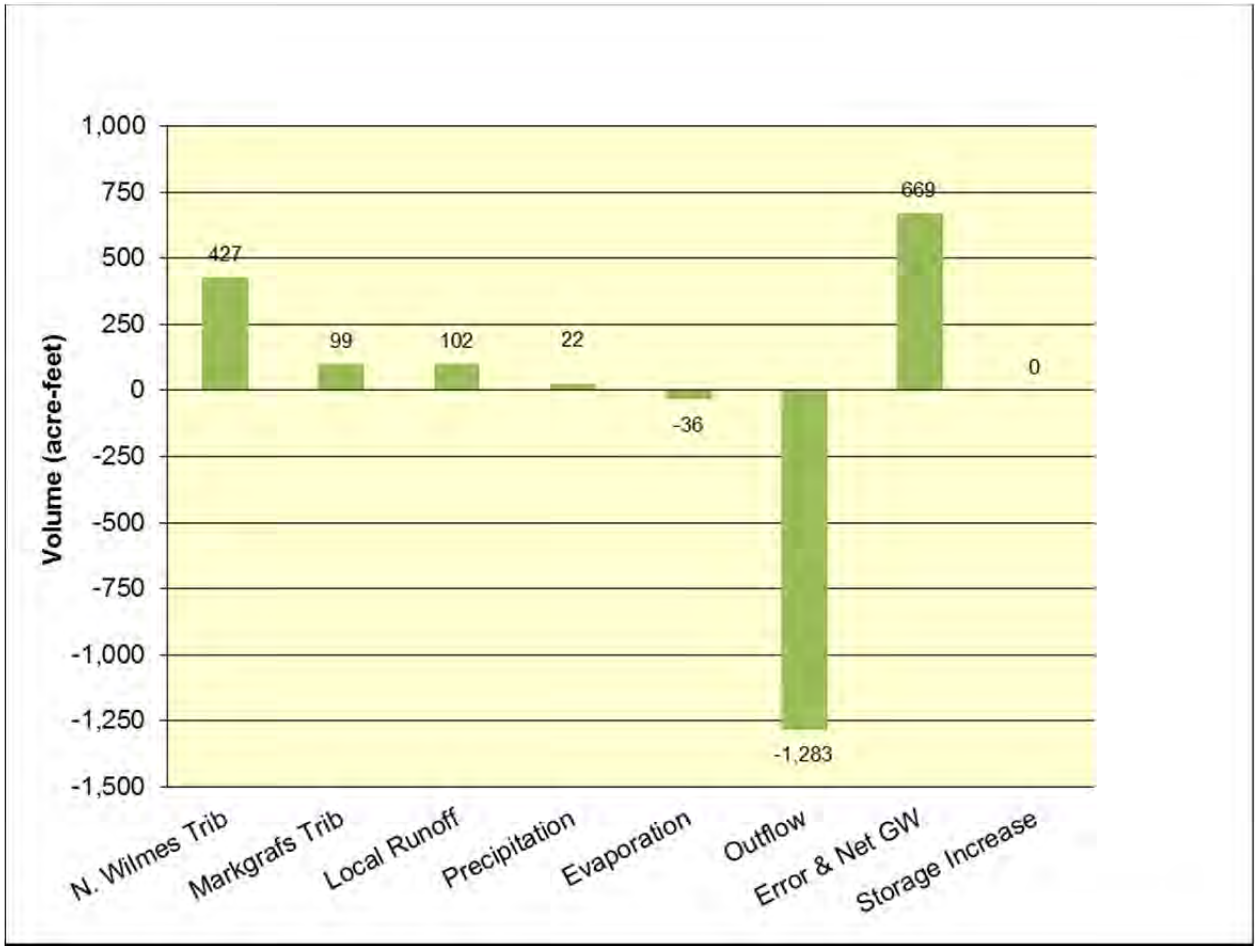


Figure 24. Long-term average South Wilmes Lake summer season (June through September) hydrologic budget



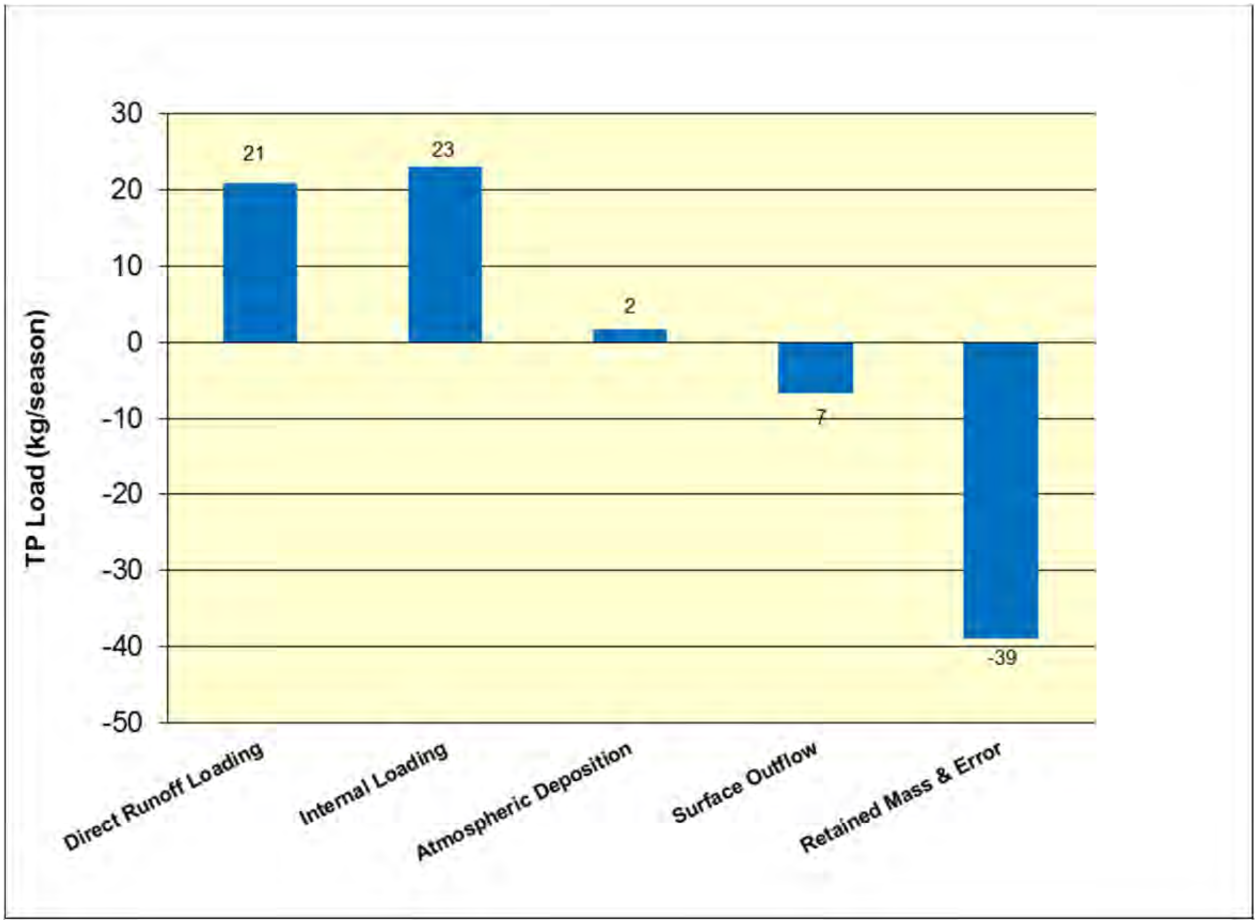
4.0 EUTROPHICATION RESPONSE, LOADING CAPACITY AND TMDL EQUATION

To simulate the load reductions and therefore the maximum allowable load (i.e., loading capacity) needed to achieve the State water quality standard in Armstrong, Markgrafs, and Wilmes Lakes, a series of model simulations were performed. Each simulation reduced the total amount of TP entering a lake during the summer season, computing the anticipated response within the lake. The goal of the modeling was to identify the loading capacity of each lake (i.e., the maximum allowable load to the system, while allowing it to meet water quality standards) during the June 1 – September 30 summer season. The loading capacity is then allocated to the various sources in the TMDL equation. Consistent with recent MPCA guidance, it was assumed that if a lake meets the State's TP water quality standard that chl-*a* and SD within the system will respond accordingly and eventually also reach the State-defined goals (even if the results of the CNET modeling don't predict that they will). This approach assumes that data collected and extensively analyzed by the MPCA during standards development provides a more accurate estimate of how lakes will respond when moved from an impaired to unimpaired state than the relationships that exist within the CNET program.

4.1 Armstrong Lake Eutrophication Response and Loading Capacity

Figure 25 shows the long-term average TP mass balance of Armstrong Lake (i.e., the current condition scenario) as simulated in the CNET model. Results show that Armstrong Lake currently receives a total summer season TP loading of approximately 46 kg. About 21 kg of that TP comes from surface water runoff; the other major source of TP is from internal load. The CNET model then computes that 39 kg/season TP is removed (on average) from the system.

Figure 25. Long-term average Armstrong Lake summer season (June through September) TP mass balance.



4.1.1 Armstrong Lake Eutrophication Response

Figure 26 to **Figure 31** show the effects of reducing summer season TP loads to Armstrong Lake on the summer mean TP, chl-*a* and Secchi disk depth within the lake (based on the CNET model). Loads were reduced incrementally within the CNET model and assumed to come from the surface runoff and internal loading components of the mass balance. Results are presented both in terms of the seasonal mean concentrations as shown by the column graphs and the results of the Monte Carlo analysis. The Monte Carlo analysis results are presented as a series of lines, where each line represents a statistical distribution of the seasonal mean values.

Figure 26. Armstrong Lake Seasonal Mean (June through September) TP Concentrations under Select Load Reduction Scenarios; Current Conditions = 46 kg/season.

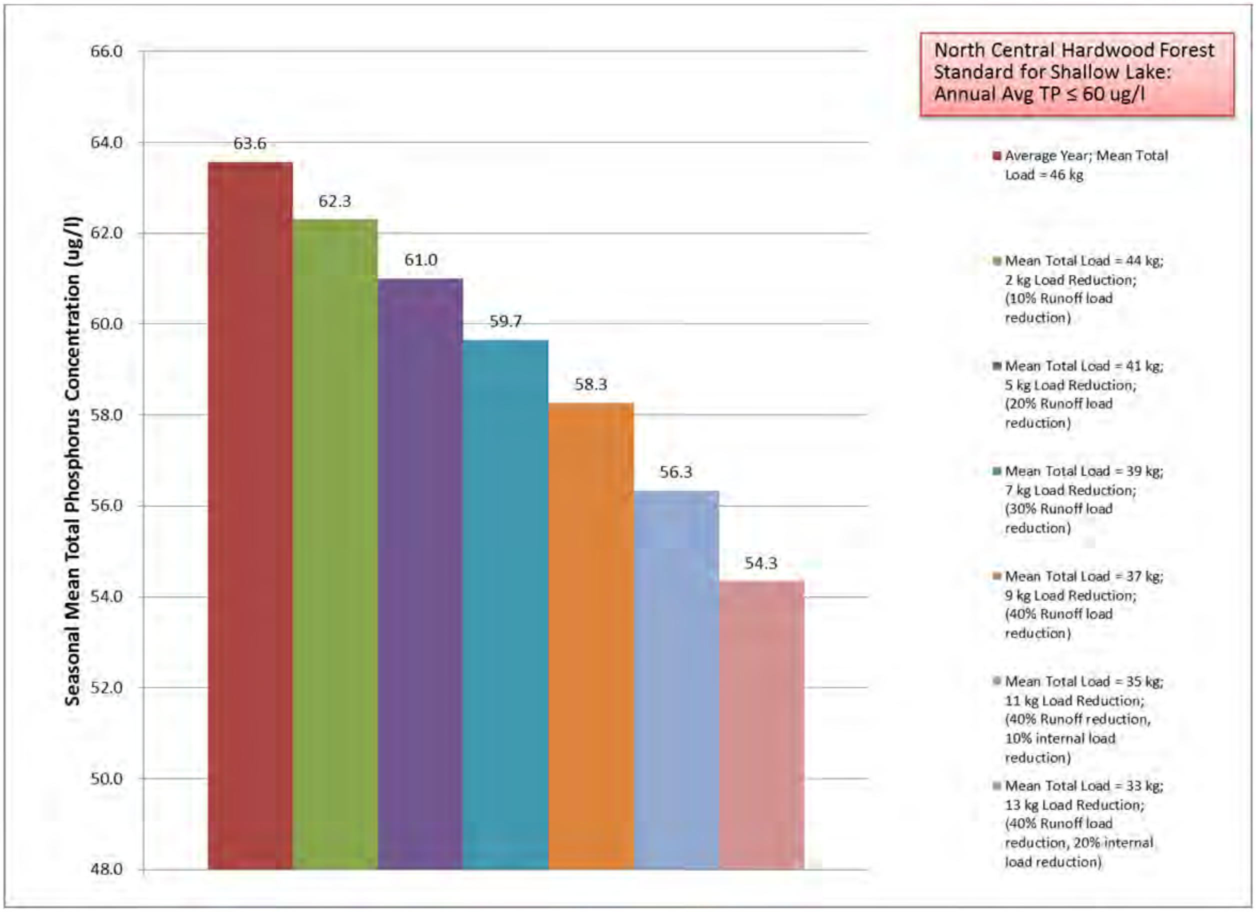
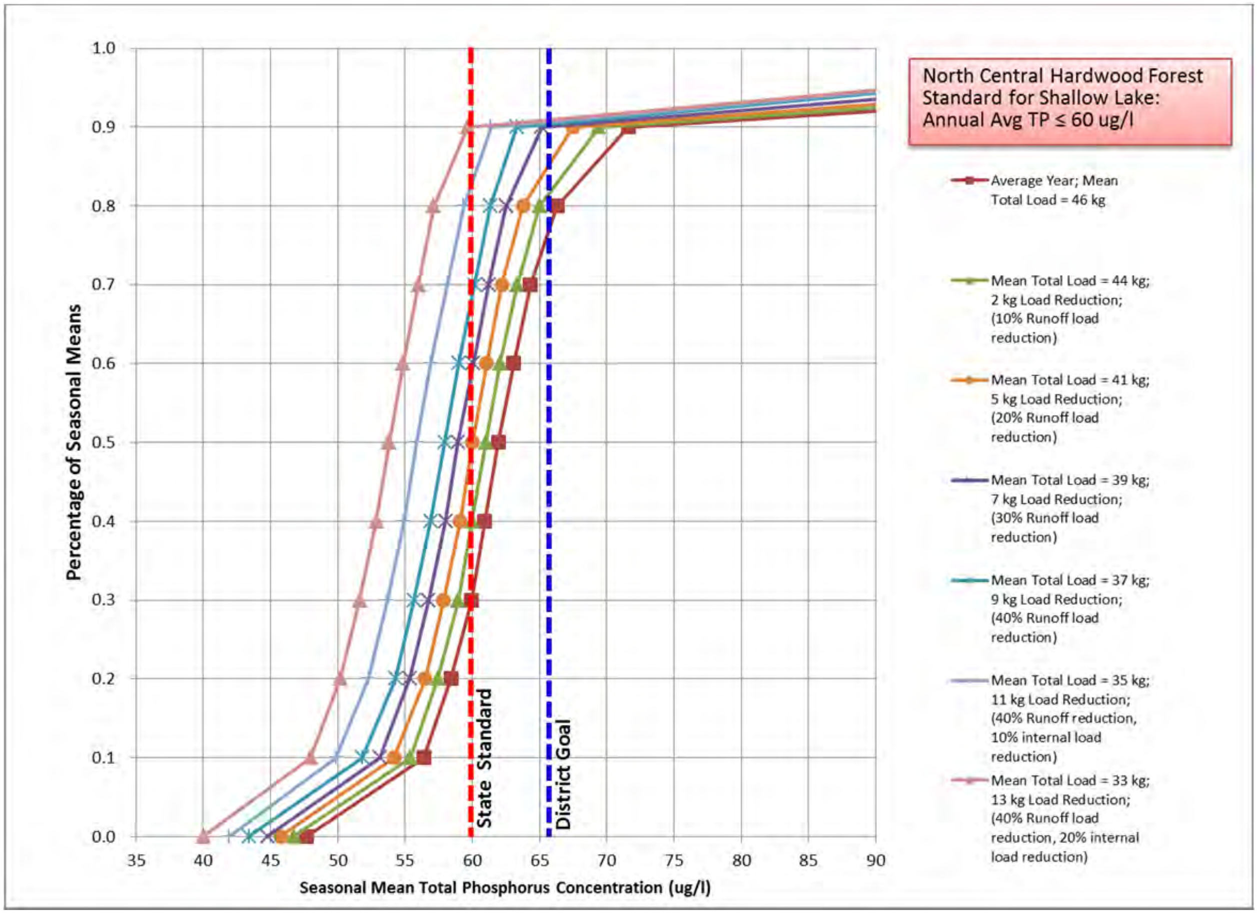


Figure 27. Armstrong Lake Frequency Distribution of Seasonal (June through September) Mean TP Concentrations Resulting from Select Load Reduction Scenarios and Table of Data used to Produce the Graphical Illustration; Current Conditions = 46 kg/season.



		Load Reduction from Current Load for Average Summer Season					
Non-exceedance Percentile	Average Year (current)	2 kg	5 kg	7 kg	9 kg	11 kg	13 kg
Mean	63.6	62.3	61.0	59.7	58.3	56.3	54.3
0%	47.7	46.8	45.8	44.8	43.4	41.9	40.0
10%	56.4	55.4	54.2	53.1	51.8	49.9	48.0
20%	58.4	57.5	56.5	55.4	54.3	52.3	50.2
30%	60.0	59.0	57.9	56.8	55.7	53.7	51.6
40%	60.9	60.0	59.1	58.0	56.9	54.9	52.9
50%	61.9	61.0	60.0	59.0	58.0	55.9	53.8
60%	63.1	62.1	61.1	60.1	59.0	56.9	54.9
70%	64.3	63.4	62.2	61.2	60.2	58.1	56.0
80%	66.3	65.0	63.8	62.5	61.4	59.4	57.2
90%	71.6	69.4	67.5	65.2	63.3	61.4	59.7
100%	161.2	153.1	144.4	135.0	125.0	124.5	124.0

Figure 28. Armstrong Lake Seasonal (June through September) Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 46 kg/season.

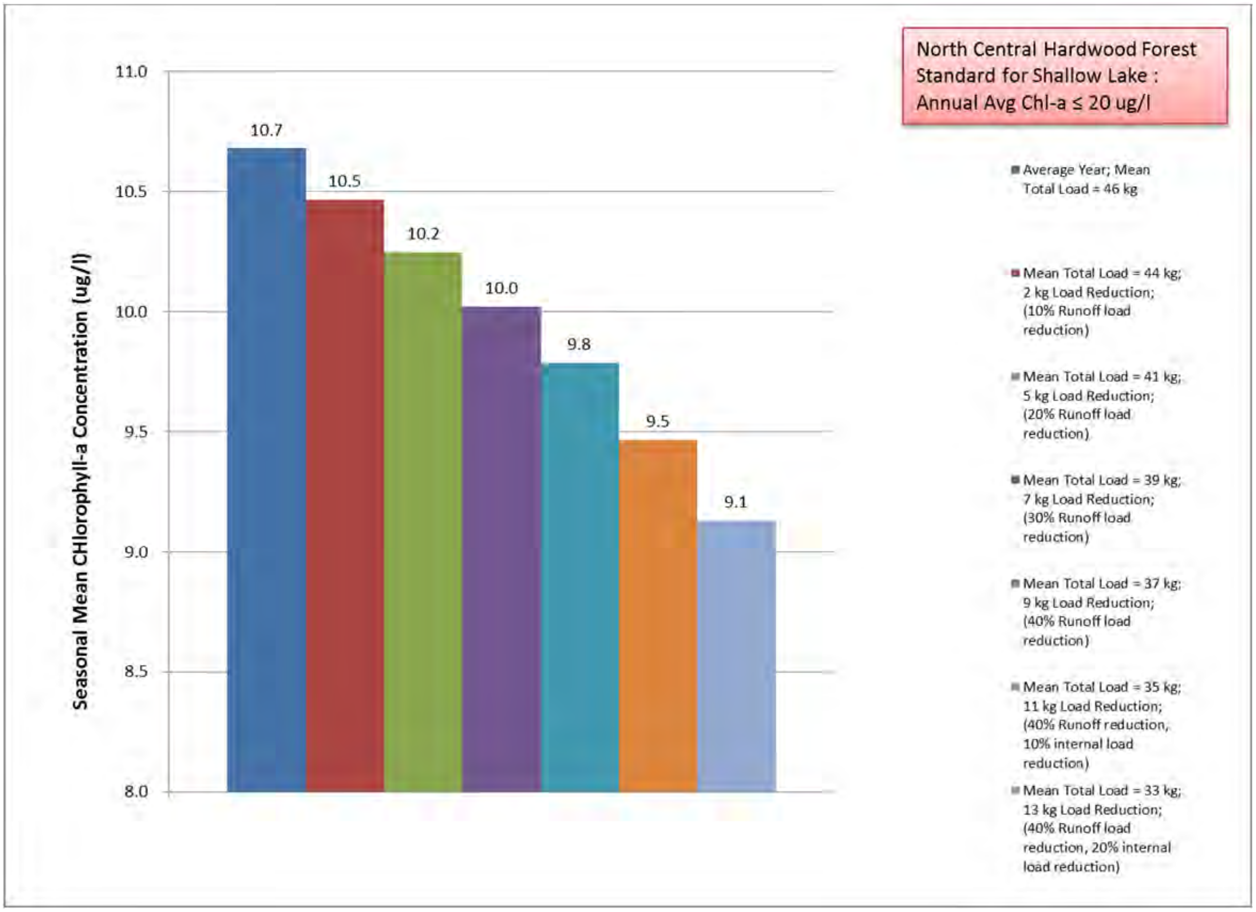


Figure 29. Armstrong Lake Frequency Distribution of Seasonal Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 46 kg/season.

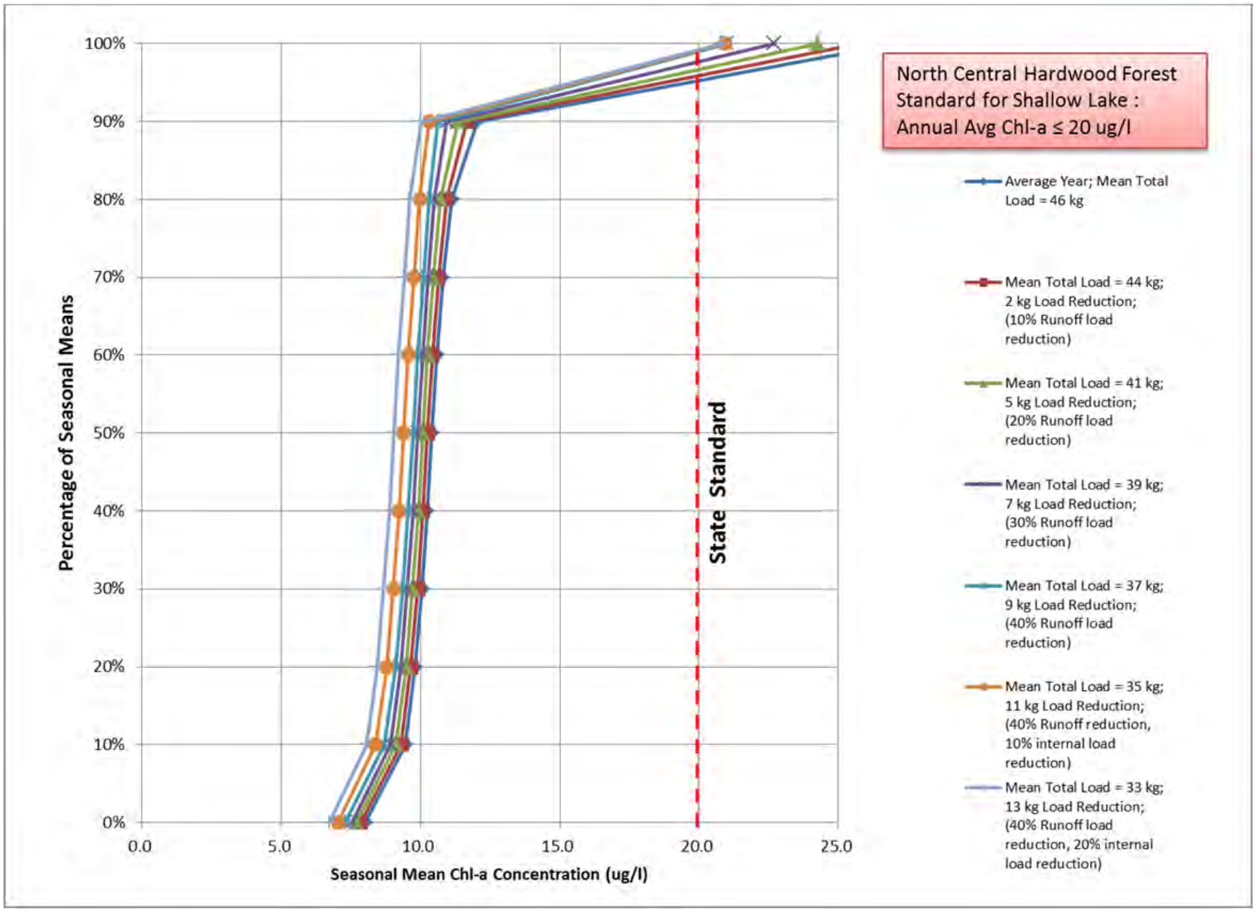


Figure 30. Armstrong Lake Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 46 kg/season.

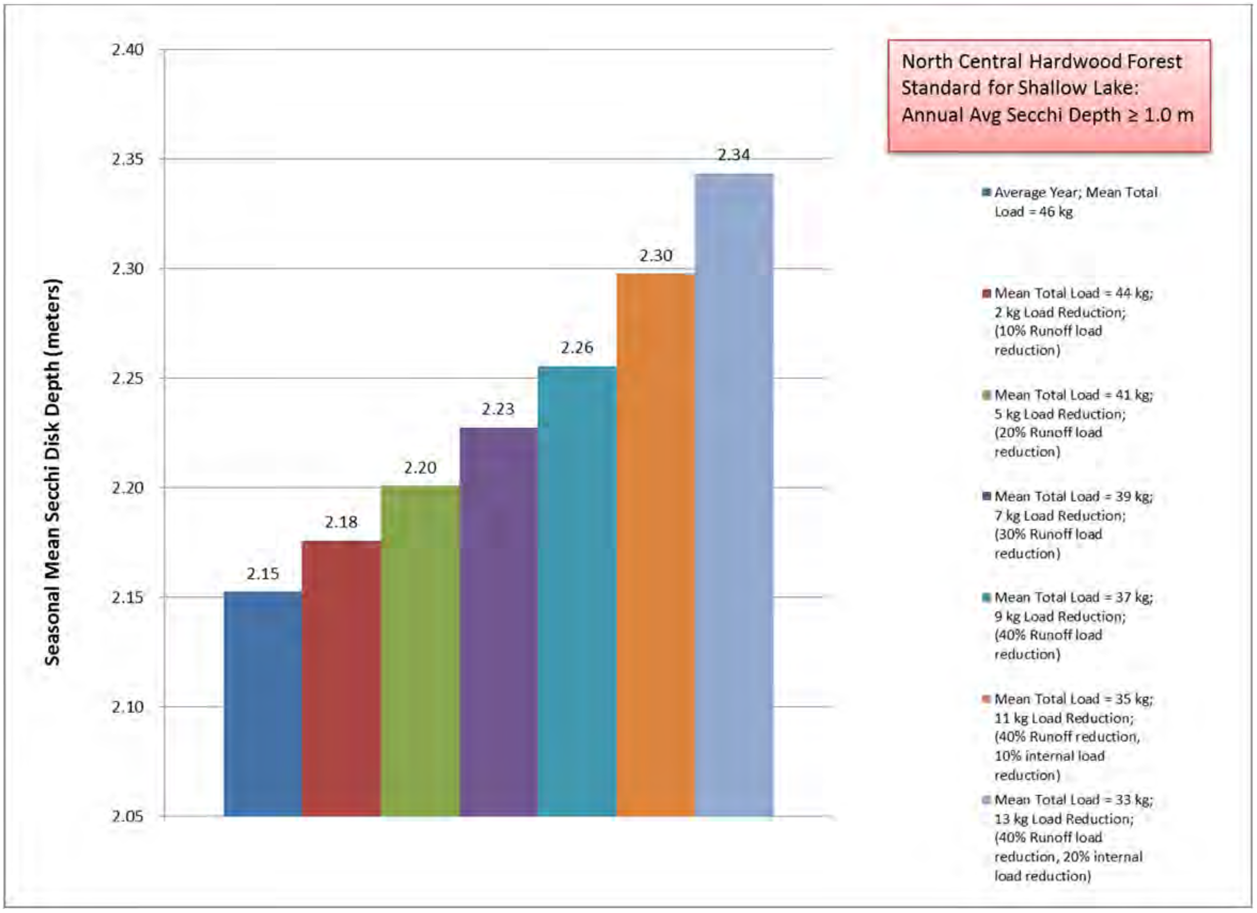
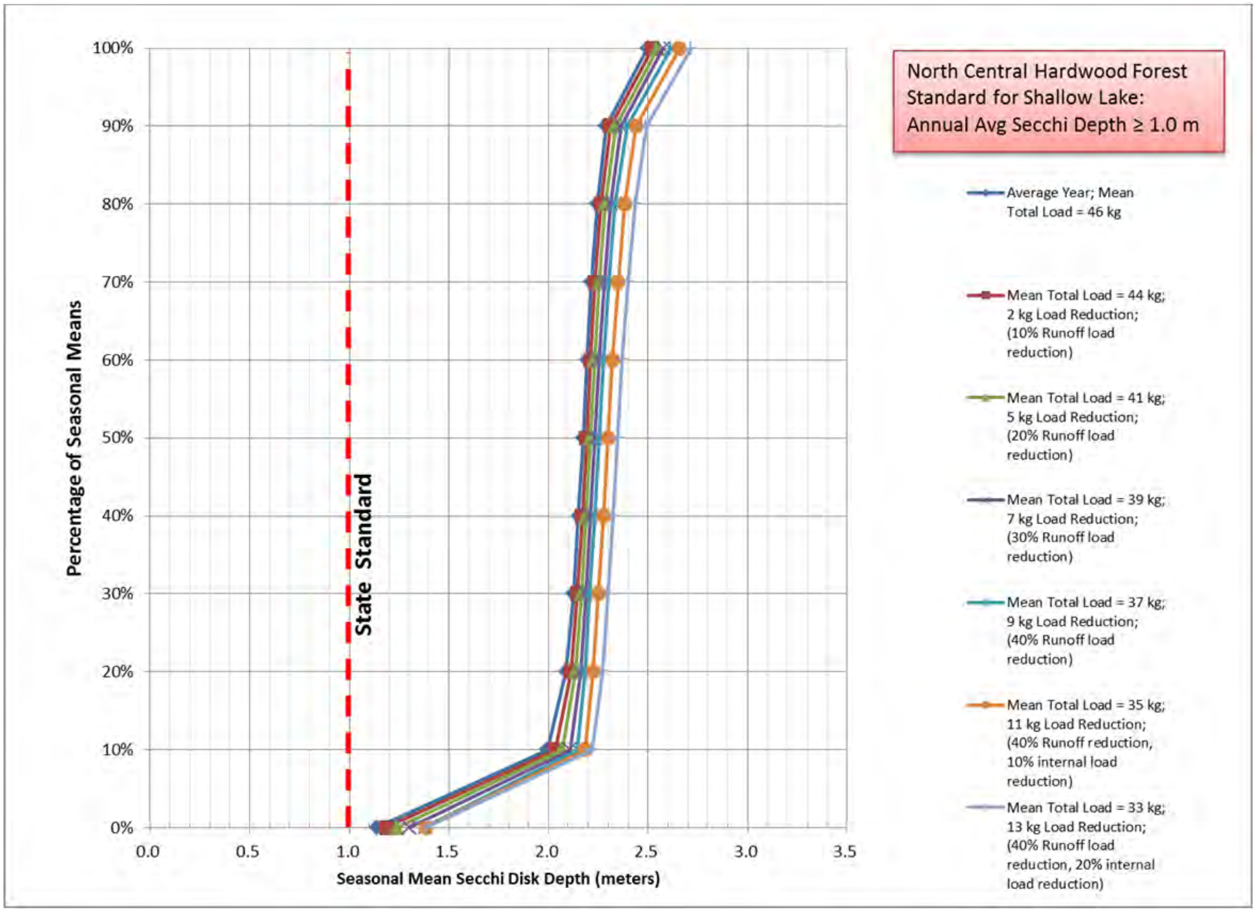


Figure 31. Armstrong Lake Frequency Distribution of Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 46 kg/season.



4.1.2 Armstrong Lake Loading Capacity

The loading capacity is the maximum allowable TP load to Armstrong Lake which can occur, while still achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l. The SWWD also has goal for Armstrong Lake that the TP Trophic State Index (TSI) value will range between 63 and 66. A TSI value of 63-66 correlates to a TP concentration of 59.2-72.9 ug/l, and the District has selected the average value of 66.1 ug/l as the TP goal for Armstrong Lake. Since the State standard 60 ug/l is more stringent, it will be the basis for computing the allowable load. Although this study is not, technically a Total Maximum Daily Load (TMDL) study, the function of a loading capacity defined here replicates that developed under a TMDL. Given the similarity between this work and a TMDL, the loading capacity computed for Armstrong Lake is allocated between non-point sources (i.e., the load allocation – LA – in a TMDL study), point sources (i.e., the wasteload allocation – WLA – in a TMDL study), and a margin of safety (MOS). The LA component of the loading capacity includes existing and future nonpoint sources (i.e., atmospheric deposition and internal load); the WLA component includes storm-sewered and overland runoff from the Armstrong Lake watershed. The MOS used is an explicit expression, intended to reflect the lack of knowledge and uncertainty in establishing the load capacity.

In this study, the loading capacity of Armstrong Lake was computed using a stochastic approach based on the hydrology and water quality simulated by the P8/CNET modeling. The loading capacity (allowable load) of the Lake was defined as that which reduces the seasonal mean TP concentration for the 50^{th} percentile non-exceedance value to the MPCA numeric standard (60 ug/l). Given that the SWWD's lake-specific standards for Armstrong Lake are less conservative than the MPCA's, achieving the State standard will satisfy those of the District. Since the loading capacity of Armstrong Lake is computed using a stochastic approach (which takes uncertainty and variability into consideration), the MOS was computed as 5% of the allowable load.

Results of the loading capacity analysis are shown in **Figure 27**. A line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the North Central Hardwood Forest ecoregion. A table accompanying **Figure 27** shows the values for the values used to produce the figure. Results of this analysis show that a 5 kg summer season TP load reduction is needed to achieve the water quality standard. **Table 29** shows the load allocations that would be employed if Armstrong Lake were to be evaluated as a TMDL-listed water body. The summer season daily values presented in **Table 29** were computed based on seasonal values shown in **Figure 27** and its accompanying table.

Table 29. Armstrong Lake Loading Capacity to Meet State Standards June through September growing season.

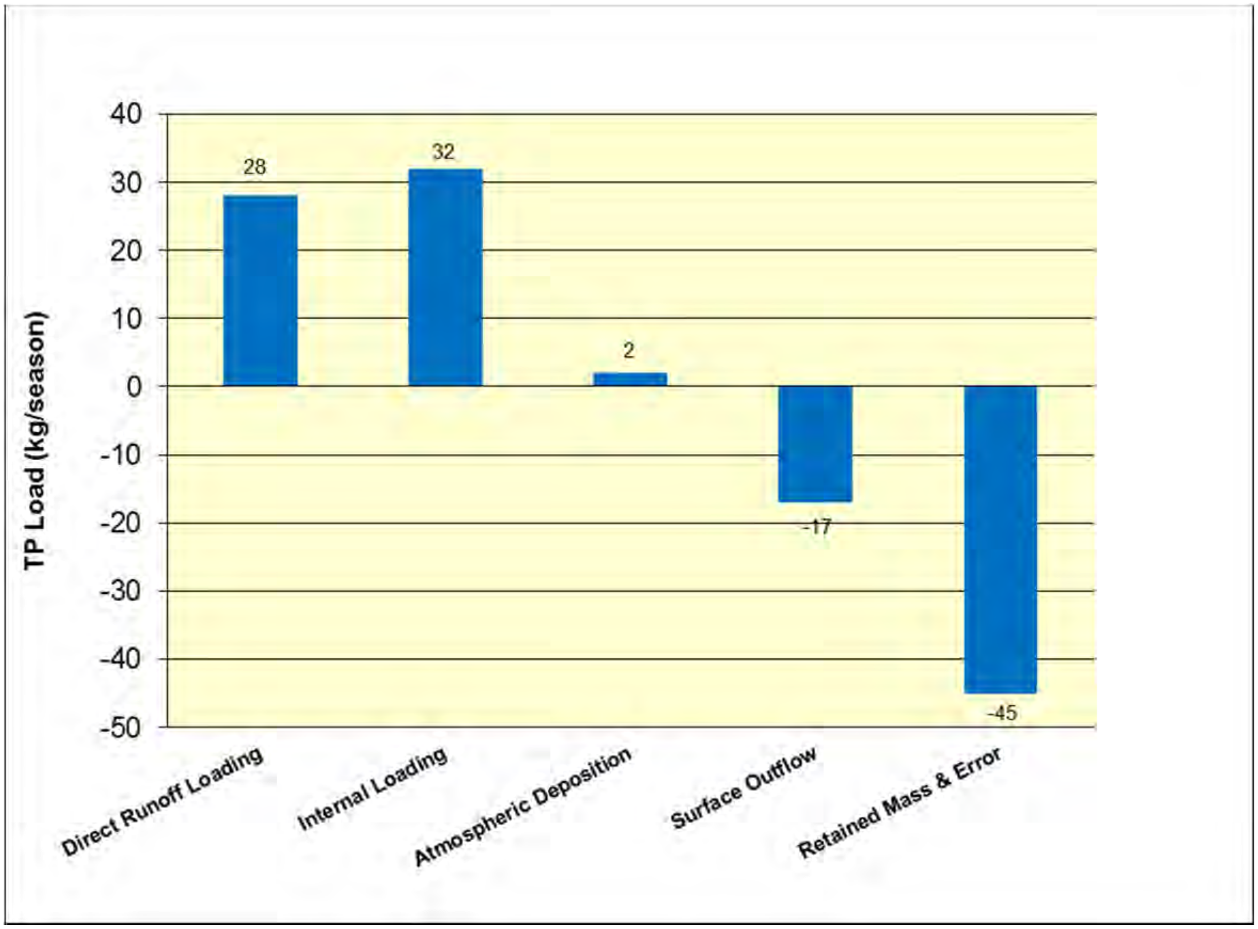
	Loading (kg/day)	=	Load Allocation (kg/day)	+	Wasteload Allocation (kg/day)	+	Margin of Safety (kg/day)
Current Condition (46 kg; 122 days)	0.377	=	0.205	+	0.172	+	0
Goal: 60 ug/L (41 kg; 122 days)	0.336	=	0.205	+	0.114	+	0.017

As summarized in **Table 29**, it is estimated that the current 0.377 kg/d summer season TP load to Armstrong Lake would have to be reduced to 0.336 kg/d. Under this scenario, the wasteload allocation (storm-sewered runoff from the watershed) would have to be reduced from 0.172 to 0.114 kg/d (21.0 to 16 kg/season). The wasteload allocation represents what is considered a technically feasible reduction through the installation of BMPs as the fully developed watershed redevelops. If the entire load reduction is achieved through reductions in wasteload, then no reduction in load allocation is necessary, which is comprised of both atmospheric and internal loading from the phosphorus-laden bottom sediments. In reality any combination of waste load allocation and load allocation equaling 0.336 kg/d is able to achieve the loading capacity.

4.2 Markgrafs Lake Eutrophication Response and Loading Capacity

Figure 32 shows the long-term average TP mass balance of Marksgrafs Lake (i.e., the current condition scenario) as simulated in the CNET model. Results show that Marksgrafs Lake currently receives a total summer season TP loading of approximately 63 kg. About 28 kg of that TP comes from surface water runoff; and 32 kg comes from internal load. The CNET model then computes that 46 kg/season TP is removed (on average) from the system.

Figure 32. Long-term average Markgrafs Lake summer season (June through September) TP mass balance.



4.2.1 Markgrafs Lake Eutrophication Response

Figure 33 through **Figure 38** show the effects of reducing summer season TP loads to Armstrong Lake on the summer mean TP, chl-*a* and Secchi disk depth within the lake (based on the CNET model). Loads were reduced incrementally within the CNET model and assumed to come from the surface runoff and internal loading components of the mass balance. Results are presented both in terms of the seasonal mean concentrations as shown by the column graphs and the results of the Monte Carlo analysis. The Monte Carlo analysis results are presented as a series of lines, where each line represents a statistical distribution of the seasonal mean values.

Figure 33. Markgrafs Lake Seasonal Mean (June through September) TP Concentrations under Select Load Reduction Scenarios; Current Conditions = 63 kg/season.

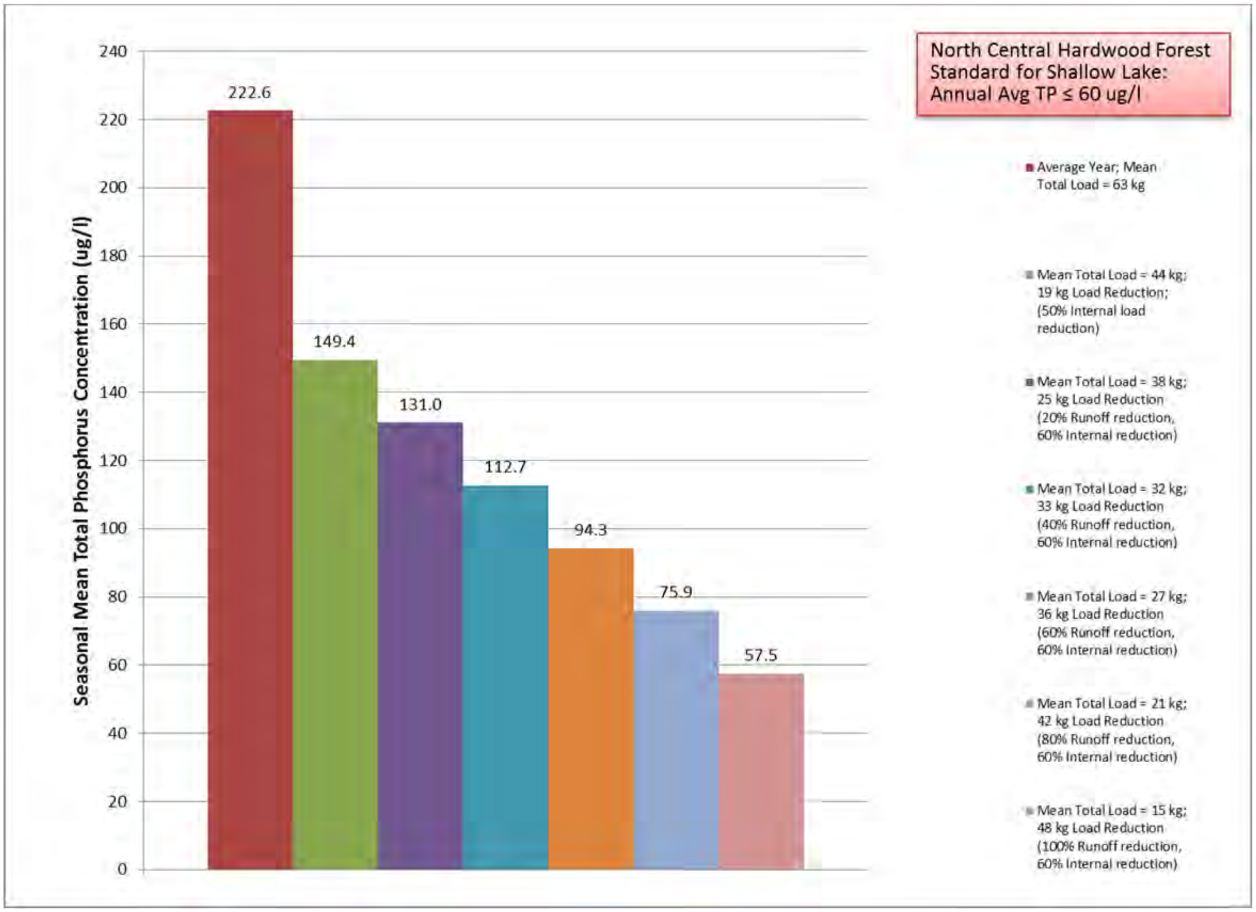
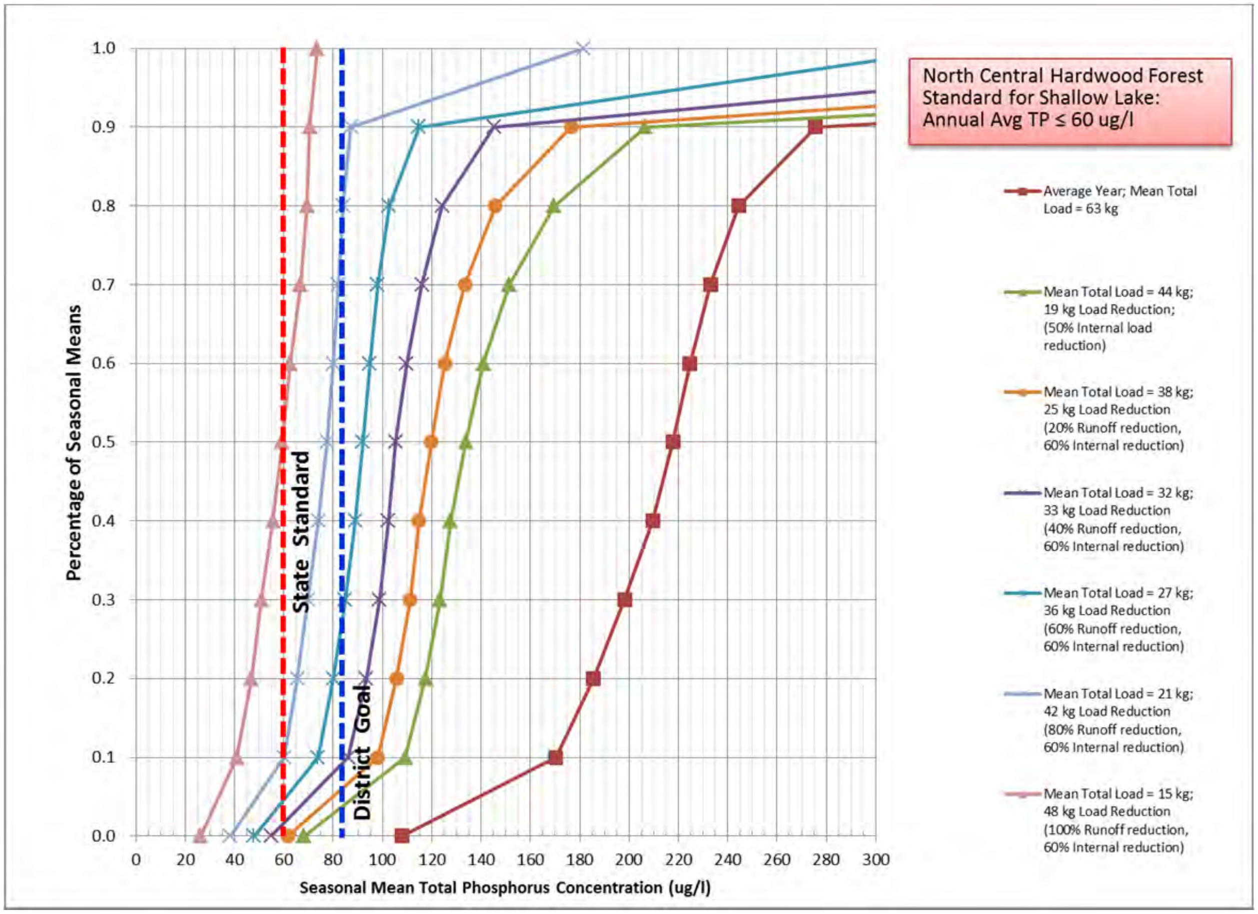


Figure 34. Markgrafs Lake Frequency Distribution of Seasonal (June through September) Mean TP Concentrations Resulting from Select Load Reduction Scenarios and Table of Data used to Produce the Graphical Illustration; Current Conditions = 63 kg/season.



		Load Reduction from Current Load for Average Summer Season					
Non-exceedance Percentile	**Average Year (current)**	**19 kg**	**25 kg**	**33 kg**	**36 kg**	**42 kg**	**48 kg**
Mean	222.6	149.4	131.0	112.7	94.3	75.9	57.5
0%	107.9	68.2	61.6	54.9	47.9	38.3	26.2
10%	170.3	109.2	98.0	86.1	73.9	60.3	41.0
20%	185.6	117.4	105.7	93.4	80.1	65.6	46.9
30%	198.2	123.3	111.3	98.8	84.9	69.8	51.0
40%	209.5	127.7	114.8	102.3	89.1	74.0	55.5
50%	217.7	133.8	119.7	105.3	92.1	77.5	59.3
60%	224.7	141.0	125.3	109.9	94.8	80.1	62.6
70%	233.1	151.5	133.4	116.0	98.1	82.0	66.8
80%	244.5	169.5	145.7	124.2	102.6	84.0	69.4
90%	275.6	206.6	176.5	145.3	114.8	87.3	70.6
100%	827.5	792.5	639.8	487.1	334.4	181.7	73.6

Figure 35. Markgrafs Lake Seasonal (June through September) Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 63 kg/season.

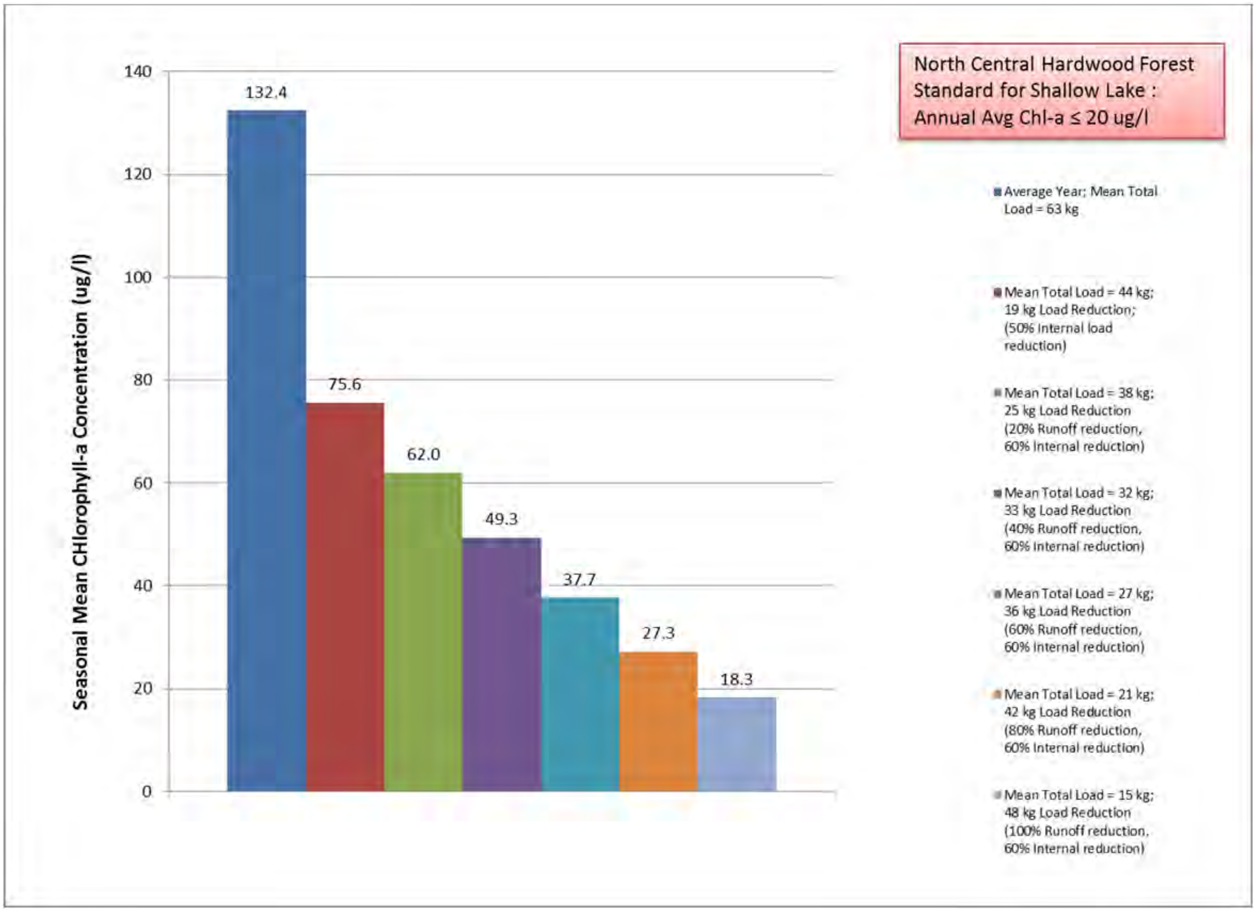


Figure 36. Markgrafs Lake Frequency Distribution of Seasonal Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 63 kg/season.

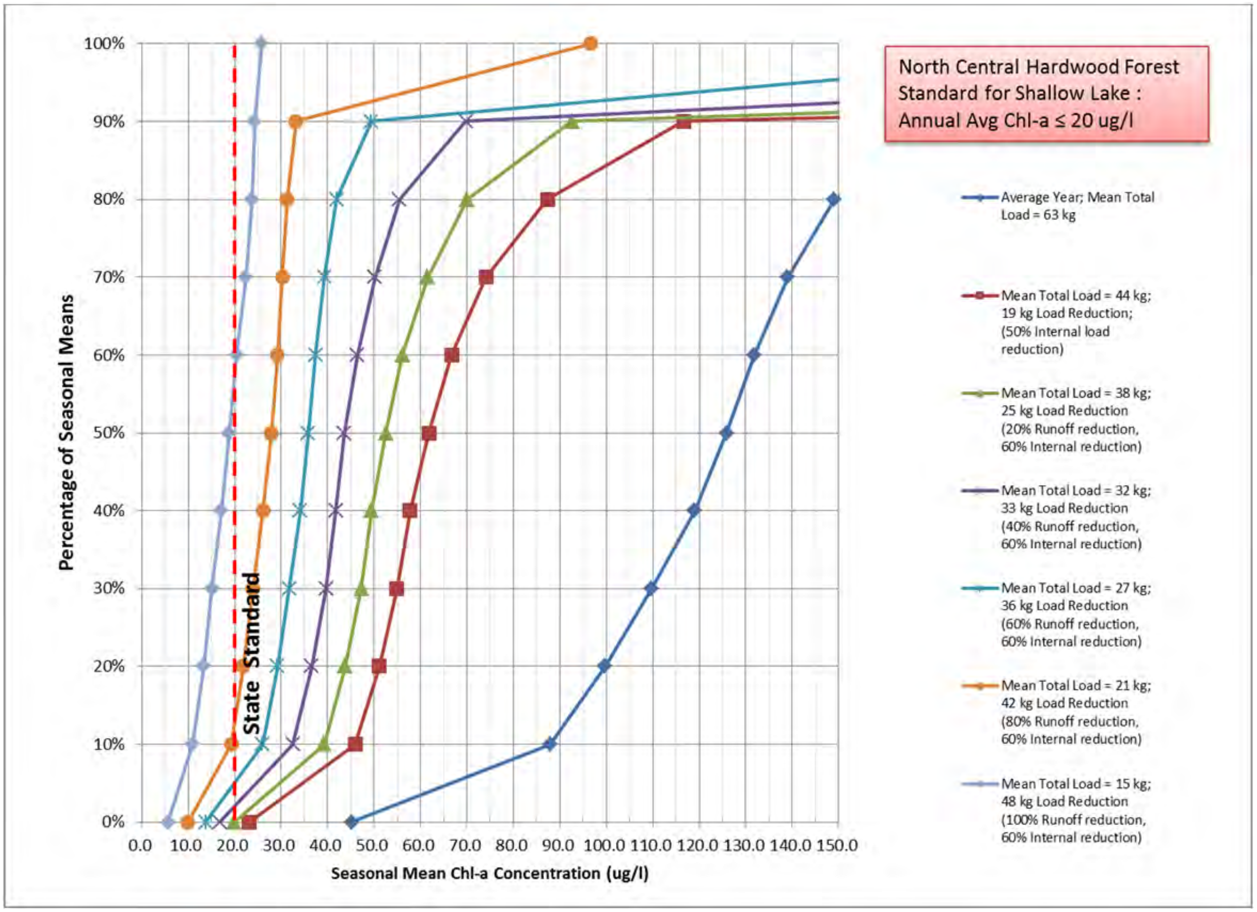


Figure 37. Markgrafs Lake Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 63 kg/season.

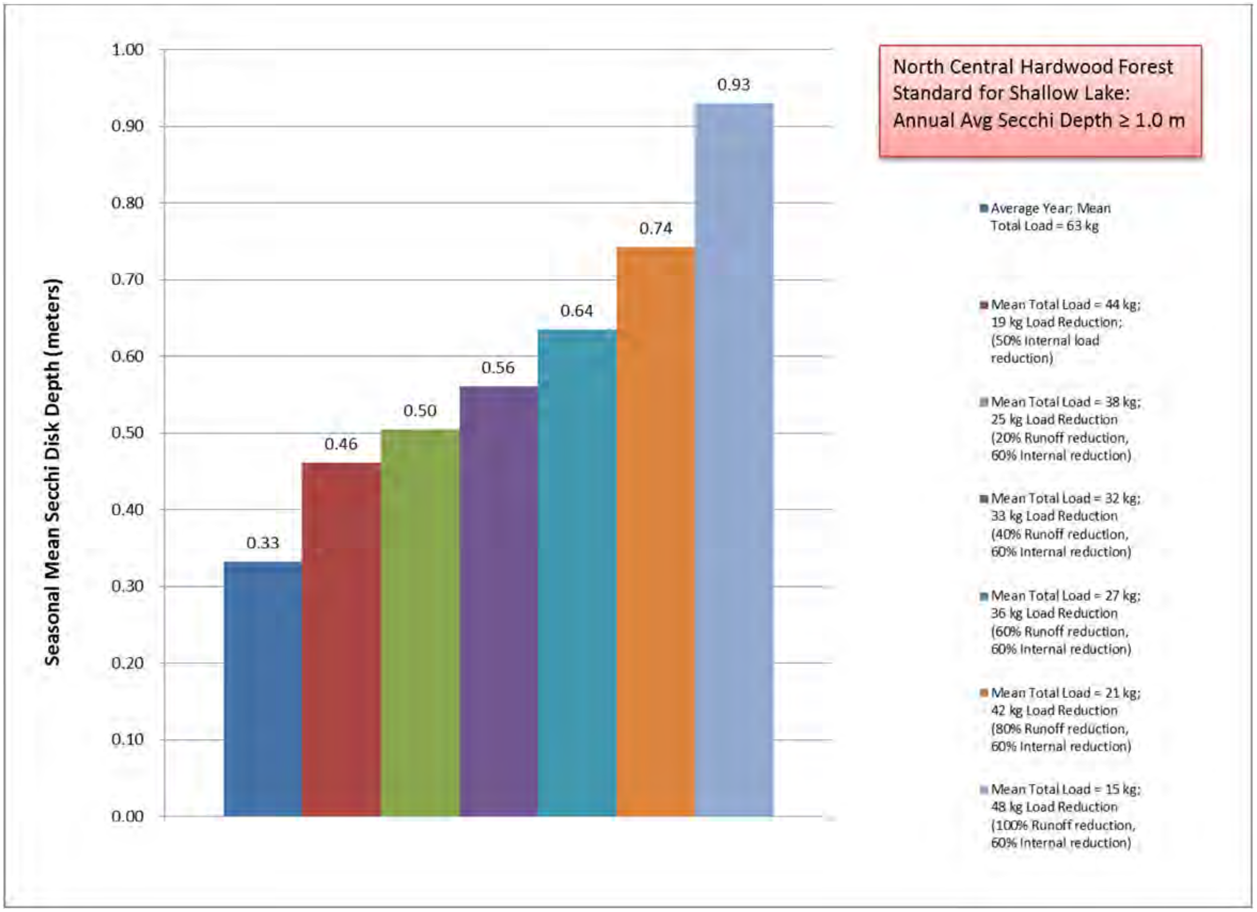
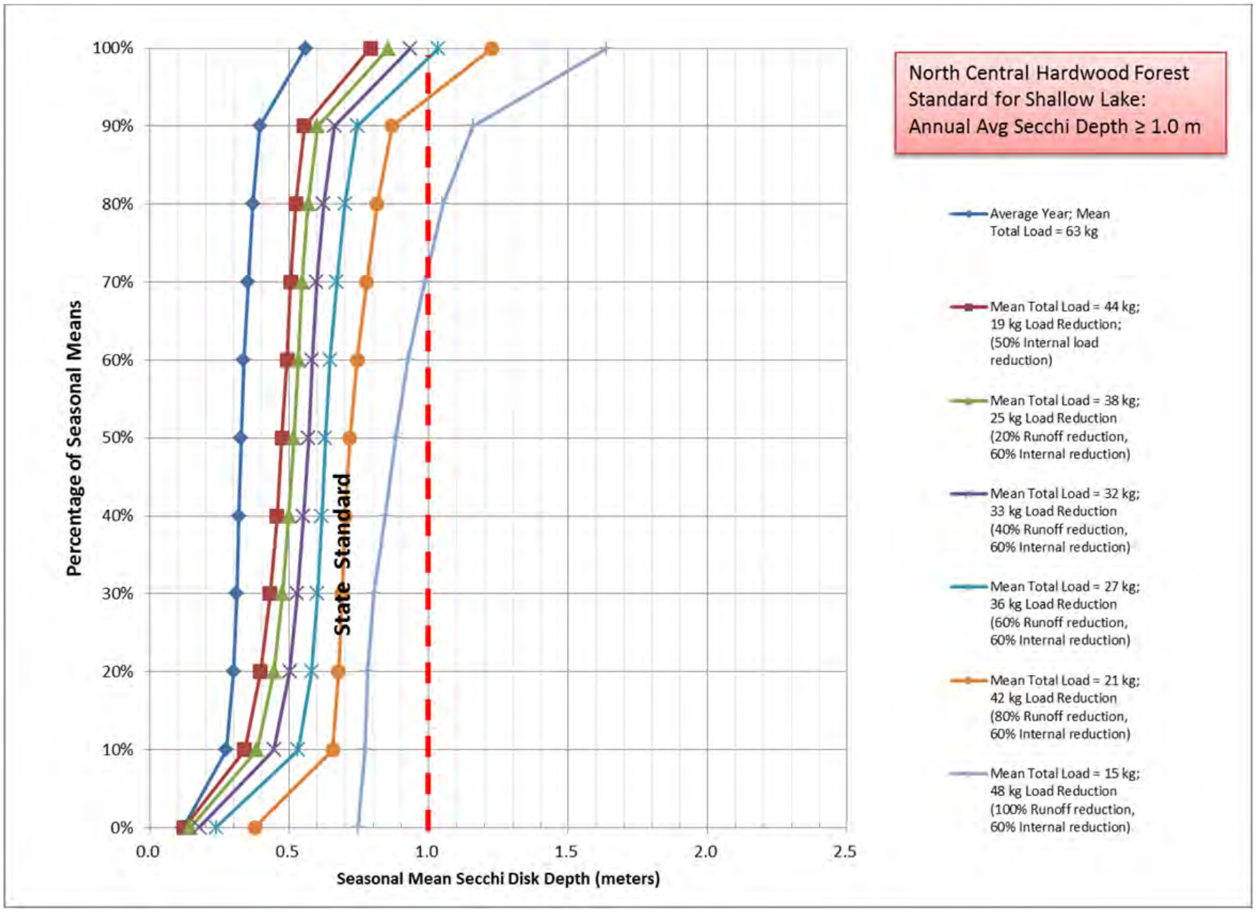


Figure 38. Markgrafs Lake Frequency Distribution of Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 63 kg/season.



4.2.2 Markgrafs Lake Loading Capacity

The loading capacity is the maximum allowable TP load to Markgrafs Lake which can occur, while still achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l. The SWWD also has goal for Markgrafs Lake that the TP Trophic State Index (TSI) value will range between 66 and 70. A TSI value of 66-70 correlates to a TP concentration of 72.9-96.2 ug/l, and the District has selected the average value of 84.6 ug/l as the TP goal for Markgrafs Lake. Since the State standard 60 ug/l is more stringent, it will be the basis for computing the allowable load. Although this study is not, technically a Total Maximum Daily Load (TMDL) study, the function of a loading capacity defined here replicates that developed under a TMDL. Given the similarity between this work and a TMDL, the loading capacity computed for Markgrafs Lake is allocated between non-point sources (i.e., the load allocation – LA – in a TMDL study), point sources (i.e., the wasteload allocation – WLA – in a TMDL study), and a margin of safety (MOS). The LA component of the loading capacity includes existing and future nonpoint sources (i.e., atmospheric deposition and internal load); the WLA component includes storm-sewered and overland runoff from the Markgrafs Lake watershed. The MOS used is an explicit expression, intended to reflect the lack of knowledge and uncertainty in establishing the load capacity.

In this study, the loading capacity of Markgrafs Lake was computed using a stochastic approach based on the hydrology and water quality simulated by the P8/CNET modeling. The loading capacity (allowable load) of the Lake was defined as that which reduces the seasonal mean TP concentration for the 50^{th} percentile non-exceedance value to the MPCA numeric standard (60 ug/l). Given that the SWWD's lake-specific standards for Markgrafs Lake are less conservative than the MPCA's, achieving the State standard will satisfy those of the District. Since the loading capacity of Markgrafs Lake is computed using a stochastic approach (which takes uncertainty and variability into consideration), the MOS was computed as 5% of the allowable load.

Results of the loading capacity analysis are shown in Figure 34. A line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the North Central Hardwood Forest ecoregion. A table accompanying **Figure 34** shows the values for the values used to produce the figure. Results of this analysis show that a 48 kg summer season TP load reduction is needed to achieve the water quality standard. **Table 30** shows the load allocations that would be employed if Markgrafs Lake were to be evaluated as a TMDL-listed water body. The summer season daily values presented in **Table 30** were computed based on seasonal values shown in **Figure 34** and its accompanying table.

Table 30. Markgrafs Lake Loading Capacity to Meet State Standards.

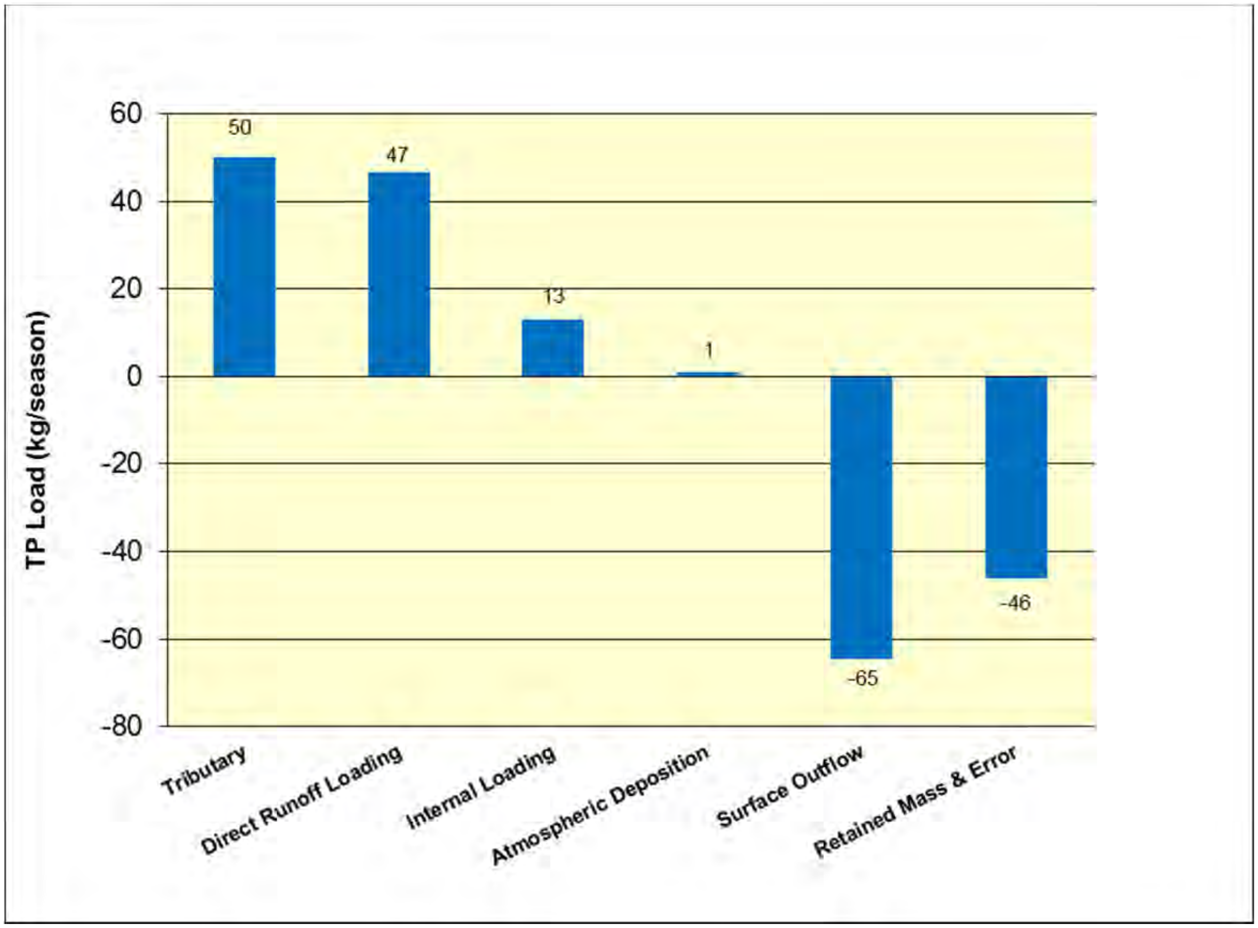
	Loading (kg/day)	=	**Load Allocation (kg/day)**	+	**Wasteload Allocation (kg/day)**	+	**Margin of Safety (kg/day)**
Current Condition (63 kg; 122 days)	0.516	=	0.287	+	0.230	+	0
Goal: 60 ug/L (15 kg; 122 days)	0.123	=	0.117	+	0.000	+	0.006

As summarized in **Table 30**, it is estimated that the current 0.516 kg/d summer season TP load to Markgrafs Lake would have to be reduced to 0.123 kg/d. Under this scenario, the amount of reduction from the load allocation, which is comprised of both atmospheric and internal loading from the phosphorus-laden bottom sediments, was maximized at 60%. However, with this reduction in load allocation, wasteload allocation (storm-sewered runoff from the watershed) would need to be reduced to zero to achieve the 0.123 kg/d total allowable load needed to meet the 60 ug/L goal 50% of the time. Because the goal of attaining 60 ug/L, 50% of the time in Markgrafs Lake is clearly not feasible, this may be a case where a site specific standard is necessary.

4.3 North Wilmes Lake Eutrophication Response and Loading Capacity

Figure 39 shows the long-term average TP mass balance of North Wilmes Lake (i.e., the current condition scenario) as simulated in the CNET model. Results show that North Wilmes Lake currently receives a total summer season TP loading of approximately 111 kg. About 47 kg of that TP comes from surface water runoff; 50 kg comes from tributary inflow from the north, and 13 kg is from internal load. The CNET model then computes that 46 kg/season TP is removed (on average) from the system.

Figure 39. Long-term average North Wilmes Lake summer season (June through September) TP mass balance.



4.3.1 North Wilmes Lake Eutrophication Response

Figure 40 through **Figure 45** show the effects of reducing summer season TP loads to North Wilmes Lake on the summer mean TP, chl-*a* and Secchi disk depth within the lake (based on the CNET model). Loads were reduced incrementally within the CNET model and assumed to come from the surface runoff and internal loading components of the mass balance. Results are presented both in terms of the seasonal mean concentrations as shown by the column graphs and the results of the Monte Carlo analysis. The Monte Carlo analysis results are presented as a series of lines, where each line represents a statistical distribution of the seasonal mean values.

Figure 40. North Wilmes Lake Seasonal Mean (June through September) TP Concentrations under Select Load Reduction Scenarios; Current Conditions = 111 kg/season.

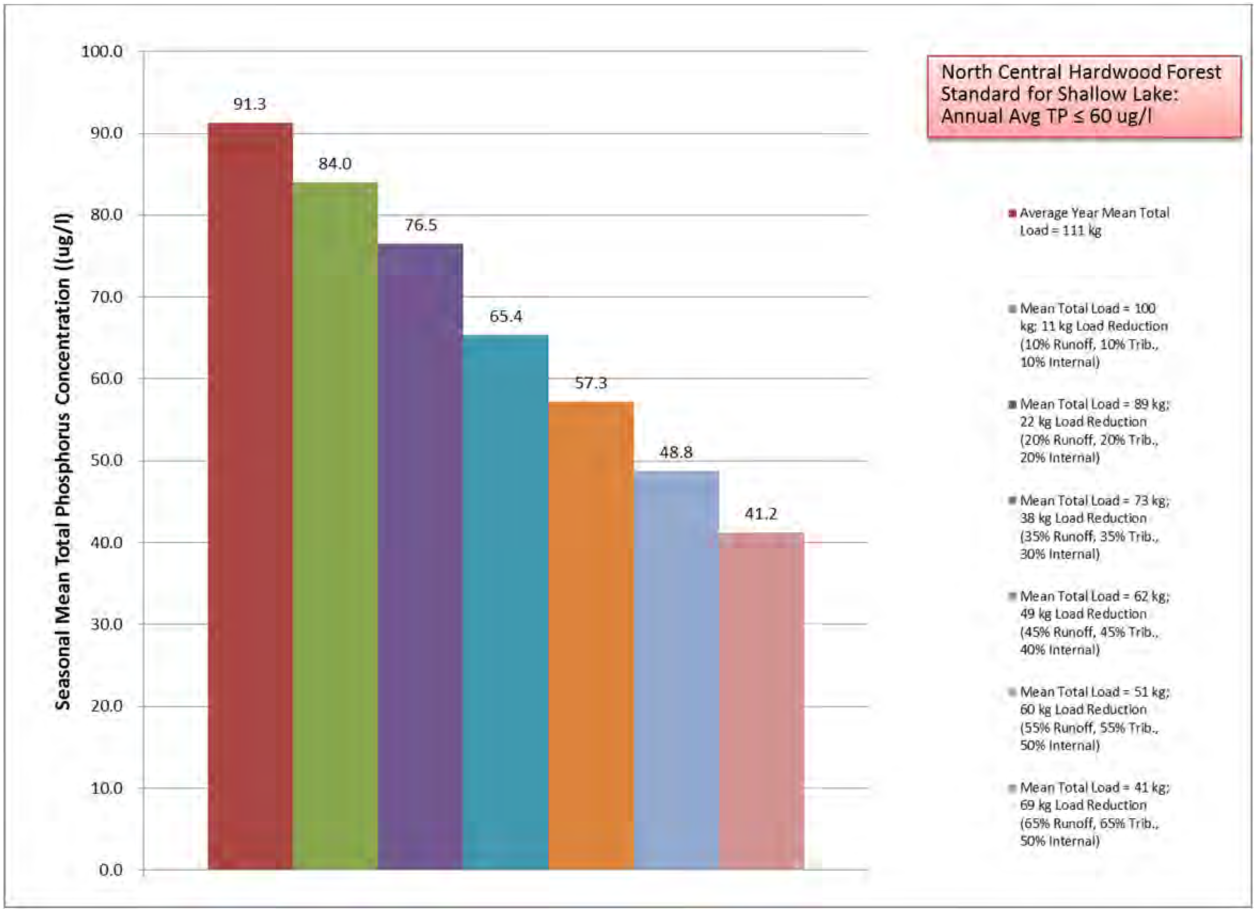
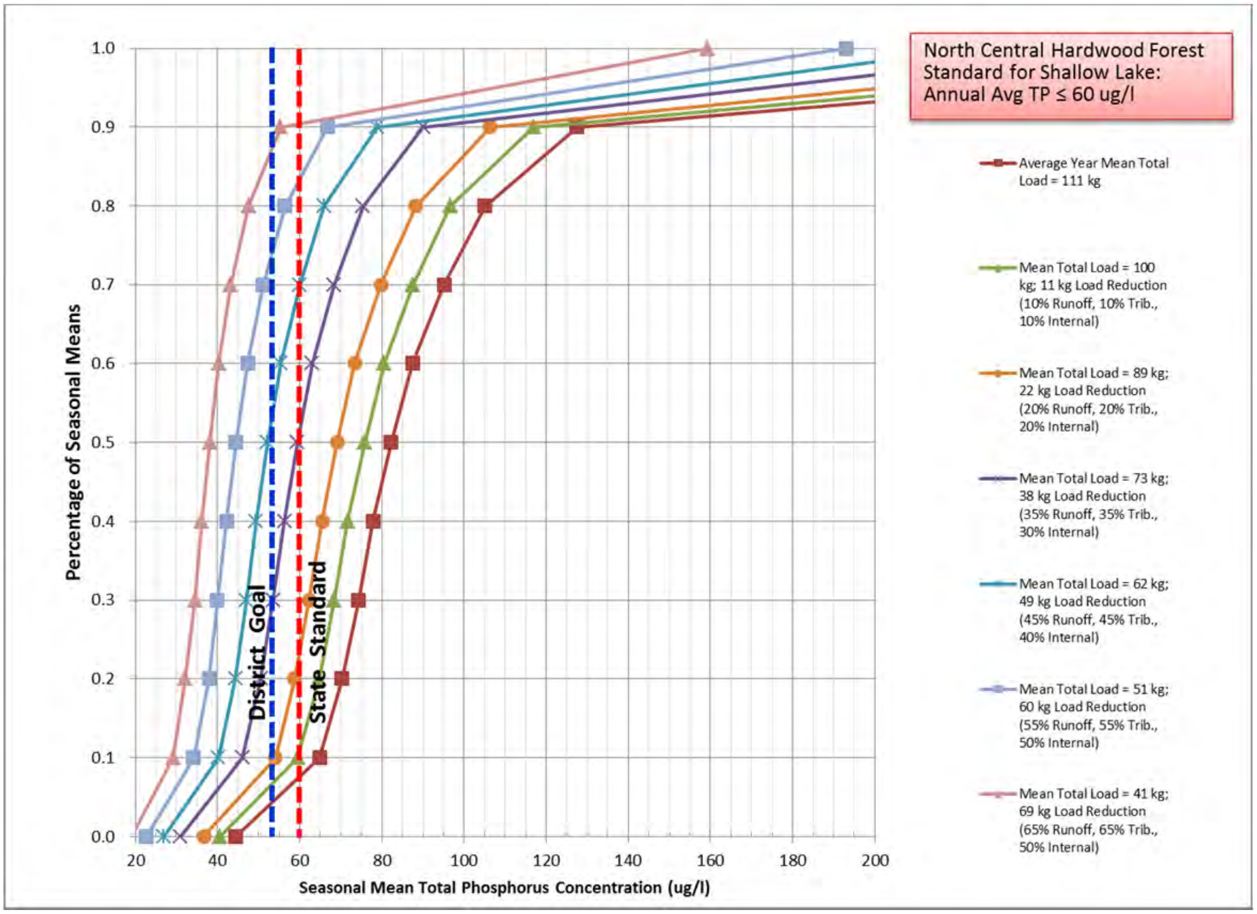


Figure 41. North Wilmes Lake Frequency Distribution of Seasonal (June through September) Mean TP Concentrations Resulting from Select Load Reduction Scenarios and Table of Data used to Produce the Graphical Illustration; Current Conditions = 111 kg/season.



		Load Reduction from Current Load for Average Summer Season					
Non-exceedance Percentile	Average Year (current)	11 kg	22 kg	38 kg	49 kg	60 kg	69 kg
Mean	91.3	84.0	76.5	65.4	57.3	48.8	41.2
0%	44.4	40.6	36.7	31.1	26.9	22.7	19.1
10%	64.8	59.5	54.1	46.1	40.2	34.3	29.2
20%	70.3	64.7	58.8	50.6	44.4	37.9	32.1
30%	74.4	68.4	62.3	53.5	47.0	40.0	34.5
40%	77.9	71.7	65.5	56.3	49.3	42.2	36.2
50%	82.3	75.9	69.1	59.4	52.1	44.5	38.2
60%	87.5	80.5	73.4	63.1	55.4	47.3	40.3
70%	95.2	87.6	79.8	68.4	60.1	51.1	43.2
80%	105.1	96.7	88.2	75.4	66.0	56.4	47.5
90%	127.5	117.0	106.3	90.1	78.9	66.8	55.4
100%	351.9	325.6	298.3	255.6	225.1	193.0	159.4

Figure 42. North Wilmes Lake Seasonal (June through September) Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 111 kg/season

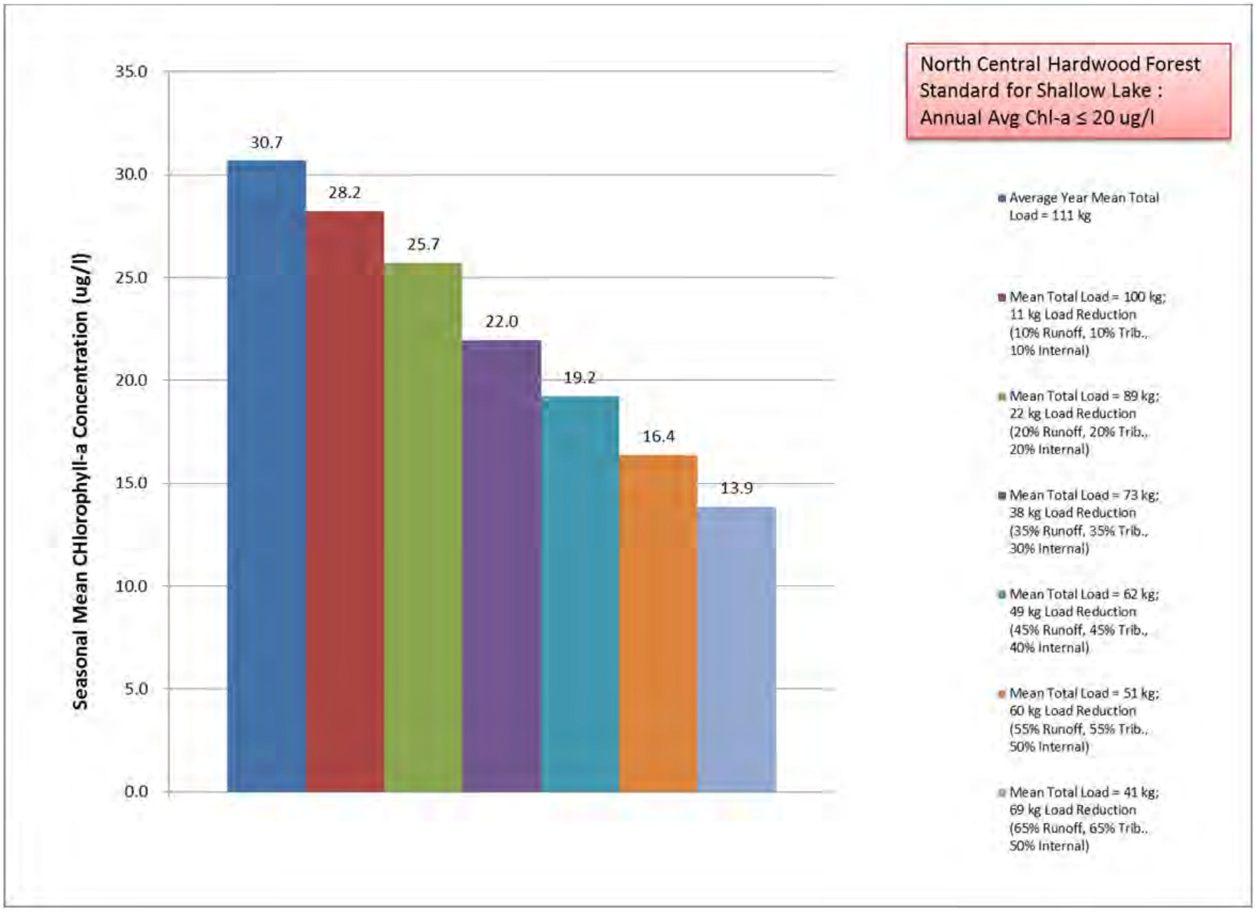


Figure 43. North Wilmes Lake Frequency Distribution of Seasonal Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 111 kg/season

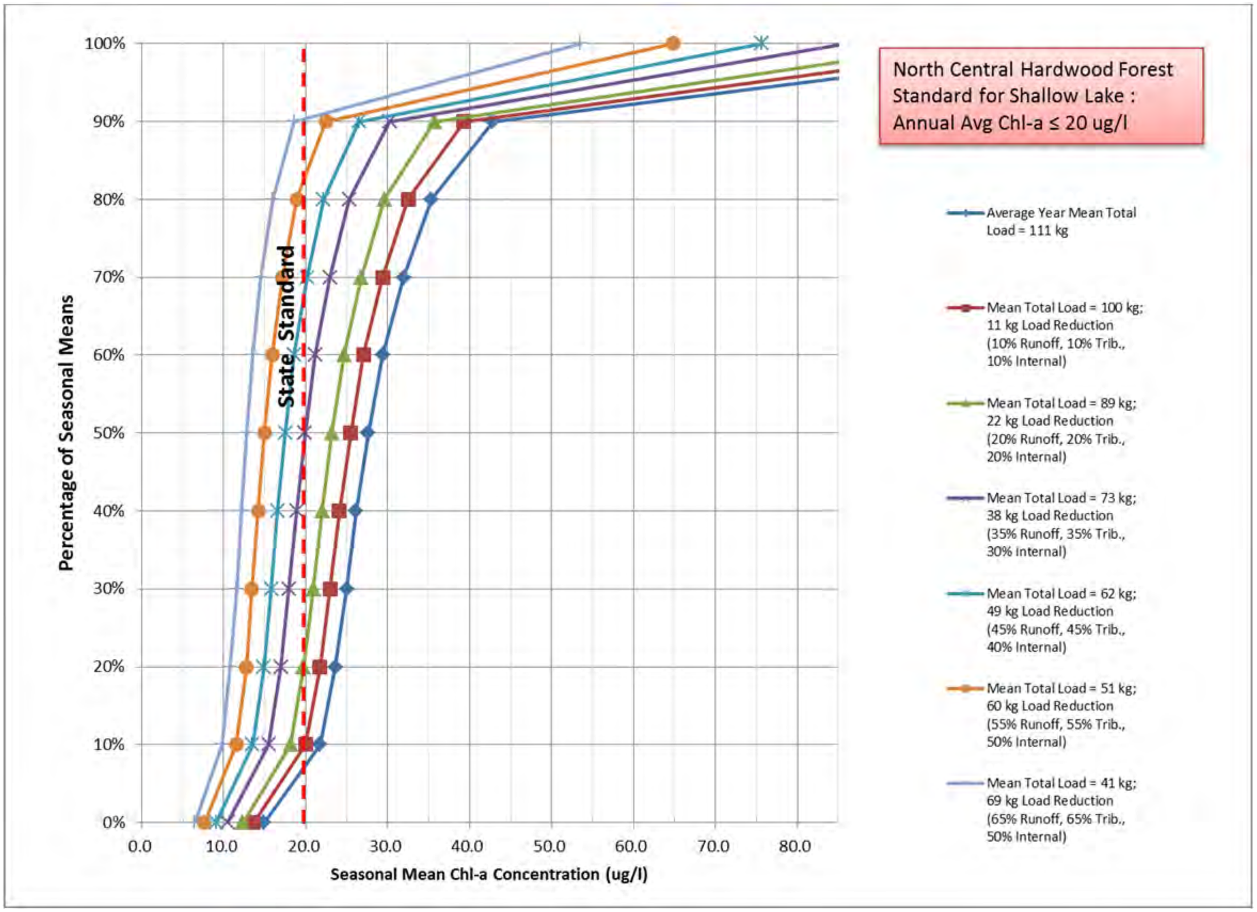


Figure 44. North Wilmes Lake Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 111 kg/season

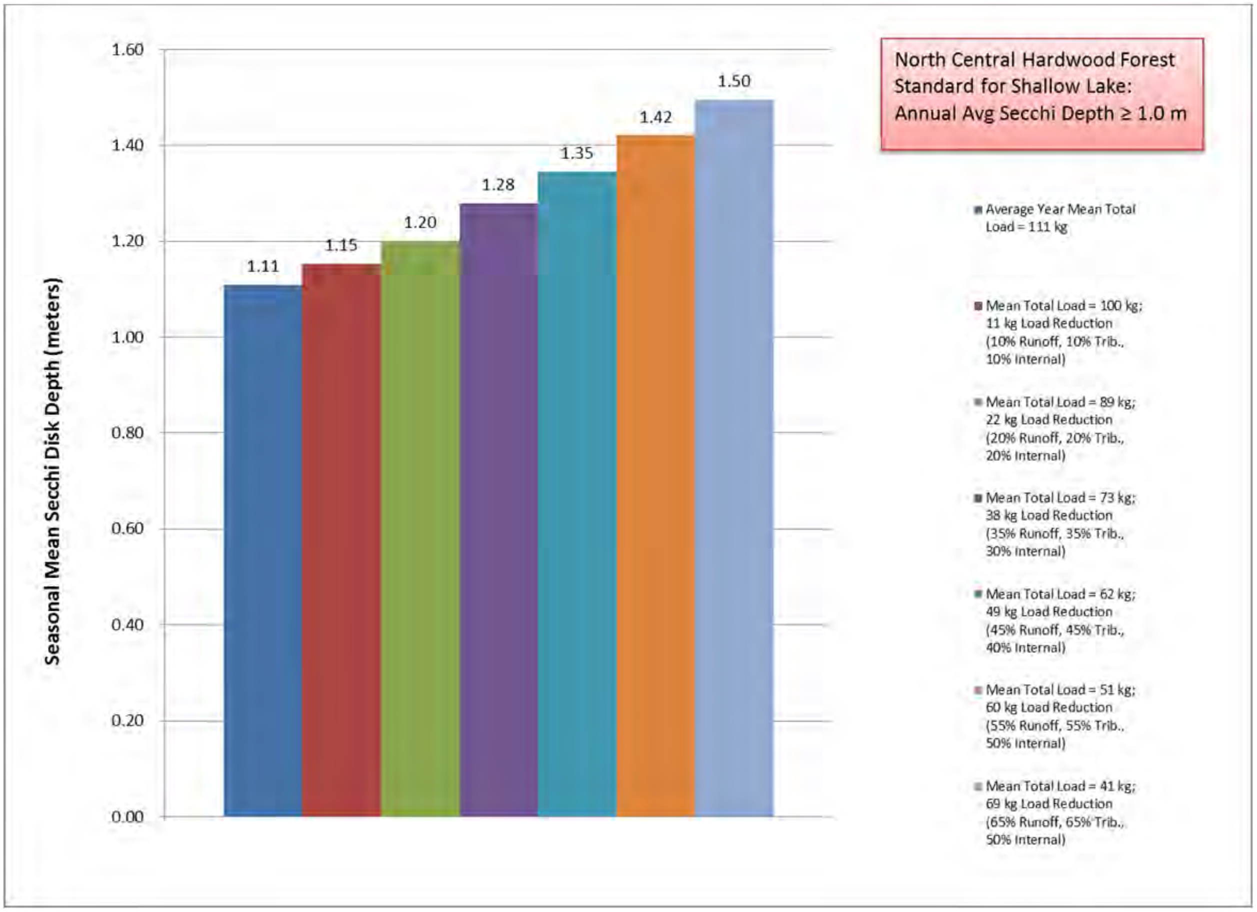
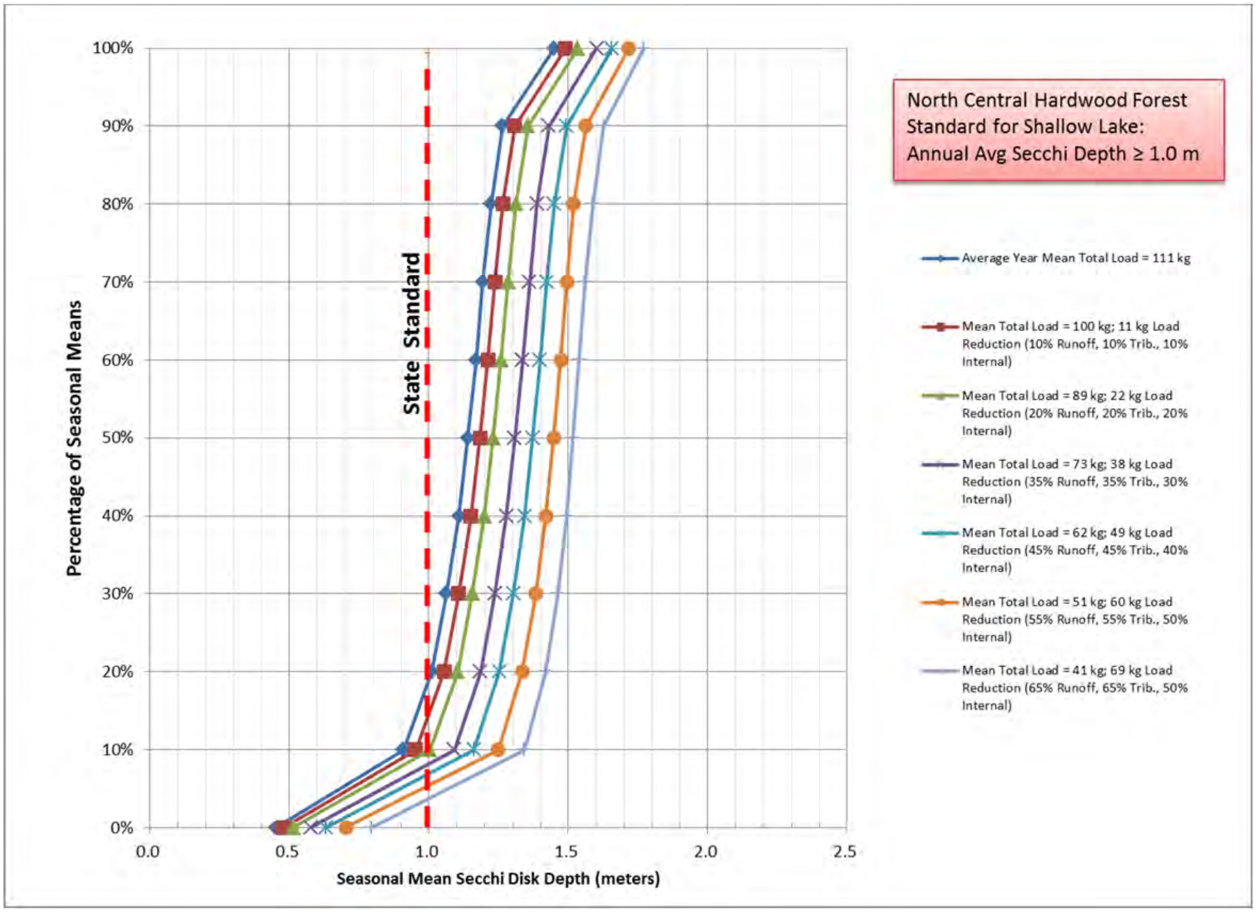


Figure 45. North Wilmes Lake Frequency Distribution of Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 111 kg/season



4.3.2 North Wilmes Lake Loading Capacity

The loading capacity is the maximum allowable TP load to North Wilmes Lake which can occur, while still achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l. The SWWD also has goal for Wilmes Lake (both north and south) that the TP Trophic State Index (TSI) value will range between 60 and 63. A TSI value of 60-63 correlates to a TP concentration of 48.1-59.2 ug/l, and the District has selected the average value of 53.7 ug/l as the TP goal for North Wilmes Lake. Since the District goal of 53.7 ug/l is more stringent State standard 60 ug/l, it will be the basis for computing the allowable load. Although this study is not, technically a Total Maximum Daily Load (TMDL) study, the function of a loading capacity defined here replicates that developed under a TMDL. Given the similarity between this work and a TMDL, the loading capacity computed for North Wilmes Lake is allocated between non-point sources (i.e., the load allocation – LA – in a TMDL study), point sources (i.e., the wasteload allocation – WLA – in a TMDL study), and a margin of safety (MOS). The LA component of the loading capacity includes existing and future nonpoint sources (i.e., atmospheric deposition and internal load); the WLA component includes storm-sewered and overland runoff from the North Wilmes Lake watershed. In the case of North Wilmes the WLA is comprised of local runoff and tributary inflow from watersheds to the north. The MOS used is an explicit expression, intended to reflect the lack of knowledge and uncertainty in establishing the load capacity.

In this study, the loading capacity of North Wilmes Lake was computed using a stochastic approach based on the hydrology and water quality simulated by the P8/CNET modeling. The loading capacity (allowable load) of the Lake was defined as that which reduces the seasonal mean TP concentration for the 50th percentile non-exceedance value to the District numeric goal (53.7 ug/l). Given that the SWWD's lake-specific standards for Wilmes Lake are more conservative than the MPCA's, achieving the District goals will satisfy the State standard. Since the loading capacity of North Wilmes Lake is computed using a stochastic approach (which takes uncertainty and variability into consideration), the MOS was computed as 5% of the allowable load.

Results of the loading capacity analysis are shown in **Figure 41**. A line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the North Central Hardwood Forest ecoregion. A table accompanying **Figure 41** shows the values for the values used to produce the figure. Results of this analysis show that a 49 kg summer season TP load reduction is needed to achieve the water quality standard. **Table 30** shows the load allocations that would be employed if North Wilmes Lake were to be evaluated as a TMDL-listed water body. The summer season daily values presented in **Table 30** were computed based on seasonal values shown in **Figure 41** and its accompanying table.

Table 31. North Wilmes Lake Loading Capacity to Meet State Standards

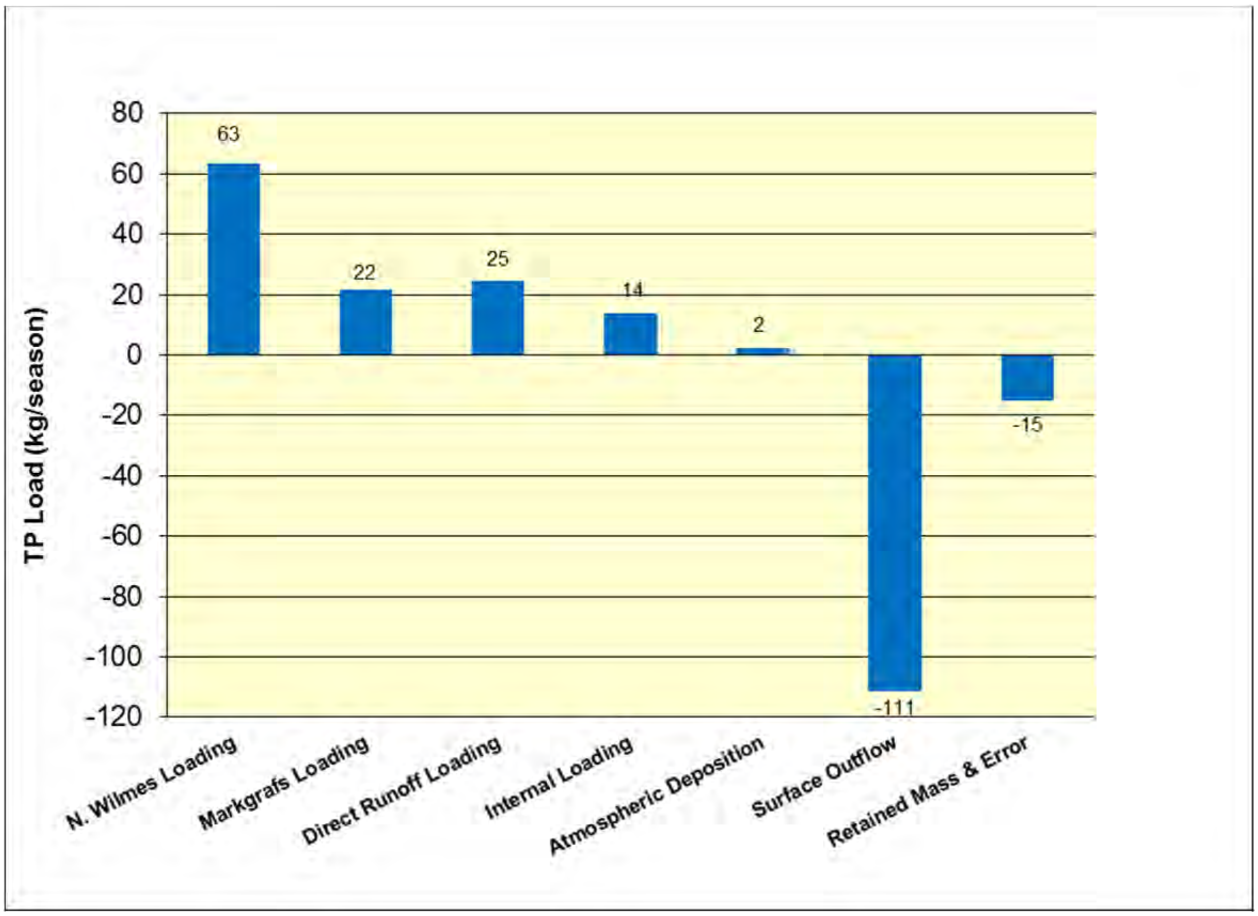
	Loading (kg/day)	=	Load Allocation (kg/day)	+	Wasteload Allocation (kg/day)	+	Margin of Safety (kg/day)
Current Condition (111 kg; 122 days)	0.910	=	0.115	+	0.795	+	0
Goal: 53.7 ug/L (73 kg; 122 days)	0.509	=	0.064	+	0.420	+	0.025

As summarized in **Table 31**, it is estimated that the current 0.910 kg/d summer season TP load to North Wilmes would have to be reduced to 0.509 kg/d. Under this scenario, the wasteload allocation (storm-sewered runoff from the watershed) would have to be reduced by about 47 %; from 0.795 to 0.420 kg/d. The wasteload allocation represents what is considered a technically feasible reduction through the installation of BMPs as the fully developed watershed redevelops. The remainder would have to come from the load allocation which is comprised of both atmospheric and internal loading from the phosphorus-laden bottom sediments. The load allocation represents what is considered a technically feasible reduction associated with changing North Wilmes Lake from the turbid to clear phase. The atmospheric loading of 0.01 kg/d is beyond the control of the SWWD, so the reduction would need to come from internal TP loading. The approximately 0.107 kg/d internal TP load would have to be reduced 6.8% to achieve the 0.055 kg/d internal load needed to meet the 53.7 ug/L goal 50% of the time. In reality, any combination of waste load allocation and load allocation equaling 0.509 kg/d is able to achieve the loading capacity.

4.4 South Wilmes Lake Eutrophication Response and Loading Capacity

Figure 46 shows the long-term average TP mass balance of South Wilmes Lake (i.e., the current condition scenario) as simulated in the CNET model. Results show that South Wilmes Lake currently receives a total summer season TP loading of approximately 125 kg. About 63 kg of that TP comes from surface water runoff, 22 kg comes from the tributary inflow originating from Markgraf's Lake, 63 kg comes from discharge out of North Wilmes, and 14 kg comes from the internal load. The CNET model then computes that 15 kg/season TP is removed (on average) from the system.

Figure 46. Long-term average South Wilmes Lake summer season (June through September) TP mass balance.



4.4.1 South Wilmes Lake Eutrophication Response

Figure 47 through **Figure 52** show the effects of reducing summer season TP loads to South Wilmes Lake on the summer mean TP, chl-*a* and Secchi disk depth within the lake (based on the CNET model). Loads were reduced incrementally within the CNET model and assumed to come from the surface runoff and internal loading components of the mass balance. Results are presented both in terms of the seasonal mean concentrations as shown by the column graphs and the results of the Monte Carlo analysis. The Monte Carlo analysis results are presented as a series of lines, where each line represents a statistical distribution of the seasonal mean values.

Figure 47. South Wilmes Lake Seasonal Mean (June through September) TP Concentrations under Select Load Reduction Scenarios; Current Conditions = 125 kg/season.

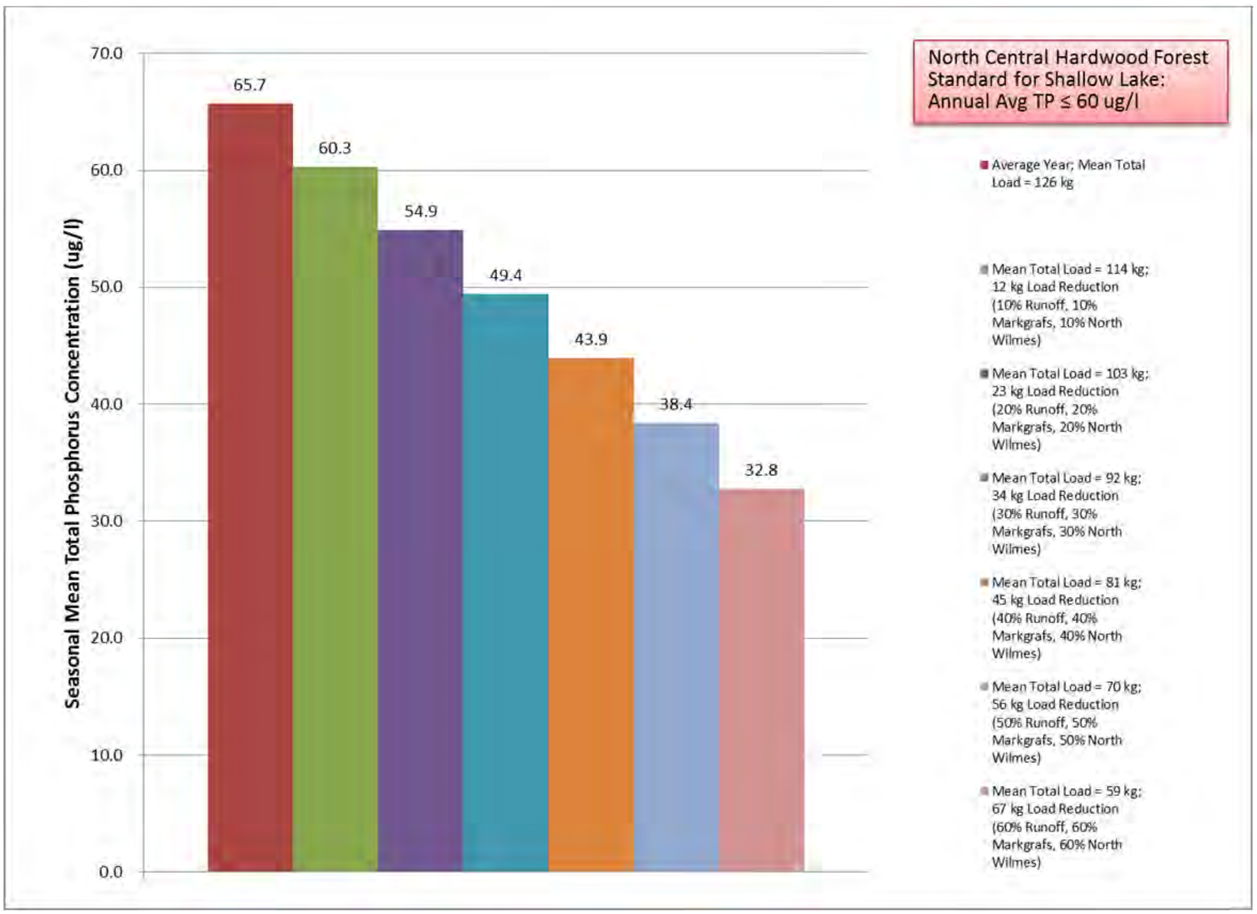
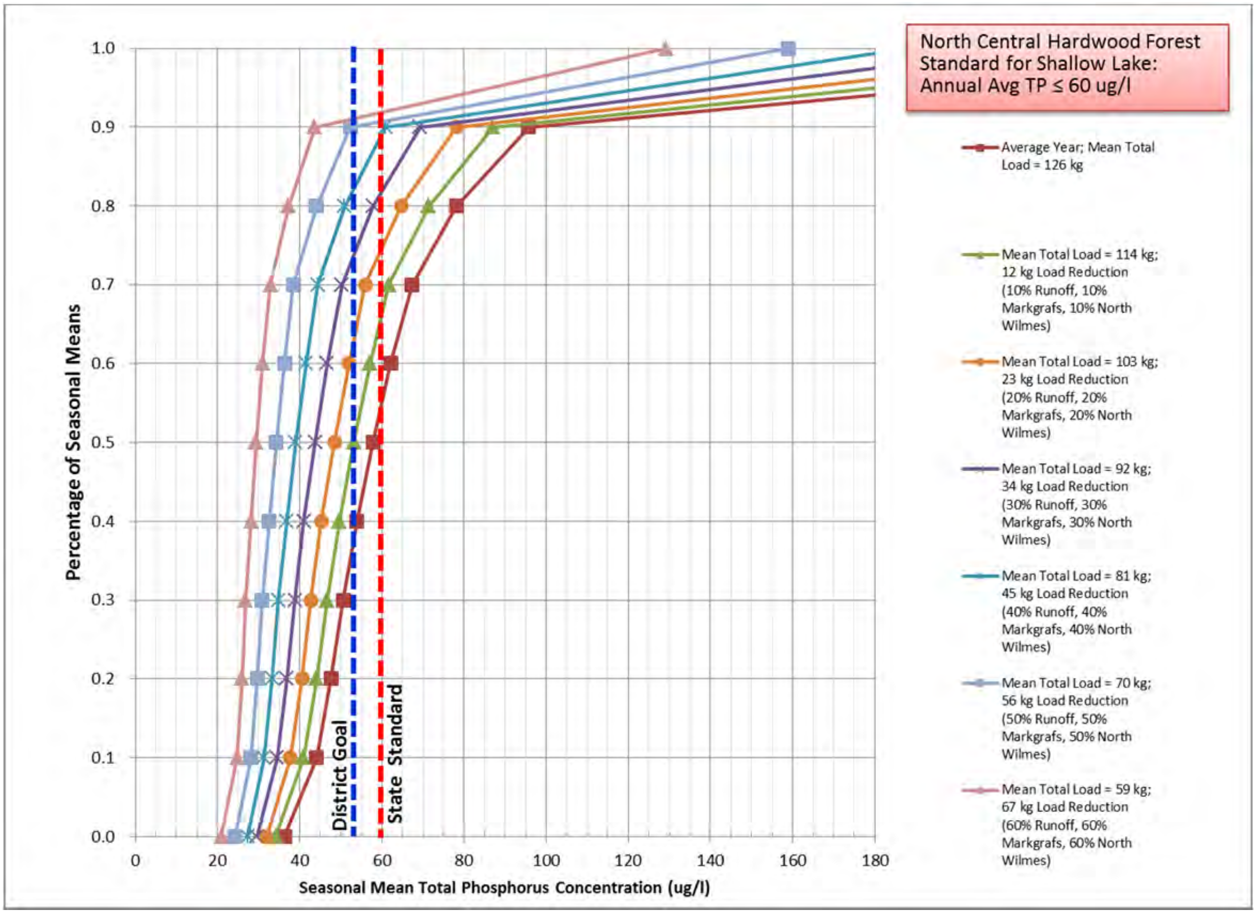


Figure 48. South Wilmes Lake Frequency Distribution of Seasonal (June through September) Mean TP Concentrations Resulting from Select Load Reduction Scenarios and Table of Data used to Produce the Graphical Illustration; Current Conditions = 125 kg/season



		Load Reduction from Current Load for Average Summer Season					
Non-exceedance Percentile	**Average Year (current)**	**12 kg**	**23 kg**	**34 kg**	**45 kg**	**56 kg**	**67 kg**
Mean	65.7	60.3	54.9	49.4	43.9	38.4	32.8
0%	36.4	34.1	31.9	29.6	27.4	24.3	21.0
10%	44.1	40.9	37.7	34.5	31.3	28.1	24.8
20%	47.7	44.2	40.6	36.9	33.4	29.7	26.0
30%	50.7	46.7	42.8	38.9	34.9	30.9	26.8
40%	54.0	49.7	45.3	41.1	36.8	32.6	28.2
50%	57.9	53.2	48.5	43.8	39.0	34.3	29.4
60%	62.2	57.2	52.0	46.7	41.6	36.3	31.0
70%	67.4	61.7	55.9	50.3	44.4	38.5	32.9
80%	78.2	71.5	64.7	57.9	51.0	44.1	37.3
90%	95.8	87.0	78.2	69.4	60.9	52.4	43.7
100%	301.8	273.8	245.6	217.0	188.1	158.9	129.3

Figure 49. South Wilmes Lake Seasonal (June through September) Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 125 kg/season

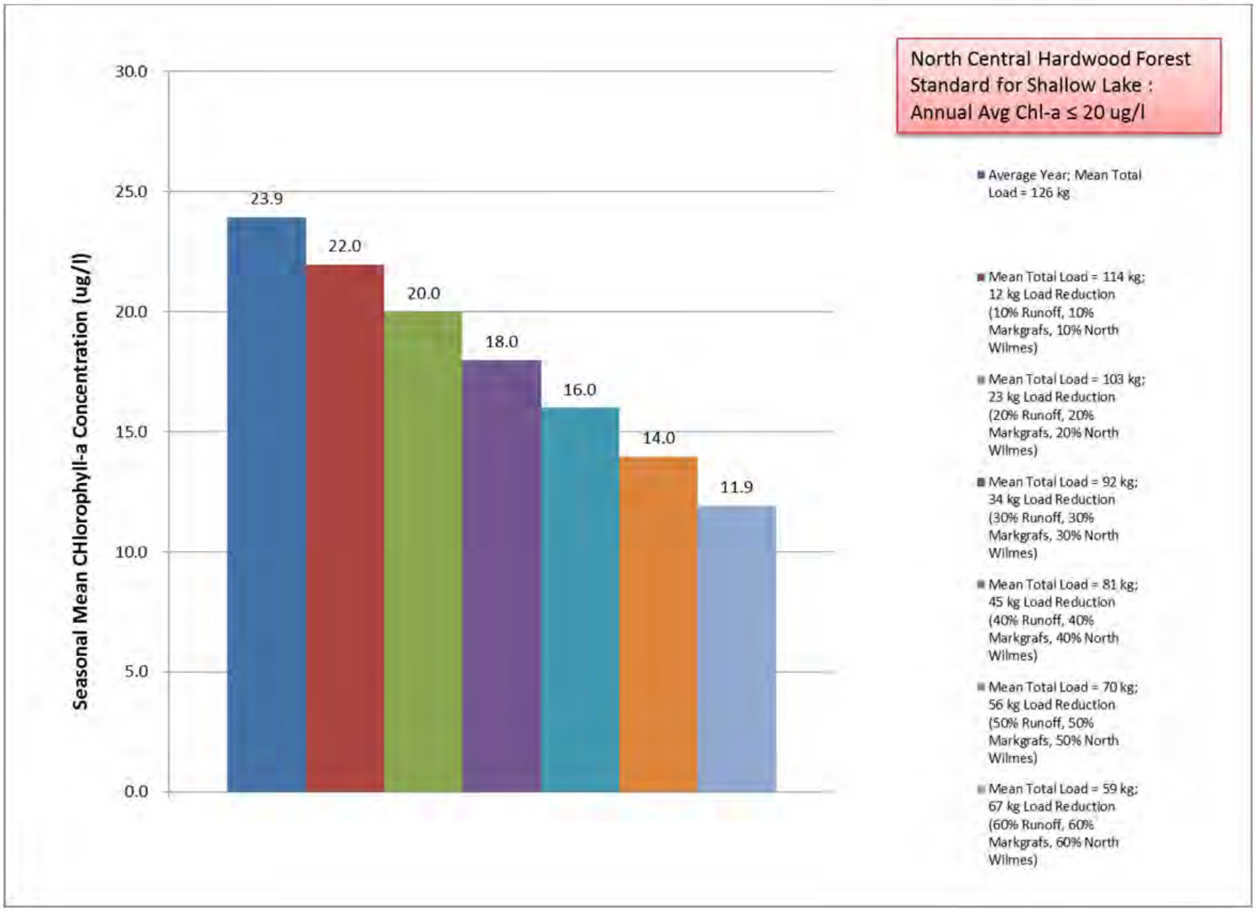


Figure 50. South Wilmes Lake Frequency Distribution of Seasonal Mean Chl-a Concentrations under Select Load Reduction Scenarios; Current Conditions = 125 kg/season

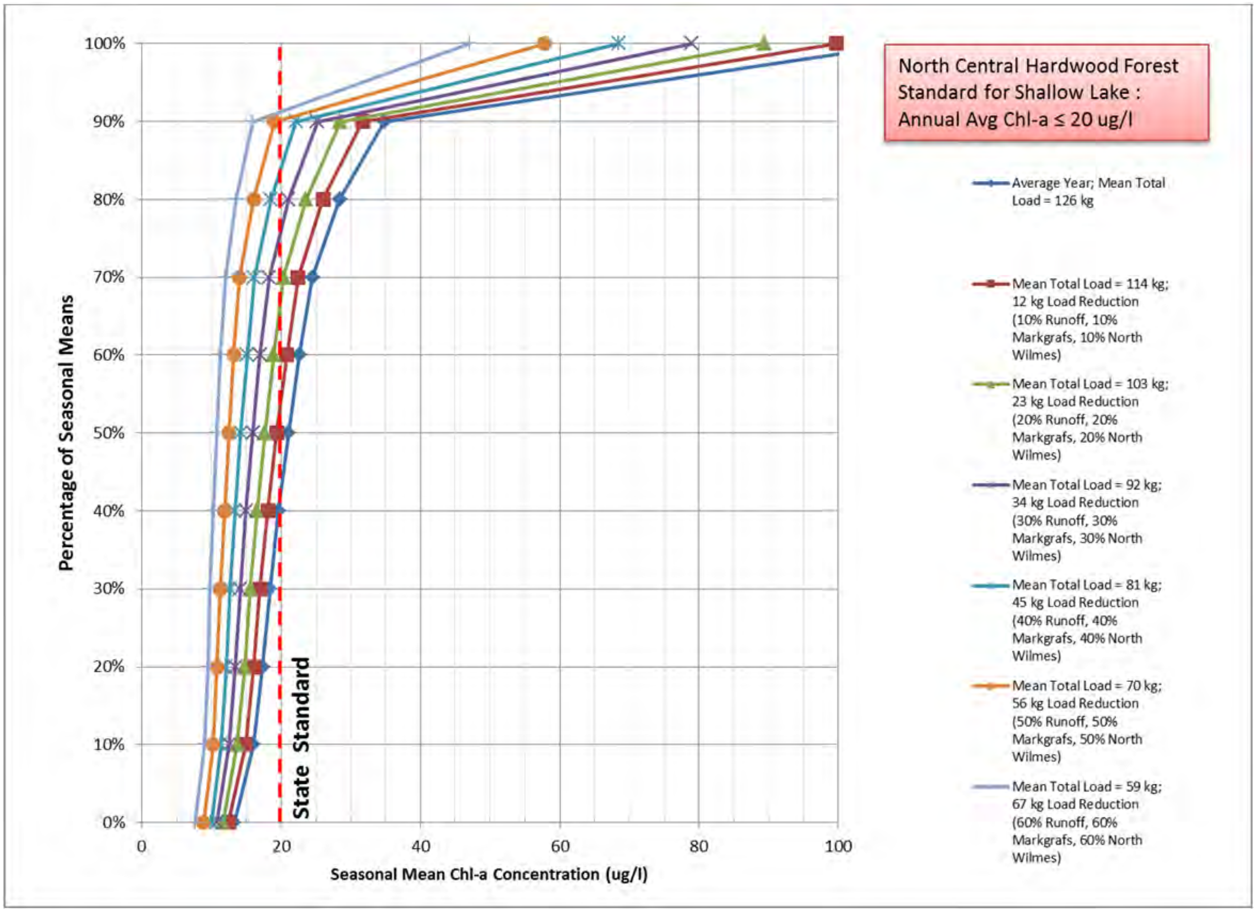


Figure 51. South Wilmes Lake Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 125 kg/season

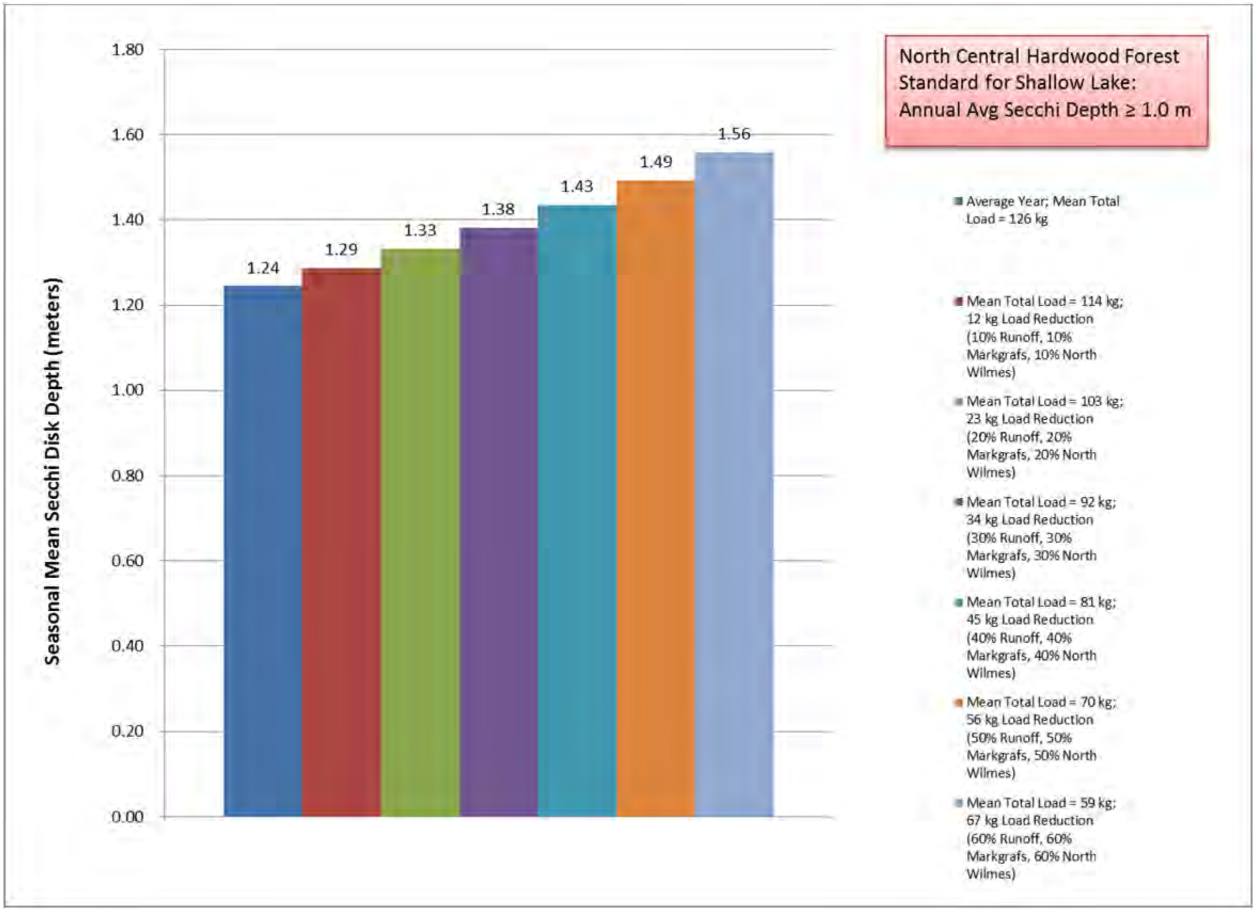
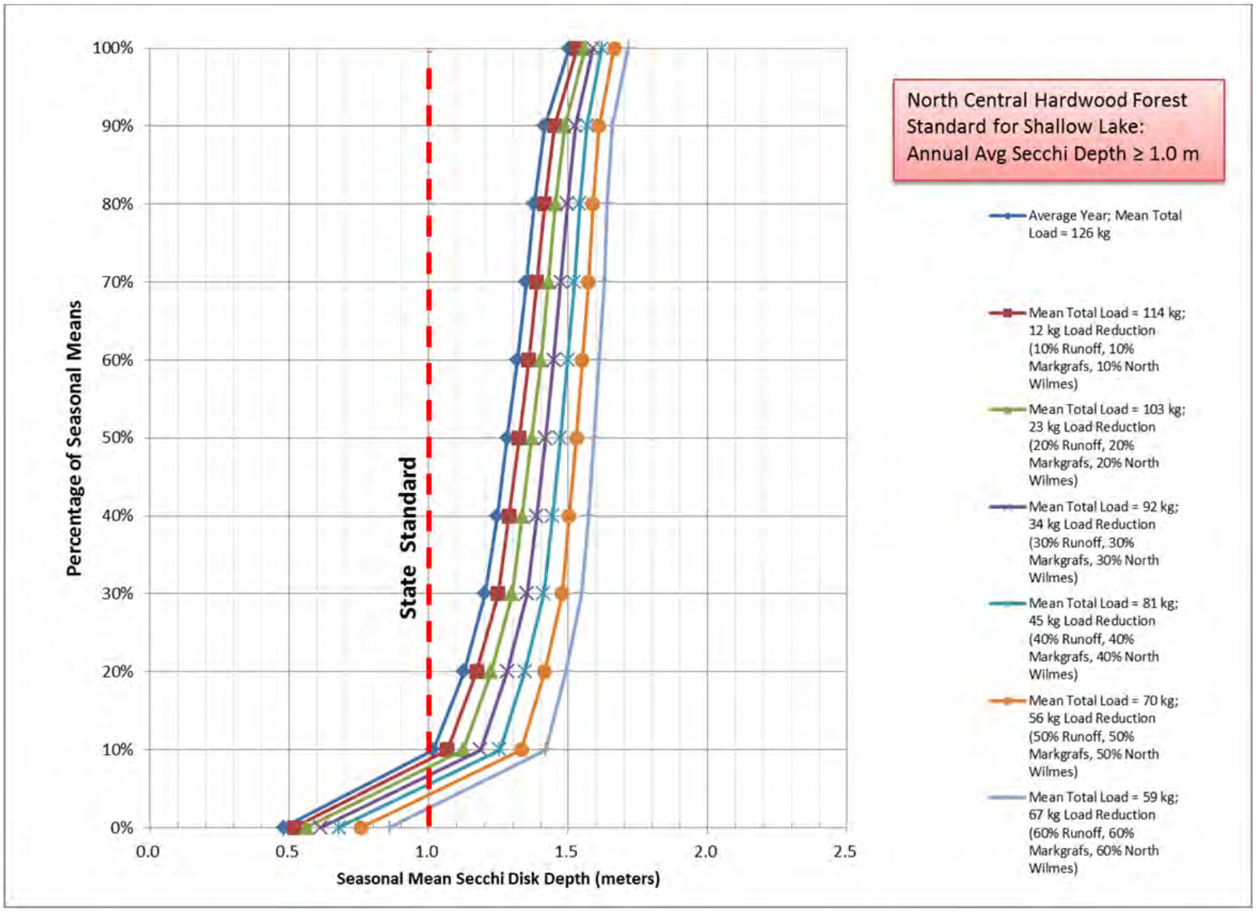


Figure 52. South Wilmes Lake Frequency Distribution of Seasonal Mean Secchi Disk Depth under Select Load Reduction Scenarios; Current Conditions = 125 kg/season



4.4.2 South Wilmes Lake Loading Capacity

The loading capacity is the maximum allowable TP load to South Wilmes Lake which can occur, while still achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l. The SWWD also has goal for Wilmes Lake (both north and south) that the TP Trophic State Index (TSI) value will range between 60 and 63. A TSI value of 60-63 correlates to a TP concentration of 48.1-59.2 ug/l, and the District has selected the average value of 53.7 ug/l as the TP goal for Wilmes Lake. Since the District goal of 53.7 ug/l is more stringent State standard 60 ug/l, it will be the basis for computing the allowable load. Although this study is not, technically a Total Maximum Daily Load (TMDL) study, the function of a loading capacity defined here replicates that developed under a TMDL. Given the similarity between this work and a TMDL, the loading capacity computed for South Wilmes Lake is allocated between non-point sources (i.e., the load allocation – LA – in a TMDL study), point sources (i.e., the wasteload allocation – WLA – in a TMDL study), and a margin of safety (MOS). The LA component of the loading capacity includes existing and future nonpoint sources (i.e., atmospheric deposition and internal load); the WLA component includes storm-sewered and overland runoff from the South Wilmes Lake watershed. In the case of South Wilmes, the WLA is comprised of local runoff, tributary inflow from North Wilmes Lake, and tributary inflow stemming from Markgrafs Lake discharge and downstream watersheds. The MOS used is an explicit expression, intended to reflect the lack of knowledge and uncertainty in establishing the load capacity.

In this study, the loading capacity of South Wilmes Lake was computed using a stochastic approach based on the hydrology and water quality simulated by the P8/CNET modeling. The loading capacity (allowable load) of the Lake was defined as that which reduces the seasonal mean TP concentration for the 50^{th} percentile non-exceedance value to the District numeric goal (53.7 ug/l). Given that the SWWD's lake-specific standards for Wilmes Lake are more conservative than the MPCA's, achieving the District goals will satisfy the State standard. Since the loading capacity of South Wilmes Lake is computed using a stochastic approach (which takes uncertainty and variability into consideration), the MOS was computed as 5% of the allowable load.

Results of the loading capacity analysis are shown in **Figure 48**. A line at 60 ug/L represents the average summer season TP concentration eutrophication standard for the protection of lake quality in Class 2 surface waters in the North Central Hardwood Forest ecoregion. A table accompanying **Figure 48** shows the values for the values used to produce the figure. Results of this analysis show that a 12 kg summer season TP load reduction is needed to achieve the water quality standard. **Table 30** shows the load allocations that would be employed if South Wilmes Lake were to be evaluated as a TMDL-listed water body. The summer season daily values presented in **Table 30** were computed based on seasonal values shown in **Figure 48** and its accompanying table.

Table 32. South Wilmes Lake Loading Capacity to Meet State Standards

	Loading (kg/day)	=	Load Allocation (kg/day)	+	Wasteload Allocation (kg/day)	+	Margin of Safety (kg/day)
Current Condition (126 kg; 122 days)	1.032	=	0.131	+	0.902	+	0
Goal: 53.7 ug/L (114 kg; 122 days)	0.934	=	0.131	+	0.612	+	0.047

As summarized in **Table 32**, it is estimated that the current 1.032 kg/d summer season TP load to South Wilmes would have to be reduced to 0.934 kg/d. Under this scenario, the wasteload allocation (storm-sewered runoff from the watershed) would have to be reduced by 32 %; from 0.902 to 0.612 kg/d. The wasteload allocation represents what is considered a technically feasible reduction through the installation of BMPs as the fully developed watershed redevelops. If the entire load reduction is achieved through reductions in wasteload, then no load allocation is necessary, which is comprised of both atmospheric and internal loading from the phosphorus-laden bottom sediments. In reality any combination of waste load allocation and load allocation equaling 0.934 kg/d is able to achieve the loading capacity.

5.0 IMPLEMENTATION TO ACHIEVE THE LOADING CAPACITY

There are any number of implementation scenarios that could be employed in the Armstrong Lake or Wilmes Lake system to reduce the TP loading to the lakes and (eventually) attain the water quality standard. To reduce TP loading to the lake due to surface water runoff, various watershed-based BMPs can be targeted and implemented. To reduce internal TP loadings to the lakes, some form of phosphorus sequestration would be needed. Various methods can be employed toward that goal; one of the more common methods is alum treatment. Alternatively and perhaps more probable, is that the internal load reduction can be realized by transitioning the lake from the turbid to clear state, through a combination of curly leaf pond weed control, fish management, and the establishment of native aquatic vegetation. Data from Lake Christina in west-central Minnesota collected by the MnDNR shows a 50% reduction in TP when the lake is in a clear state rather than a turbid state (Deutschman, 2011).

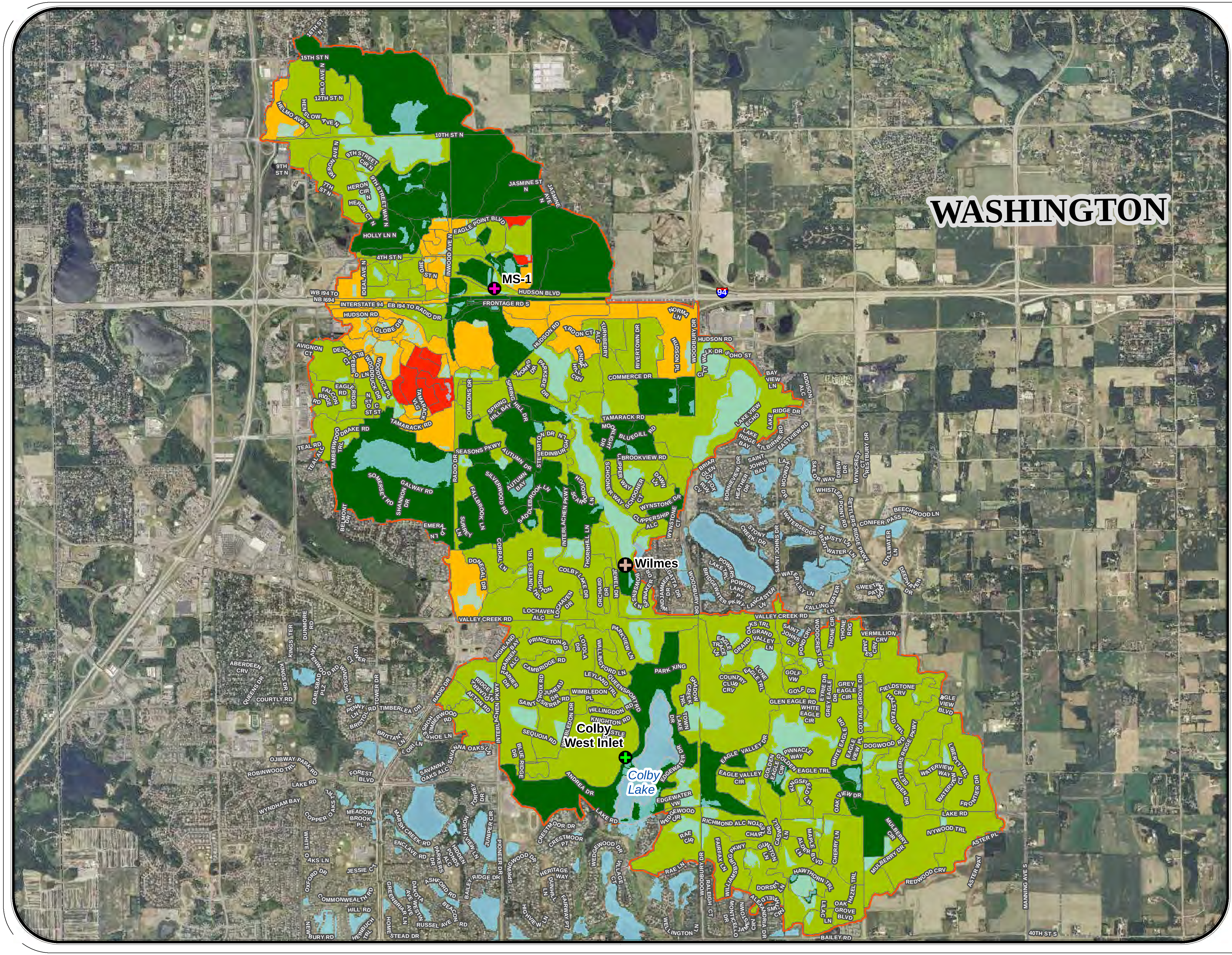
The goal of achieving the in-lake TP water quality numeric standard of the MPCA, 60 ug/l, 50% of the time is not feasible in Markgrafs Lake. This may be a case where a site specific standard is necessary.

5.1 Priority Implementation Areas

The work of the SWWD/WCD will rely heavily upon the results of the Armstrong, Markgrafs, and Wilmes Lake Watershed P8 models, using the results to determine existing storage-node (retention pond) performance for the watersheds and identifying areas where further improvements can be made. Details on the (estimated) storage-node performance under current conditions is included in the P8 Watershed Modeling Report, which is included as Appendix A.

Other results of the P8 model that will be useful when identifying areas for improved TP load reductions are the simulated TP yield values, shown by subwatershed in **Figure 53.** The SWWD WMP identifies acceptable annual unit loads for the three lakes are: 0.18 lbs/ac/year for Armstrong Lake, 0.61 lbs/ac/year for Markgrafs, and 0.10 lbs/ac/year for Wilmes Lake (SWWD, 2007).

Colby Lake P8 Watershed Model: Existing Conditions TP Yield

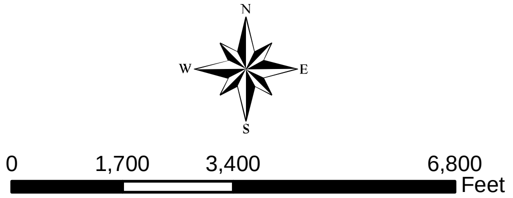


2010 Monitoring Sites

- Colby West Inlet
- MS-1
- Wilmes
- Retention Ponds/Storage Nodes

TP Yield (lbs/acre/yr)

- 0.18 - 0.35
- 0.35 - 0.55
- 0.55 - 0.75
- 0.75 - 0.95
- Colby Lake Watershed



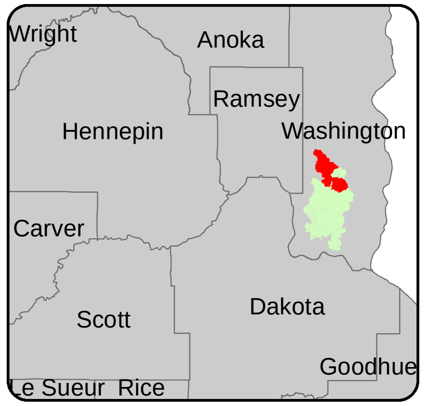


Figure 53: Existing Conditions Annual TP Yield by Subwatershed (Colby Lake Watershed P8 Model)

Scale: AS SHOWN	Drawn by: SMW	Checked by:	Project No.: 4876-017	Date: 06/26/12	Sheet:

Houston Engineering Inc.
Maple Grove
P: 763.493.4522
F: 763.493.5572

6.0 REFERENCES

Barr, 2005, Integrating Groundwater & Surface Water Management: Southern Washington County, Barr Engineering, August 2005.

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APPENDIX A

P8 Watershed Modeling

Armstrong, Markgrafs, and Wilmes Lakes

P8 Watershed Modeling
Armstrong, Markgrafs, and Wilmes Lakes

1 Introduction

The watershed modeling for Armstrong, Markgrafs, and Wilmes Lake was performed using version 3.4 of the P8 model – Program for Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds (http://wwalker.net/p8). The model was used to develop the surface water runoff and total phosphorus (TP) components of the long-term hydrologic budget and mass balance, respectively. As part of the Colby Lake Water Quality Modeling Project,[1] completed in 2011, a P8 model was developed, calibrated, and then used to predict volumes and loads to Colby Lake. This report describes how the P8 models developed in the Colby Lake Project were used to estimate the June through September total volume and TP loading to Armstrong, Markgrafs, and Wilmes Lakes.

2 Model Inputs

The P8 model requires user input relative to local precipitation and temperature, watershed characteristics, water quality parameters, and treatment device geometry. The routing information and most other required inputs were adopted from the Colby Lake watershed P8 model, which in turn was based on the inputs to a hydrologic and hydraulic XPSWMM model[2] which was developed for the South Washington Watershed District (District) as part of the Central Draw Project.[3] Details of this process can be found in the Colby Lake Project report.

2.1 Precipitation and Temperature

The P8 model requires hourly precipitation and daily temperature data to be input for hydrologic simulation. These data were obtained at the Minneapolis-St. Paul airport, as it was the closest station (approximately 20 miles away) with sufficient data to perform long-term model simulations. For the Colby Lake Project, data from 1949 to 2010 were used to model a

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[1] Report on the "Colby Lake Water Quality Modeling Project" prepared for the South Washington Watershed District by Houston Engineering, June, 2011.
[2] http://www.xpsoftware.com/products/xpswmm/
[3] XP-SWMM model developed for the "Central Draw Project and Flood Storage Area Maps," by HDR Engineering, Inc., June 2002.

50-year period of record. For the watershed modeling of Armstrong, Markgrafs, and Wilmes Lakes, data from the year 2011 was added to the precipitation and temperature files so that the 50-year period of record used was from 1950 to 2011.

2.2 Watershed Characteristics

Due to limitations on the number of nodes in the P8 modeling framework, the Colby Lake P8 model was divided into four separate models, i.e. Model 1, Model 2, Model 3, and Model 4 (see **Figure 1**). Model 1 encompasses the subwatersheds which drain through the MS1 monitoring station north of I-94. Model 2 generally consists of the subwatersheds draining to the North basin of Wilmes Lake. Model 3 encompasses the subwatersheds draining to the South basin of Wilmes Lake. Model 4 consists of the remaining subwatersheds downstream of Wilmes Lake, many of which drain directly to Colby Lake. Models 1, 2, and 3 were used in this study to estimate surface water volume and pollutant loading to Armstrong, Markgrafs, and Wilmes Lakes.

The imperviousness fractions and pervious Curve Numbers for each subwatershed, the impervious area runoff coefficient, impervious depression storage, and the portion of the total impervious area assumed to be directly-connected (e.g. to a curb, storm sewer, or other stormwater conveyance facility) were all adopted from the calibrated Colby Lake P8 model.

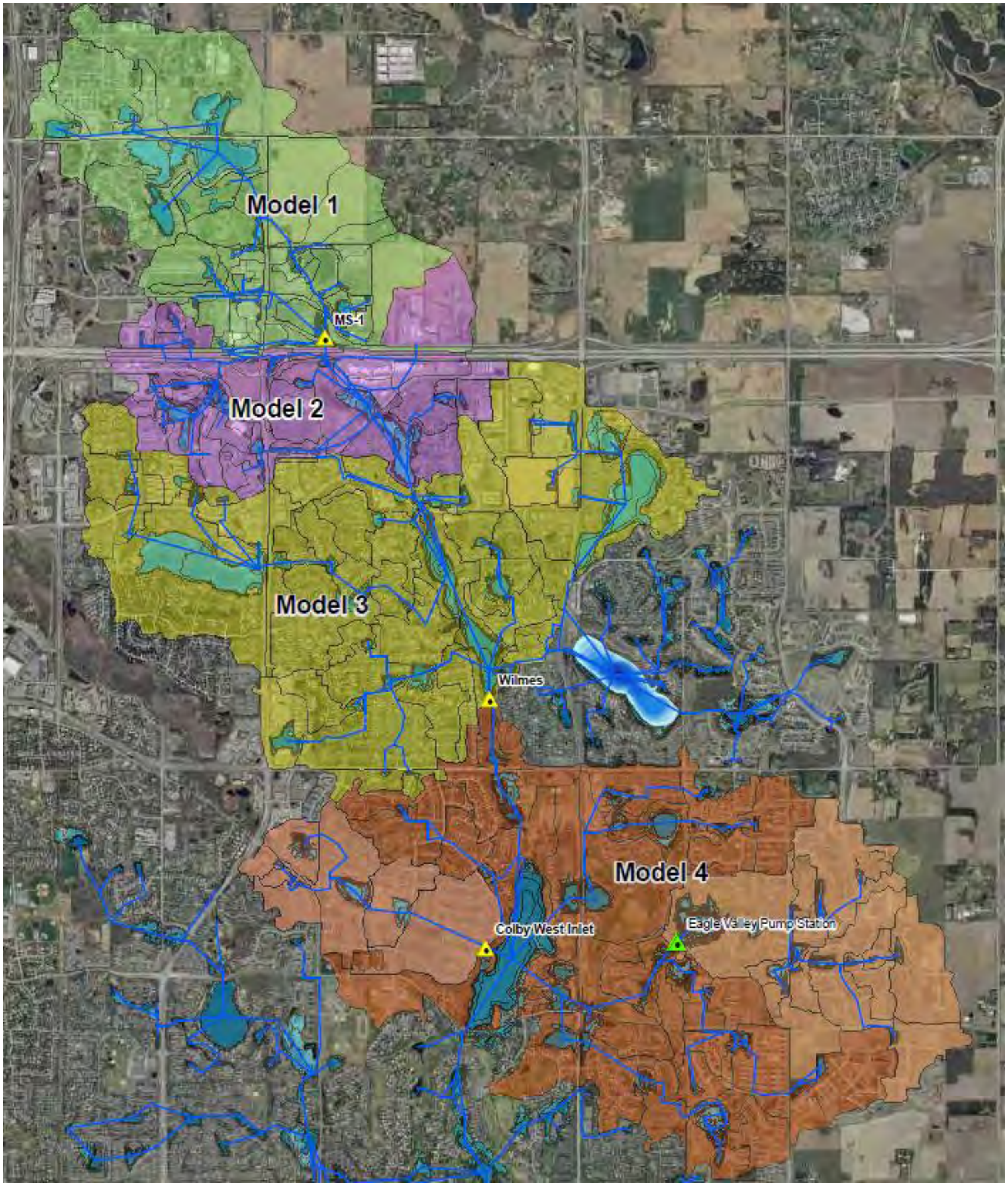
2.3 Treatment Devices

The P8 model network (which is used to route water from upstream to downstream), the locations and characteristics of treatment devices and BMPs, as well as outlet locations and characteristics, were also adopted from the calibrated Colby Lake P8 model.

2.4 Water Quality Particle Parameters and Components

The NURP50.PAR (i.e., NURP 50 particle file), the P8 model default, was selected for model development during the Colby Lake Project. The NURP50.PAR represents typical concentrations and the distribution of particle settling velocities for a number of stormwater pollutants. P8 also provides particle compositions (mg/kg) for various particle classes. During the Colby Lake model calibration, the scale factors for TSS and TP were adjusted. These adjusted values were adopted for this project as well.

Figure 1: P8 Models for Colby Lake Watershed



3 P8 Model Calibration and Validation

In the Colby Lake Project, three years (2008-2010) of observed watershed hydrology and water quality data were available for use in the calibration/validation effort. The Colby Lake watershed P8 model was calibrated to summer season (June 1 – September 30) runoff volumes, TP loads, and TSS loads during the years of 2008 and 2009. Parameters determined through the calibration process remained unchanged and were used to validate the model by simulating the same June through September period in 2010. As a final assessment of the quality of the model results, the calibrated/validated P8 model was run for a 50-year period, and annual unit volumes and pollutant yields were evaluated for reasonability by comparison to other values computed from long-term empirical data. The seasonal calibration (June 1 to September 30) resulted in the final hydrologic parameters presented in **Table 1**.

Table 1: Model Parameters Selected during the Colby Lake P8 Model Calibration

Watershed Hydrologic Parameter	Selected Value
Impervious Area Runoff Coefficient	0.9
Impervious Area Depression Storage	0.1 inch
Percent of Impervious Area disconnected*	50%
Infiltration rate from lakes to simulate evaporation loss	0.003 inches/hour
TSS loading scale factor	1.2
TP loading scale factor	0.9

* For one region of Model 4, the Colby West watershed (area west of Colby Lake draining to the Colby West Inlet on Figure 2), 75% of the impervious area was disconnected during the calibration process.

4 Treatment Device Removal Efficiencies

The average annual TSS and TP removal efficiencies for each storage node in the P8 model, based on the results from the 50-year simulation, are presented in **Tables 2 – 4** in **Appendix I**. These values are provided as a planning tool only and could be used to prioritize whether additional investigation of pond performance is warranted for those ponds with low (~ < 40%) removal efficiencies.

5 Armstrong Lake Watershed Modeling

Model 1, which was developed and calibrated in the Colby Lake study, was used to estimate inflow volumes and pollutant loads to Armstrong Lake. The model encompasses the subwatersheds which drain through the MS1 monitoring station north of I-94.

In order to remove the inflow volume resulting from precipitation falling directly onto the lake, 28.7 acres were removed from the local watershed. This acreage corresponds to the size of the permanent pool, as determined from the District's XPSWMM model.[4] The impervious percentage of the remaining local watershed was adjusted accordingly.

The P8 model was run from 1962 through 2011, and the inflow volume and TP loading data was extracted and compiled to determine the annual June through September estimate surface water volume and pollutant loading. The total volume and loading to Armstrong Lake was estimated as being the total inflow to the model node representing the lake (Node AL1_1-P).

6 Markgrafs Lake Watershed Modeling

Model 3, developed and calibrated in the Colby Lake study, was used to estimate inflow volumes and pollutant loads to Markgrafs Lake. It encompasses the subwatersheds draining to Wilmes Lake, including upstream Markgrafs Lake and its tributaries. In order to remove the inflow volume resulting from precipitation falling directly onto the lake, 40.46 acres were removed from the local watershed. This corresponds to the size of the permanent pool, as determined from the XPSWMM model. The impervious percentage of the remaining local watershed was adjusted accordingly.

The P8 model was run from 1962 through 2011, and then inflow volume and TP loading data was extracted and compiled to determine the annual June through September estimate surface water volume and pollutant loading. The total volume and loading to Markgrafs Lake was estimated as being the total inflow to the model node representing the lake (Node ML1_1-P).

[4] XP-SWMM model developed for the "Central Draw Project and Flood Storage Area Maps," by HDR Engineering, Inc., June 2002.

6 Wilmes Lake Watershed Modeling

Models 1, 2, and 3, developed and calibrated for the Colby Lake study, were used to estimate loads to Wilmes Lake. According to the MnDNR Lake Finder website, Wilmes Lake is divided into ‘Wilmes Lake North Portion’ and ‘Wilmes Lake South Portion.’

In order to remove the inflow volume resulting from precipitation falling directly on the lake, 16.6 acres were removed from the local watershed of the north portion of the lake, and 17.6 acres were removed from the local watershed of the south portion of the lake. These acreages correspond to the size of the permanent pools, as determined from the XPSWMM model. The impervious percentages in the remaining watersheds were adjusted accordingly.

The total inflow volume and pollutant loading to the north portion of Wilmes Lake was estimated by adding the following components: 1) total outflow from Model 2 (including contribution from Model 1 watershed), and 2) total inflow to the north portion of Wilmes Lake (Node WL2_1-P) from the contributing portion of the watershed in Model 3. Acquiring a sound estimate for the first component required combining models 1 and 2. The details of this procedure are provided in **Appendix II.**

The total volume and loading to the south portion of Wilmes Lake was estimated as being the total inflow to the model node representing the lake (Node WL1_1-P), less the contribution from the north portion, which is incorporated separately in the receiving water modeling (the volume and loading contributed from the north portion of the lake was estimated as part of the development of the hydrologic and TP budgets prior to the receiving water modeling).

The P8 model was run from 1962 through 2011, and the inflow volume and TP loading data was extracted and compiled to determine the annual June through September estimate surface water volume and pollutant loading.

Appendix I

Removal Efficiencies as Predicted by the P8 Model

Notes:

Device names ending in –P are modeled as ponds
Devices names ending in –W are wetlands (modeled with increased particle removal scale factor)
Devices names ending in –PI are modeled as junction nodes with no storage

Table 2: Model 1- Predicted Removal Efficiencies

Storage Node	TSS Removal (%)	TP Removal (%)
AL1N1_1-P	81	56
AL1N2_2-W	73	43
AL1N2_3-W	94	73
AL1N2_1-W	55	24
AL1S1_1-P	92	76
AL1_1-P	75	49
EP2_5-PI	0	0
EP2_2p-P	59	34
Ept_P10-P	86	57
Ept_P13-P	74	45
Ept_P15-P	4	1
Ept_P18-P	78	50
Ept_P1-P	77	48
Ept_P2_5-P	0	0
Ept_P2_4-P	34	9
Ept_P2_3-P	28	13
Ept_P2_1-P	9	2
Ept_P2-P	59	37
Ept_P7-P	36	15
Ept_P9-P	96	89
GA1_1-P	70	39
I94_15-PI	0	0
I94_7-P	41	14
I94_8-P	22	5
I94_9-P	34	12
I94_11-P	50	27
In_w_cu-PI	0	0
Op12-P	83	55
Op11-P	81	47
Op10-P	72	49
Op14-P	76	53
Op15-P	40	17
Op16-P	37	9
Om17_2-PI	0	0
Oc17_3-PI	0	0
Oc4_GA-PI	0	0
Op9-P	86	70
EP4_3-PI	0	0
EP4_1-PI	0	0
EP3_2-PI	0	0
Ept_P3-P	29	10
Ep_NC2.2-PI	0	0
Ep_NC2.1-PI	0	0
EP2_1-P	1	0
WLMuirP2-P	88	60
WLMuirP1-P	77	42
Oc10-PI	0	0
WLOp13_4-PI	0	0
Op13-P	81	52
EP1_1-P	3	0

Table 3: Model 2- Predicted Removal Efficiencies

Storage Node	TSS Removal (%)	TP Removal (%)
EP2_3-PI	0	0
I94_6-P	48	19
Id_hud_1-P	87	58
I94_4-PI	0	0
I94_5-PI	0	0
OM1_1-P	89	73
GA1_2-P	81	56
I94_1-PI	0	0
RadI94Dtch-P	37	10
RadI94P1_1-P	61	30
RadioI94P1-P	88	56
WL_PdV1-P	85	57
WL_PdV2-P	81	49
WL_RT_P1-P	82	53
WL_WL_21-PI	0	0
WL_WL117-PI	0	0
WL_WL_2-PI	0	0
WL3W3_4-PI	0	0
WL3W3_3-PI	0	0
WL3W3_2-P	83	56
WL3W3_1-P	64	32
WL3W2_3-P	50	17
WL3W2_2-W	39	12
WL3W2_1-P	44	11

Storage Node	TSS Removal (%)	TP Removal (%)
WL4N2_1-P	72	41
446-PI	0	0
WL5_5-PI	0	0
WL5S1_1-P	81	55
WL5W3_5-PI	0	0
WL5W3_4-PI	0	0
WL5W4_3-PI	0	0
WL5W4_2-PI	0	0
WL5W4_1-P	83	53
WL5W3_2-PI	0	0
WL5W5_1-W	92	64
GlbColPd-P	86	54
WL5W5_2-W	80	44
WL5W3_1-P	72	36
WL5W2_1-P	2	0
WL5W1_3-PI	0	0
WL5W1_2-P	8	1
WL5W1_1-P	7	1
RadioI94P2-P	24	9
WL5_10-P	3	1
RadioI94P3-P	23	9
WL5_1-P*	70	35
WL4_1-P*	58	23

* Accuracy questionable. Located along mainstem of Wilmes Lake. Model 2 does not receive drainage from Model 1 to the north.

Table 4: Model 3- Predicted Removal Efficiencies

Storage Node	TSS Removal (%)	TP Removal (%)
2857-PI	0	0
2949-PI	0	0
ML_STP1-P	89	63
ML_ST_1-PI	0	0
ML1W1_1-P	56	27
ML1W2_1-P	70	44
ML2_1-W	95	81
WL_SamPd-P	81	52
ML1_1-P	92	68
WL1E3_1-PI	0	0
WL1E2_1-PI	0	0
WL1E1_1-P	46	14
WL1N3_2-P	71	43
WL1N3_1-W	72	40
WL1N2_1-P	78	51
1072-PI	0	0
WL1W3_2-P	69	38
WL1W3_3P-P	81	53
WL1W3_4P-P	59	29
WL1W3_5P-P	39	14
WL1W4_1-P	93	72
WL1W3_1-P	58	31
WL1W2_1-P	54	28
WL1W1_1-PI	0	0

Storage Node	TSS Removal (%)	TP Removal (%)
WL2N2_1-P	82	56
WL2N1_1-P	60	28
WL2W11_1-P	73	45
WL2W10_1-P	55	28
WL2W13_1-P	78	49
WL2W14_1-P	84	55
WL2W15_1-P	65	36
WL2W9_1-PI	0	0
WL2W8_1-P	47	21
WL2W7_1-P	73	42
WL2W6_1-P	40	17
WL2W5_1A-PI	0	0
WL2W4_1-P	30	10
WL2W3_1-P	44	17
WL2W2_1-P	2	0
WL2W1_1-PI	0	0
WL3_1-P*	38	9
WL3W1_1-P	18	3
WL2_2-P*	36	15
WL6W2_1-W	82	57
WL6W1_1-P	64	35
WL2_1-P*	65	35
WL1_1-P*	44	17

* Accuracy questionable. Located along mainstem of Wilmes Lake. Model 2 does not receive drainage from Models 1 or 2 to the north.

Appendix II

Procedure to Combine Models 1 and 2 to Estimate Inflow Volume and Pollutant Loading to the North Portion of Wilmes Lake

For the Colby Lake P8 model, the results at the downstream ends of each model were summed up to estimate the total inflow to Colby Lake. Though the outflow from Model 1 was not routed through the two large waterbodies along the mainstem in the Model 2 watershed , where a certain amount of treatment would in actuality occur, the total outflow from Models 1, 2, and 3 were calibrated at the outlet from Wilmes Lake, which the critical point regarding estimating the inflow to Colby Lake. However, ensuring a reliable estimate of inflow volume and pollutant loading to the north portion of Wilmes Lake requires that the outflows from Model 1 pass through and be treated in the large waterbodies within Model 2 before entering Wilmes Lake. This has been accomplished by creating one large watershed in Model 2 to simulate outflow from Model 1. Note that Models 1 and 2 cannot simply be joined as one large model because of the node capacity limitations in P8. This watershed representing Model 1 as a whole was created by applying the total watershed drainage area, as well as the weighted average of the hydrology parameters (Pervious CN of 61, Indirect Impervious fraction of 0.298, and the portion of the impervious area which is indirectly connected of 50%).

To account for treatment occurring throughout the Model 1 watershed in the devices which are no longer specifically modeled, parameters were adjusted in this watershed until the outflow volume, TSS loading, and TP loading matched as nearly as possible to the outflow as the calibrated model. The parameters adjusted included impervious fraction, watershed depression storage, impervious runoff coefficient, and the localized scale factor for particle loads, which is applied to both TSS and TP. Individual TSS and TP scale factors are set globally in a P8 model, so that the watershed node representing Model 1 is also subject to those factors set in Model 2 (1.2 for TSS and 0.9 for TP). Because the particle scale factor which can be set specifically for each subwatershed are applied to all particles, and TSS and TP react differently to the same adjustment, the choice was made to concentrate on TP. **Table 1** presents how the model parameters were adjusted in the consolidated Model 1 watershed.

Table 1: Parameters Adjusted to Simulate Outflow from Model 1 when modeling as one watershed

	Calibrated Model 1	Model 1Consolidated into One Watershed
Impervious Fraction	0.298	0.19
Depression Storage	0.1	0.02
Runoff Coefficient	0.9	0.9
Scale Factor Particle Load	1	0.45

As in the calibration process in the Colby Lake Project, the results of 2008 and 2009 are assessed together and are the years used to determine the adjustment in model parameters. The results of 2010 are evaluated as check of how the consolidated Model 1 performs in a different year. **Table 2** shows a comparison between the volume and pollutant loading at the outlet of Model 1 between the calibrated Model 1 and Model 1 after it has been consolidated into one large watershed.

Table 2: P8 Model Results at the Outflow Point for Model 1

YEAR	Calibrated Model 1			Model 1Consolidated into One Watershed			Difference in Results			% Difference in Results		
	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (%)	TSS (%)	TP (%)
2008	65	6,700	29	82	16,785	38	17	10,085	9			
2009	104	8,013	42	110	18,224	44	6	10,211	2			
	169	14,713	71	191	35,009	81	23	20,296	10	13%	138%	14%
2010	255	16,993	98	221	33,004	81	-34	16,011	-17	-13%	94%	-17%

The model was also run for a 50-year period (1961-2010), and the annual June – September outflows from Model 1 were compared between the calibrated Model 1 and the Model 1 represented as one consolidated watershed. The results are in **Table 3.**

Table 3: 50-year P8 Model Results for Model 1, Annual June – September

Statistic	Calibrated Model 1			Model 1 Consolidated into One Watershed			Difference in Results		
	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)	Volume (ac-ft)	TSS (lbs)	TP (lbs)
Median	131	9,125	51	125	21,004	49	-4%	130%	-4%
Mean	177	37,256	126	167	44,976	96	-6%	21%	-24%
25% Percentile	93	7,721	40	95	18,283	42	3%	137%	7%
75% Percentile	210	12,367	75	175	25,131	61	-17%	103%	-19%

As mentioned above, the total volume and loading to the north portion of Wilmes Lake was estimated by adding the following components: 1) total outflow from Model 2 (including contribution from Model 1 watershed), and 2) total inflow to the north portion of Wilmes Lake from the contributing portion of the watershed in Model 3.

APPENDIX B

Statistical distribution parameters

Armstrong Lake

Crystal Ball Report - Assumptions

No Simulation Data

Assumptions

Worksheet: [CNET_Armstrong_Lake_3.xls]MODEL

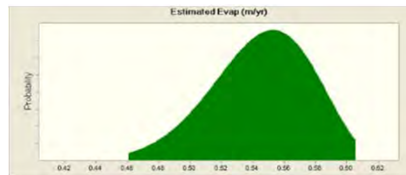
Assumption: Estimated Evap (m/yr) — **Cell: H16**

needed to adjust maximum evap so runs

Beta distribution with parameters:

Minimum	0.28
Maximum	0.64
Alpha	16.56266964
Beta	6.111223171

Selected range is from 0.46 to 0.61

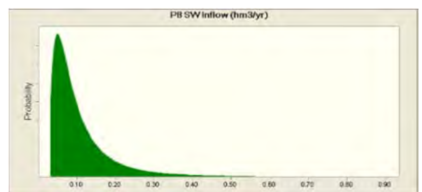


Assumption: P8 SW Inflow (hm3/yr) — **Cell: H24**

Lognormal distribution with parameters:

Location	0.02
Mean	0.11
Std. Dev.	0.09

Selected range is from 0.03 to 0.56



Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	0.84 (='P8 Model Results'!L6)
P8 SW TP Loading (kg/yr) (H26)	0.82 (='P8 Model Results'!L5)

Assumption: P8 SW TP Loading (kg/yr) — **Cell: H26**

Lognormal distribution with parameters:

Location	5.08
Mean	20.65
Std. Dev.	30.78

Selected range is from 5.44 to 576.07

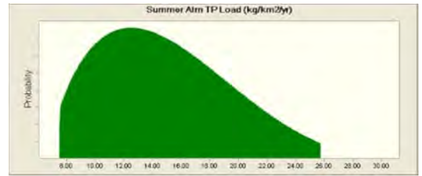
Correlated with:	Coefficient
P8 SW Inflow (hm3/yr) (H24)	0.82 (='P8 Model Results'!L5)
Summer Precip (in/summer) (H15)	0.44 (='P8 Model Results'!L7)

Armstrong Lake

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: H20**

Beta distribution with parameters:

Minimum	6.59
Maximum	32.24
Alpha	1.850660541
Beta	3.851962405



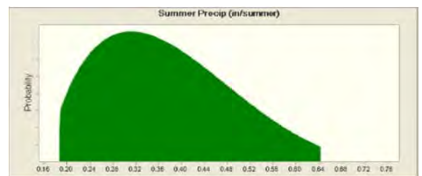
Selected range is from 7.48 to 25.73

Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	1.00

Assumption: Summer Precip (in/summer) **Cell: H15**

Beta distribution with parameters:

Minimum	0.16
Maximum	0.81
Alpha	1.850660541
Beta	3.851962405



Selected range is from 0.19 to 0.64

Correlated with:	Coefficient	
P8 SW Inflow (hm3/yr) (H24)	0.84	(='P8 Model Results'!L6)
Summer Atm TP Load (kg/km2/yr) (H20)	1.00	
P8 SW TP Loading (kg/yr) (H26)	0.44	(='P8 Model Results'!L7)

End of Assumptions

Markgrafs Lake

Crystal Ball Report - Assumptions

No Simulation Data

Assumptions

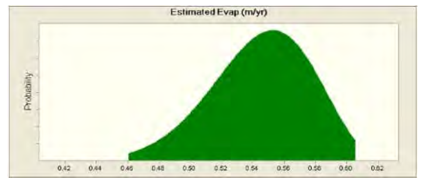
Worksheet: [CNET_Markgrafs_Lake.xls]MODEL

Assumption: Estimated Evap (m/yr) — **Cell: H16**

Beta distribution with parameters:

Minimum	0.28
Maximum	0.64
Alpha	16.56266964
Beta	6.111223171

Selected range is from 0.46 to 0.61

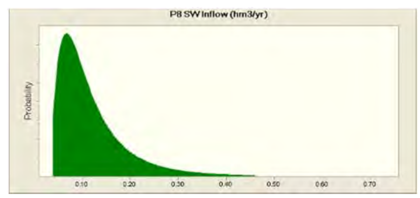


Assumption: P8 SW Inflow (hm3/yr) — **Cell: H24**

Lognormal distribution with parameters:

Location	0.02
Mean	0.12
Std. Dev.	0.08

Selected range is from 0.04 to 0.46



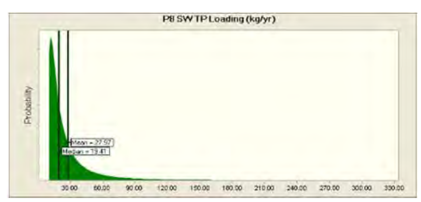
Correlated with:	Coefficient
P8 SW TP Loading (kg/yr) (H26)	0.78 (='P8 Model Results'!L5)
Summer Precip (m/summer) (H15)	0.91 (='P8 Model Results'!L6)

Assumption: P8 SW TP Loading (kg/yr) — **Cell: H26**

Lognormal distribution with parameters:

Location	9.04
Mean	28.02
Std. Dev.	29.56

Selected range is from 9.76 to 444.62



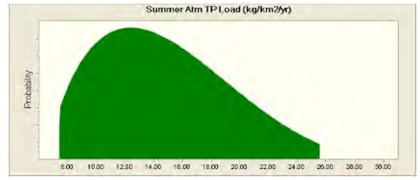
Correlated with:	Coefficient
P8 SW Inflow (hm3/yr) (H24)	0.78 (='P8 Model Results'!L5)
Summer Precip (m/summer) (H15)	0.50 (='P8 Model Results'!L7)

Markgrafs Lake

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: H20**

Beta distribution with parameters:

Minimum	6.55
Maximum	32.02
Alpha	1.850660541
Beta	3.851962405



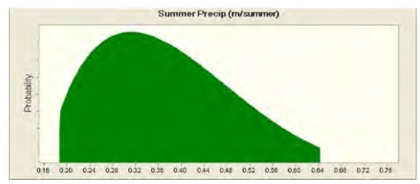
Selected range is from 7.43 to 25.56

Correlated with:	Coefficient
Summer Precip (m/summer) (H15)	1.00

Assumption: Summer Precip (m/summer) **Cell: H15**

Beta distribution with parameters:

Minimum	0.16
Maximum	0.81
Alpha	1.850660541
Beta	3.851962405



Selected range is from 0.19 to 0.64

Correlated with:	Coefficient	
Summer Atm TP Load (kg/km2/yr) (H20)	1.00	
P8 SW Inflow (hm3/yr) (H24)	0.91	(='P8 Model Results'!L6)
P8 SW TP Loading (kg/yr) (H26)	0.50	(='P8 Model Results'!L7)

End of Assumptions

North Wilmes Lake

Crystal Ball Report - Assumptions

No Simulation Data

Assumptions

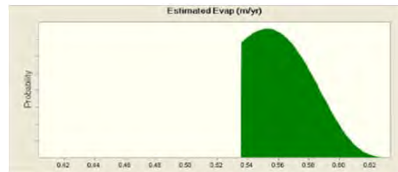
Worksheet: [CNET_North Wilmes_Lake.xls]MODEL

Assumption: Estimated Evap (m/yr) **Cell: H16**

Beta distribution with parameters:

Minimum	0.28
Maximum	0.64
Alpha	16.56266964
Beta	6.111223171

Selected range is from 0.54 to 0.69

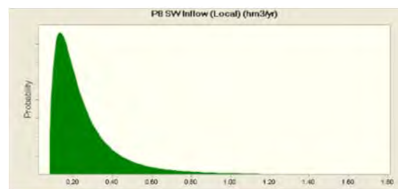


Assumption: P8 SW Inflow (Local) (hm3/yr) **Cell: H24**

Lognormal distribution with parameters:

Location	0.06
Mean	0.25
Std. Dev.	0.19

Selected range is from 0.08 to 1.15



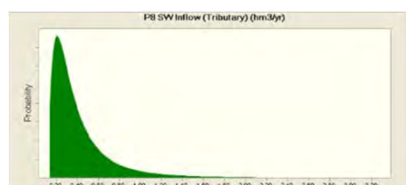
Correlated with:	Coefficient
P8 SW TP Loading (Local) (kg/yr) (H27)	0.82 (='P8 Model Results'!J5)
Summer Precip (in/summer) (H15)	0.86 (='P8 Model Results'!U6)

Assumption: P8 SW Inflow (Tributary) (hm3/yr) **Cell: H25**

Lognormal distribution with parameters:

Location	0.10
Mean	0.43
Std. Dev.	0.34

Selected range is from 0.13 to 2.09



Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	0.83 (='P8 Model Results'!J6)
P8 SW TP Loading (Tributary) (kg/yr) (H28)	0.82 (='P8 Model Results'!J5)

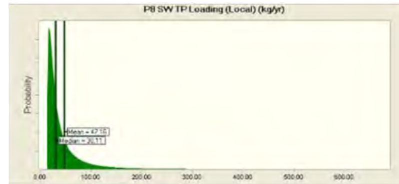
North Wilmes Lake

Assumption: P8 SW TP Loading (Local) (kg/yr) **Cell: H27**

Lognormal distribution with parameters:

Location	13.03
Mean	47.12
Std. Dev.	59.94

Selected range is from 14.06 to 1159.39



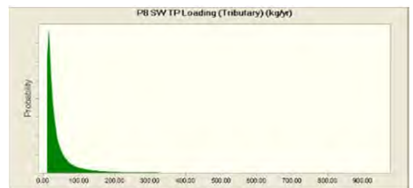
Correlated with:	Coefficient
P8 SW Inflow (Local) (hm3/yr) (H24)	0.82 (='P8 Model Results'!J5)
Summer Precip (in/summer) (H15)	0.44 (='P8 Model Results'!U7)

Assumption: P8 SW TP Loading (Tributary) (kg/yr) **Cell: H28**

Lognormal distribution with parameters:

Location	9.36
Mean	48.66
Std. Dev.	83.00

Selected range is from 9.98 to 1551.76



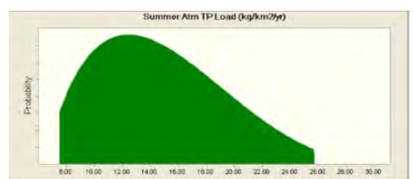
Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	0.43 (='P8 Model Results'!J7)
P8 SW Inflow (Tributary) (hm3/yr) (H25)	0.82 (='P8 Model Results'!J5)

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: H20**

Beta distribution with parameters:

Minimum	6.58
Maximum	32.17
Alpha	1.850660541
Beta	3.851962405

Selected range is from 7.48 to 25.73



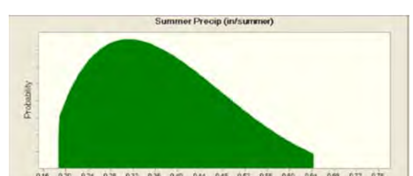
Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	1.00

Assumption: Summer Precip (in/summer) **Cell: H15**

Beta distribution with parameters:

Minimum	0.16
Maximum	0.81
Alpha	1.850660541
Beta	3.851962405

Selected range is from 0.19 to 0.64



North Wilmes Lake

Correlated with:	Coefficient	
P8 SW TP Loading (Tributary) (kg/yr) (H28)	0.43	(='P8 Model Results'!J7)
P8 SW Inflow (Tributary) (hm3/yr) (H25)	0.83	(='P8 Model Results'!J6)
P8 SW Inflow (Local) (hm3/yr) (H24)	0.86	(='P8 Model Results'!U6)
Summer Atm TP Load (kg/km2/yr) (H20)	1.00	
P8 SW TP Loading (Local) (kg/yr) (H27)	0.44	(='P8 Model Results'!U7)

End of Assumptions

South Wilmes Lake

Crystal Ball Report - Assumptions

No Simulation Data

Assumptions

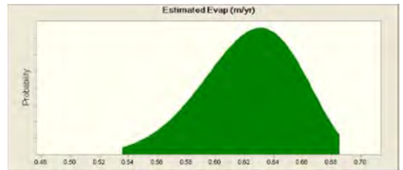
Worksheet: [CNET_South Wilmes_Lake_3.xls]MODEL

Assumption: Estimated Evap (m/yr) **Cell: H16**

Beta distribution with parameters:

Minimum	0.35
Maximum	0.72
Alpha	16.56266964
Beta	6.111223171

Selected range is from 0.54 to 0.69

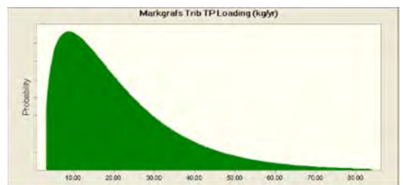


Assumption: Markgrafs Trib TP Loading (kg/yr) **Cell: H30**

Gamma distribution with parameters:

Location	2.78
Scale	12.80
Shape	1.461301357

Selected range is from 3.09 to 93.42



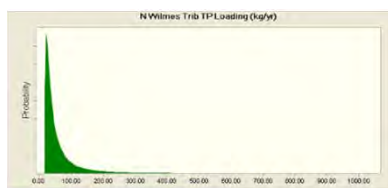
Correlated with:	Coefficient	
Summer Precip (in/summer) (H15)	0.88	(='P8 Model Results'!AE13)
P8 SW Inflow (Markgrafs) (hm3/yr) (H26)	0.98	(='P8 Model Results'!AE11)

Assumption: N Wilmes Trib TP Loading (kg/yr) **Cell: H31**

Lognormal distribution with parameters:

Location	15.36
Mean	64.89
Std. Dev.	92.08

Selected range is from 16.67 to 1730.84



Correlated with:	Coefficient	
Summer Precip (in/summer) (H15)	0.44	(='P8 Model Results'!AE19)
SW Inflow (N. Wilmes) (hm3/yr) (H27)	0.80	(='P8 Model Results'!AE17)

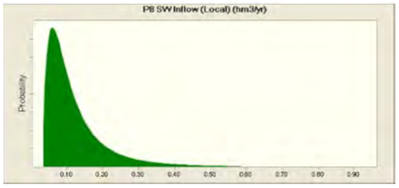
South Wilmes Lake

Assumption: P8 SW Inflow (Local) (hm3/yr) **Cell: H25**

Lognormal distribution with parameters:

Location	0.02
Mean	0.12
Std. Dev.	0.10

Selected range is from 0.03 to 0.59



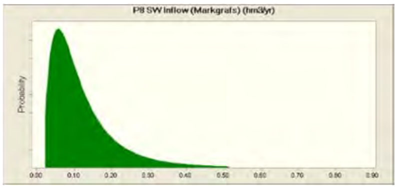
Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	0.86 (='P8 Model Results'!AE6)
P8 SW TP Loading (Local) (kg/yr) (H29)	0.80 (='P8 Model Results'!AE5)

Assumption: P8 SW Inflow (Markgrafs) (hm3/yr) **Cell: H26**

Lognormal distribution with parameters:

Location	0.00
Mean	0.12
Std. Dev.	0.10

Selected range is from 0.02 to 0.52



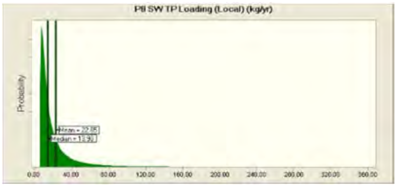
Correlated with:	Coefficient
Markgrafs Trib TP Loading (kg/yr) (H30)	0.98 (='P8 Model Results'!AE11)
Summer Precip (in/summer) (H15)	0.91 (='P8 Model Results'!AE12)

Assumption: P8 SW TP Loading (Local) (kg/yr) **Cell: H29**

Lognormal distribution with parameters:

Location	5.42
Mean	22.85
Std. Dev.	31.86

Selected range is from 5.90 to 612.36



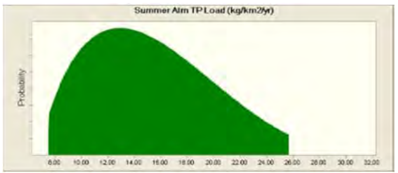
Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	0.44 (='P8 Model Results'!AE7)
P8 SW Inflow (Local) (hm3/yr) (H25)	0.80 (='P8 Model Results'!AE5)

Assumption: Summer Atm TP Load (kg/km2/yr) **Cell: H20**

Beta distribution with parameters:

Minimum	6.82
Maximum	33.32
Alpha	1.850660541
Beta	3.851962405

Selected range is from 7.48 to 25.73



South Wilmes Lake

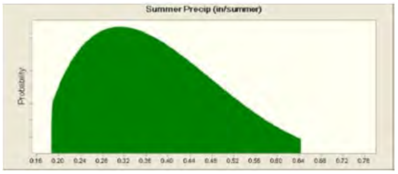
Correlated with:	Coefficient
Summer Precip (in/summer) (H15)	1.00

Assumption: Summer Precip (in/summer) **Cell: H15**

Beta distribution with parameters:

Minimum	0.16
Maximum	0.81
Alpha	1.850660541
Beta	3.851962405

Selected range is from 0.19 to 0.64



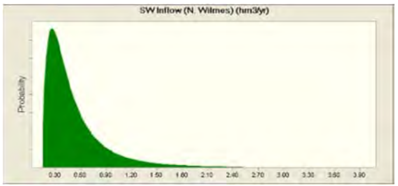
Correlated with:	Coefficient	
P8 SW Inflow (Local) (hm3/yr) (H25)	0.86	(='P8 Model Results'!AE6)
P8 SW TP Loading (Local) (kg/yr) (H29)	0.44	(='P8 Model Results'!AE7)
N Wilmes Trib TP Loading (kg/yr) (H31)	0.44	(='P8 Model Results'!AE19)
Markgrafs Trib TP Loading (kg/yr) (H30)	0.88	(='P8 Model Results'!AE13)
SW Inflow (N. Wilmes) (hm3/yr) (H27)	0.83	(='P8 Model Results'!AE18)
Summer Atm TP Load (kg/km2/yr) (H20)	1.00	
P8 SW Inflow (Markgrafs) (hm3/yr) (H26)	0.91	(='P8 Model Results'!AE12)

Assumption: SW Inflow (N. Wilmes) (hm3/yr) **Cell: H27**

Lognormal distribution with parameters:

Location	0.10
Mean	0.53
Std. Dev.	0.42

Selected range is from 0.15 to 2.52



Correlated with:	Coefficient	
N Wilmes Trib TP Loading (kg/yr) (H31)	0.80	(='P8 Model Results'!AE17)
Summer Precip (in/summer) (H15)	0.83	(='P8 Model Results'!AE18)

End of Assumptions