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South Washington Watershed District Lake Management Plan

Prepared for:

South Washington Watershed District
and the City of Woodbury, MN

WENCK
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Executive Summary

The South Washington Watershed District (SWWD) manages 7 lakes for water quantity and quality. In 2012, the District developed several lake management plans to identify projects to improve water quality and overall lake condition. The purpose of this study is to update the watershed and lake models for those lakes where this work was completed, develop models for new lakes, provide in-lake best management practice options, and to provide load reduction goals to meet lake water quality standards. Sediment data was collected for each of the lakes to refine internal phosphorus load estimates and watershed models were updated with new developments and BMPs.

The majority of the lakes in this study (all, except Powers) are shallow lakes that require a unique management approach that includes understanding the ecological balance in the lakes as well as physical conditions such as water quality.

Historic Water Quality

Five of the seven lakes assessed in this report are on Minnesota's 303(d) list of impaired waters for excess nutrients. Excess nutrients create poor ecological conditions and can lead to poor water clarity, fish kills, and poor recreational conditions. Lake water quality varies depending on annual precipitation, annual temperature, biotic population dynamics, and other factors. Annual summer averages from 2012 to 2016 demonstrated a broad range of water quality conditions in these lakes ranging from excellent water quality in Powers Lake to highly eutrophic conditions in Markgrafs and Colby Lake.

Fisheries and Aquatic Vegetation

Biological conditions (fish, plants, zooplankton, and invertebrates) in shallow lakes play a critical role in maintaining water quality. The Minnesota DNR routinely monitors fish communities in the District's FiN lakes. These data were organized by trophic structure to evaluate the current conditions of the fish communities. Surveys in Colby Lake measured high numbers and biomass of black bullhead which likely contribute to the degradation of water quality of Colby Lake. Power's Lake has maintained a relatively balanced fish community since the 1980s with few bullheads and large top predators. Ravine historically (2001) had a large bullhead population, but the lake has shifted to a more balanced panfish community. Other than Colby Lake, stocking appears to have maintained a healthy fish community in these lakes.

Aquatic vegetation communities in these lakes are relatively healthy. Vegetative cover is relatively high, especially in littoral areas where several lakes have 100 percent or close to 100 percent of littoral areas vegetated. Maximum depths of vegetative growth are also relatively deep, especially in Wilmes and Ravine, which has vegetation down to 11 and 15 feet, respectively. All lakes except Wilmes have vegetation communities with at least one non-native taxon with Eurasian watermilfoil and Curly-leaf pondweed being the most common non-native/invasive taxa. The MnDNR used the Floristic Quality Index to develop impairment thresholds to relate the health of the vegetation community to eutrophication stress. Powers has a fairly poor FQI, but otherwise these lakes have FQI values near or above the "good" threshold. Powers has a poor FQI in large part because its vegetation community is dominated by Eurasian watermilfoil.

Nutrient Budget

Nutrient budgets were developed for each of the lakes using watershed loading from P8, internal load measurements, and estimates of atmospheric loading. Lake response models were then calibrated to in-lake monitoring data by adjusting the sedimentation rate in the Canfield-Bachmann model.

P8 water quality models developed for *The Water Quality Modeling Report: Armstrong Lake, Markgrafs Lake, and Wilmes Lake Report* in 2012 served as the basis for the P8 models used in this study. The 2012 models were modified to match the 2017 XPSWMM model. Four of the seven lakes required significant watershed load reductions from the watershed to meet state water quality standards

Implementation Plan

Recommended management activities for each of the lakes include a mix of internal and external (watershed) nutrient reduction projects, fisheries management, aquatic vegetation management and shoreline management. The goal of this project was to update the nutrient budgets for the lakes and identify in-lake management opportunities to enhance water quality and lake conditions.

Watershed Load Reductions

These studies were used as the basis for identifying watershed load reductions. However, this study does include a preliminary analysis of internal loading in stormwater ponds to determine if this currently unquantified source of phosphorus should be addressed. Reductions in phosphorus loading from the watersheds will be challenging and will require additional analyses to determine where additional reductions may be achievable. These projects should be implemented using adaptive management where the initial projects are implemented, and the lake response is measured. Recent evidence suggests that stormwater pond sediments can be a source of phosphorus to surface waters. Pond sediments measured in this study suggests that there is a significant pool of P available for release from stormwater pond sediments. Further, pond monitoring demonstrated frequent and large anoxic areas in many of the ponds with several ponds showing high bottom water TP concentrations indicative of sediment P release in ponds. Based on the evidence developed in this report, further investigation of pond sediment loading is warranted. The investigation should focus on key watersheds with large watershed loads including Colby, Markgrafs, and N. Wilmes Lake. These lakes demonstrated poor water quality, have a large number of ponds, and demonstrate large watershed loads. The study should investigate sediment P release through lab measurements, frequent DO measurements, and bottom phosphorus concentrations. The following ponds could be further investigated to determine if internal load reductions will impact watershed P loading:

Colby Lake
- CD-39
- CD-54

North and South Wilmes Lake
- CD-6

Powers Lake

- CD-26
- CD-26.1

Internal P Load Reductions

Five lakes were identified as having internal P loading large enough to recommend alum applications as viable options for lake phosphorus management. Over half of each of these lakes' TP budgets is from internal phosphorus loading.

Fisheries and Aquatic Vegetation Management and Monitoring

The vegetation management goal of these lakes ideally is to maintain broad lake coverage, manage invasive species such as Curly-leaf pondweed, and increase diversity where possible through nutrient and water level management and via changes in sediment chemistry ultimately.

Fisheries management is critical in maintaining clear water conditions in shallow lakes. Ideally, the fish community is balanced between top predators and panfish populations, lacks stunting in the panfish community, and has low numbers of fathead minnows and rough fish. The lakes also lack carp populations or if carp are present, they are managed to maintain low densities of carp. Regular monitoring of the fish community by the Minnesota DNR and/or the District will continue to provide information to evaluate any changes that may need to be addressed, including fishery balance, rough fish (especially carp), and decline in numbers or biomass. Ideally each lake will be surveyed once every five years, according to DNR standard protocol.

1.0 Introduction

1.1 PURPOSE

The South Washington Watershed District (SWWD) manages 8 lakes for water quantity and quality, seven of which are addressed in this report. In 2012, the District developed several lake management plans to identify projects to improve water quality and overall lake condition. Since the completion of these reports, the District has implemented watershed Best Management Practices (BMPs) aimed at reducing phosphorus loading to the lakes. Additionally, new data has been collected including submerged aquatic vegetation surveys, some fish surveys, and additional water quality monitoring.

The purpose of this study is to update the watershed and lake models for those lakes where this work was completed, develop models for new lakes, provide in-lake best management practice options, and to provide load reduction goals to meet lake water quality standards. Sediment data was collected for each of the lakes to refine internal phosphorus load estimates and watershed models were updated with new developments and BMPs. The focus of this report is on the in-lake management options for each of the lakes.

1.2 PREVIOUS STUDIES

The South Washington Watershed District completed several previous studies that act as the basis for this study. As part of these studies, watershed loading and in-lake eutrophication response models were created for each lake. The previous studies include:

- Watershed Management Plan: South Washington Watershed District (2016)
- The Water Quality Modeling Report: Armstrong Lake, Markgrafs Lake, and Wilmes Lake Report (Houston Engineering, 2012)
- Ravine Lake Water Quality Modeling and Management Report (Houston Engineering, 2013)
- Colby Lake Water Quality Modeling Project (Houston Engineering, 2011)
- Powers Lake Management Plan (2010)

SWWD also performed watershed retrofit assessments on four lakes including:

- Colby Lake Stormwater Retrofit Assessment (Washington Conservation District, 2011)
- Wilmes Lake Subwatershed Retrofit Analysis (Washington Conservation District, 2014)
- Powers Lake Stormwater Retrofit Assessment (Washington Conservation District, 2011)
- Armstrong Lake Stormwater Retrofit Assessment (Washington Conservation District, in development)

The retrofit assessment reports outline recommended catchments for placement of BMP retrofits. The current study investigates load reductions within the watershed, including these recommended watershed improvements, and in-lake improvements to achieve delisting from the 303d list. At the time of this report there are no retrofit assessments for Armstrong (in development), Markgrafs, Ravine and La.

1.3 SHALLOW LAKE MANAGEMENT

The majority of the lakes in this study (all, except Powers) are shallow lakes that require a unique management approach that includes understanding the ecological balance in the lakes as well as physical conditions such as water quality.

1.3.1 Shallow Lake Ecology

Shallow lakes are ecologically different from deep lakes. Compared to deep lakes, shallow lakes have a greater proportion of sediment area to lake volume, allowing potentially larger sediment contributions to nutrient loads and higher potential sediment resuspension that can decrease water clarity. Biological organisms also play a greater role in maintaining water quality. Rough fish, especially carp, can uproot submerged aquatic vegetation and stir up sediment. Submerged aquatic vegetation stabilizes the sediment, reducing the amount that can be resuspended and cloud water clarity. Submerged aquatic vegetation also provides refugia for zooplankton, a group of small crustaceans that consumes algae.

All of these interactions in shallow lakes occur within a theoretical paradigm of two alternative stable states: a clear water state and a turbid water state (Scheffer 2004). The clear water state is characterized by a robust and diverse submerged aquatic vegetation community, balanced fish community and large daphnia (zooplankton that are very effective at consuming algae). Alternatively, the turbid water state typically lacks submerged aquatic vegetation, is dominated by rough fish, and is characterized by both sediment resuspension and algal productivity. The state in which the lake persists depends on the biological community as well as the nutrient conditions in the lake. Therefore, lake management must focus on the biological community as well as the water quality of the lake.

The following five-step process for restoring shallow lakes that (Moss et al. 1996) was developed in Europe is also applicable here in the United States:

- Forward “switch” detection and removal
- External and internal nutrient control
- Biomanipulation (reverse “switch”)
- Plant establishment
- Stabilizing and managing restored system

The first step refers to identifying and eliminating those factors, also known as “switches,” that are driving the lake into a turbid water state. These can include high nutrient loads, invasive species such as carp and Curly-leaf pondweed, altered hydrology, and direct physical impacts such as plant removal. Once the switches have been eliminated, an acceptable nutrient load must be established. After the first two steps, the lake is likely to remain in the turbid water state even though conditions have improved, and it must be forced back into the clear lake state by manipulating its biology (also known as biomanipulation). Biomanipulation typically includes whole lake drawdown and fish removal. Once the submerged aquatic vegetation has been established, management will focus on stabilizing the lake in the clear lake state (steps 4 and 5).

2.0 Watershed and Lake Characterization

2.1 OVERVIEW

The purpose of this study is to develop management plans for seven lakes in the South Washington Watershed District including Armstrong Lake, Markgrafs Lake, Wilmes Lake (North and South), Powers Lake, Colby Lake, La Lake, and Ravine Lake (Figure 2-1). All of the lakes except Armstrong (Oakdale/Lake Elmo) and Ravine (Cottage Grove) Lakes are located in the City of Woodbury who also actively manages the lakes for water quality.

2.2 IMPAIRMENT SUMMARY

The State of Minnesota maintains water quality standards for the protection of aquatic life and recreation in waters of the state. This study used these standards as benchmarks for the development of water quality goals. Following is a description of the standards and how they apply to these lakes.

2.2.1 Impairment Status

Five of the seven lakes assessed in this report are on Minnesota's 303(d) list of impaired waters for excess nutrients (Table 2-1). Excess nutrients create poor ecological conditions and can lead to poor water clarity, fish kills, and poor recreational conditions.

Table 2-1. Shallow lake growing season averages for water quality parameters.

Lake Name	Lake ID	Depth Class	Impairment Status (2018)
Armstrong	82-0116-00	Shallow	Not Impaired
Colby	82-0094-00	Shallow	Impaired
La	82-0097-00	Shallow	Impaired
Markgrafs	82-0089-00	Shallow	Impaired
Ravine	82-0087-00	Shallow	Impaired
Wilmes	82-0090-00	Shallow	Impaired
Powers	82-0092-00	Deep	Not Impaired

2.2.2 Beneficial Use Classifications

All waters of Minnesota are assigned classes based on their suitability for the following beneficial uses (Minn. Rules Ch. 7050.0140 and 7050.0220):

1. Domestic consumption
2. Aquatic life and recreation
3. Industrial consumption
4. Agriculture and wildlife
5. Aesthetic enjoyment and navigation
6. Other uses

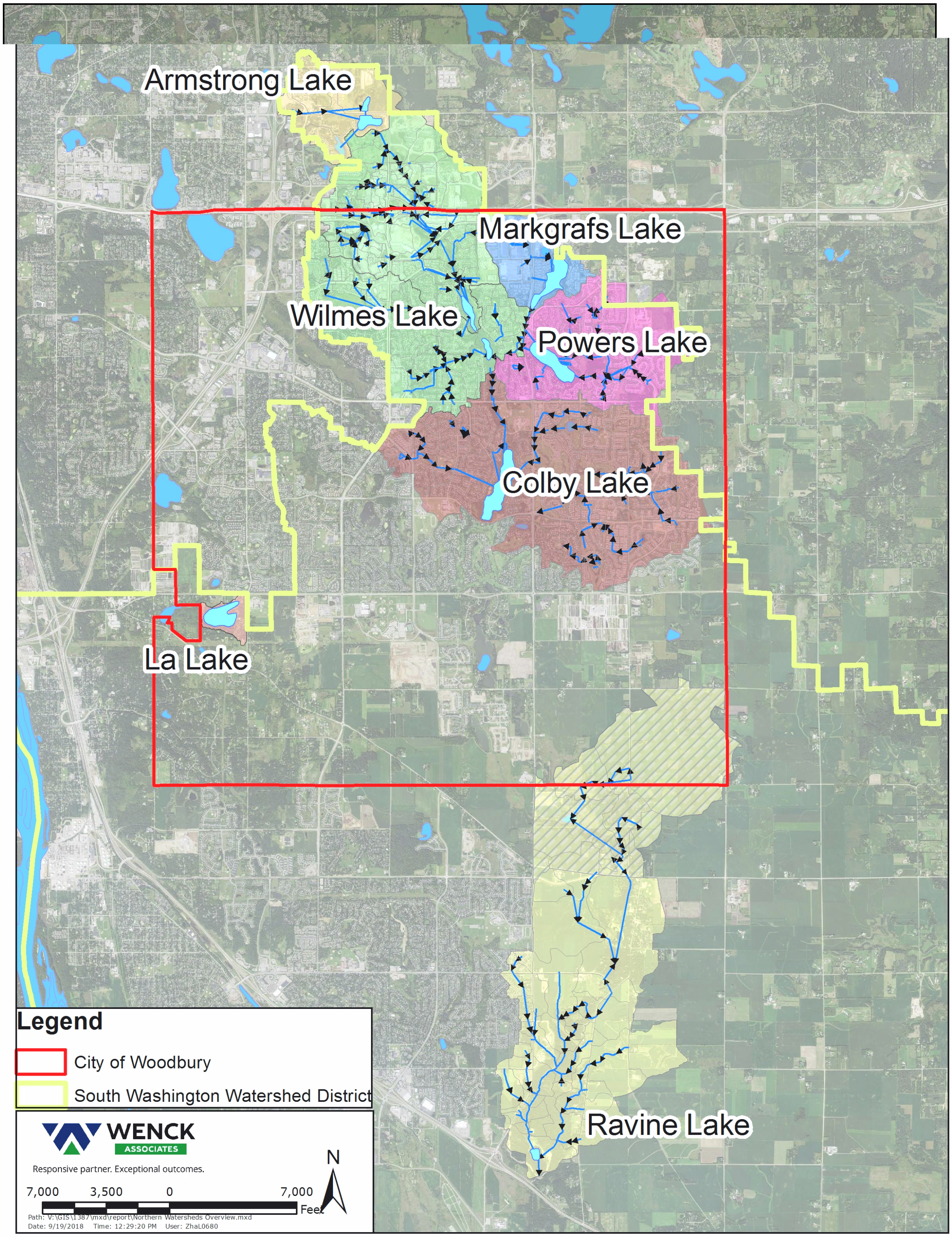


Figure 2-1. SWWD lakes and general flow area.

After each water body is assigned a beneficial use, they are also assigned a subcategory if applicable. So, for the aquatic life beneficial use, the life category that is targeted for protection is one of the classes below. This is important since each of these categories has different requirements to support a healthy biological community. For example, cold water species such as trout are more sensitive to dissolved oxygen concentrations and therefore require higher minimum dissolved oxygen concentrations.

A. Cold water sport fish (trout waters), also protected for drinking water
B. Cool and warm water sport fish, also protected for drinking water
C. Cool and warm water sport fish, indigenous aquatic life, and wetlands, and
D. Limited resource value waters

"2B" water is intended to protect cool and warm water fisheries, while "2C" water is intended to protect indigenous fish and associated aquatic communities, and a "3C" classification protects water for industrial use and cooling. All Class 2 surface waters are also protected for industrial, agricultural, aesthetics, navigation, and other uses (Classes 3, 4, 5, and 6, respectively). Minn. Rules Ch. 7050 contains general provisions, definitions of water use classes, specific standards of quality and purity for classified waters of the state, and the general and specific standards for point source dischargers to waters of the state.

The designated beneficial use for Class 2 waters (the most protective use class in the project area) is as follows (Minn. Rules Ch. 7050.0140):

> **Class 2 waters, aquatic life and recreation.** Aquatic life includes all waters of the state which do or may support fish, other aquatic life, bathing, boating, or other recreational purposes, and where quality control is or may be necessary to protect aquatic or terrestrial life or their habitats, or the public health, safety, or welfare.

All of the lakes in this report are "2B" waters.

2.2.3 Water Quality Standards for Designated Uses

The applicable water body classifications and water quality standards are specified in Minnesota Rules Chapter 7050. Minnesota Rules Chapter 7050.0470 lists water body classifications and Chapter 7050.0222 (subp. 5) lists applicable water quality standards for Minnesota water bodies.

Under Minnesota Rules 7050.0150 and 7050.0222, Subp. 4, the lakes addressed in this study are within the North Central Hardwood Forest ecoregion, with numeric targets dependent on depth as listed in Table 2-2. Therefore, this management plan estimates load reductions assuming an end point of ≤60 μg/L and ≤40 μg/L total phosphorus for shallow lakes and deep lakes, respectively.

Table 2-2. Numeric standards for lakes in the North Central Hardwood Forest Ecoregion.

Parameters	Shallow[1] Lake Standard	Deep Lake Standard
Total Phosphorus (μg/L)	≤60	≤40
Chlorophyll-*a* (μg/L)	≤20	≤14
Secchi disk transparency (meters)	≥1.0	≥1.4

[1] Shallow lakes are defined as having a maximum depth of 15 feet or less, or with 80% or more of the lake area shallow enough to support emergent and submerged rooted aquatic plants (littoral zone).

In addition to meeting a respective phosphorus limit of 60 μg/L and 40 μg/L for shallow and deep lakes, chlorophyll-*a* and Secchi depth standards must also be met. In developing the lake nutrient standards for Minnesota lakes (Minn. Rule 7050), the MPCA evaluated data from a large cross-section of lakes within each of the state's ecoregions (Heiskary and Wilson, 2005). Relationships were established between total phosphorus as the causal factor and chlorophyll-*a* and Secchi disk as the response variables. Based on these relationships it is expected that by meeting the phosphorus targets of 60 μg/L and 40 μg/ for shallow and deep lakes, the chlorophyll-*a* and Secchi standards will likewise be met.

2.3 LAKE MORPHOMETRY

Most of the lakes in this study are small, shallow lakes with average depths ranging from 2 to 8 feet (Table 2-3). The State of Minnesota defines shallow lakes as any lake with a maximum depth less than 15 feet or more than 80% of the lake is less than 15 feet in depth. All of the lakes meet this definition except for Powers Lake. All of the lakes are small (<70 acres) characterized by suburban watersheds that are a mix of mostly residential and commercial land use.

Since these lakes are small and shallow, they tend to have short residence times which can be an important indicator of how sensitive a lake will be to changes in runoff water quality. Lakes with the shorter residence times tend to be more sensitive to changes in runoff water quality. All the lakes in the study, except for La, have residence times of 0.6 years or less suggesting they will be quite sensitive to stormwater phosphorus loads. This is especially true for Armstrong, Wilmes, and Colby which have residence times less than 0.1 years. Colby and Wilmes have especially large watersheds adding to the challenge of managing nutrients in these lakes.

Since all of these lakes, except Powers Lake, are shallow with littoral areas representing more than 80% of the lake area, they are expected to support a robust plant community. The littoral area is defined as the area where submerged aquatic vegetation is expected to be abundant since light can penetrate to the sediments. Consequently, submerged aquatic vegetation management will be a critical part of managing these lakes. Submerged aquatic vegetation management is also important for Powers Lake especially since it is managed as recreational fishery.

Table 2-3. Lake morphometry for all lakes in the study area.

Parameter	Surface Area	Average Depth	Max Depth	Lake Volume	Littoral zone	Residence Time	Depth Class	Total Drainage Area
Water body	acre	feet	feet	ac-ft	(%)	years	--	acre
Armstrong	18	1.9	7	34	100	0.1	Shallow	563
Colby	69	5.5	9	380	100	0.09	Shallow	2,924
La	52	3.9	8	203	100	20	Shallow	64
Markgrafs	47	4.4	8	208	100	0.6	Shallow	425
Powers	62	17.8	40	1,113	41	0.6[1]	Deep	1,257
Ravine	27	5.2	16	138	96	0.4	Shallow	2,191
North Wilmes	19	6.8	20	129	92	0.07	Shallow	2,413
South Wilmes	19	8.4	19	160	86	0.06	Shallow	615

[1]Note that Powers Lake only discharges through a lift station. This estimate assumes the lake does not have an outlet.

2.4 WATERSHED DRAINAGE PATTERNS

2.4.1 Armstrong Lake

Armstrong Lake (Public Water No. 82-0116-00) is 28.7-acre lake within the cities of Lake Elmo and Oakdale, MN. Armstrong acts as the headwaters of a multi-lake system included in this study. Armstrong outlets to multiple small wetlands and eventually to North Wilmes Lake. Armstrong Lake is divided into two sections, North and South (Figure 2-2). The North and South sections are divided by County Road 10 and connected via a 36 in reinforced concrete pipe (RCP) culvert. The southern portion of Armstrong Lake is 18 acres and with a max depth of 5 ft and was considered in the lake response and P8 models. The watershed for Armstrong Lake is 563 acres with 190.8 acres of impervious surface from residential and commercial land use.

2.4.2 Markgrafs Lake

Markgrafs Lake (Public Water No. 82-0089-00) is a 47-acre lake contributing to North Wilmes Lake via multiple small wetlands (Figure 2-3). However, during 100-year flow events, water is diverted to Powers Lake. Markgrafs receives contributions from a 425.1-acre drainage with 277.1 acres of impervious surface, made up of primarily commercial and some residential land use.

2.4.3 North and South Wilmes

North and South Wilmes Lake (Public Water No. 82-0090-00) are connected via a 48 RCP culvert under a recreational trail. North Wilmes is 19 acres with a max depth of 20 ft and a modeled hydraulic residence time of 0.07 years (Figure 2-4 and 2-5). North Wilmes received contributions from Armstrong and Markgrafs, as well as a 2,413-acre drainage area with 1,423 acres of impervious surface. North and South Wilmes are hydraulically connected and receive contributions from a 614.9-acre drainage area with 235.4 acres of impervious surface.

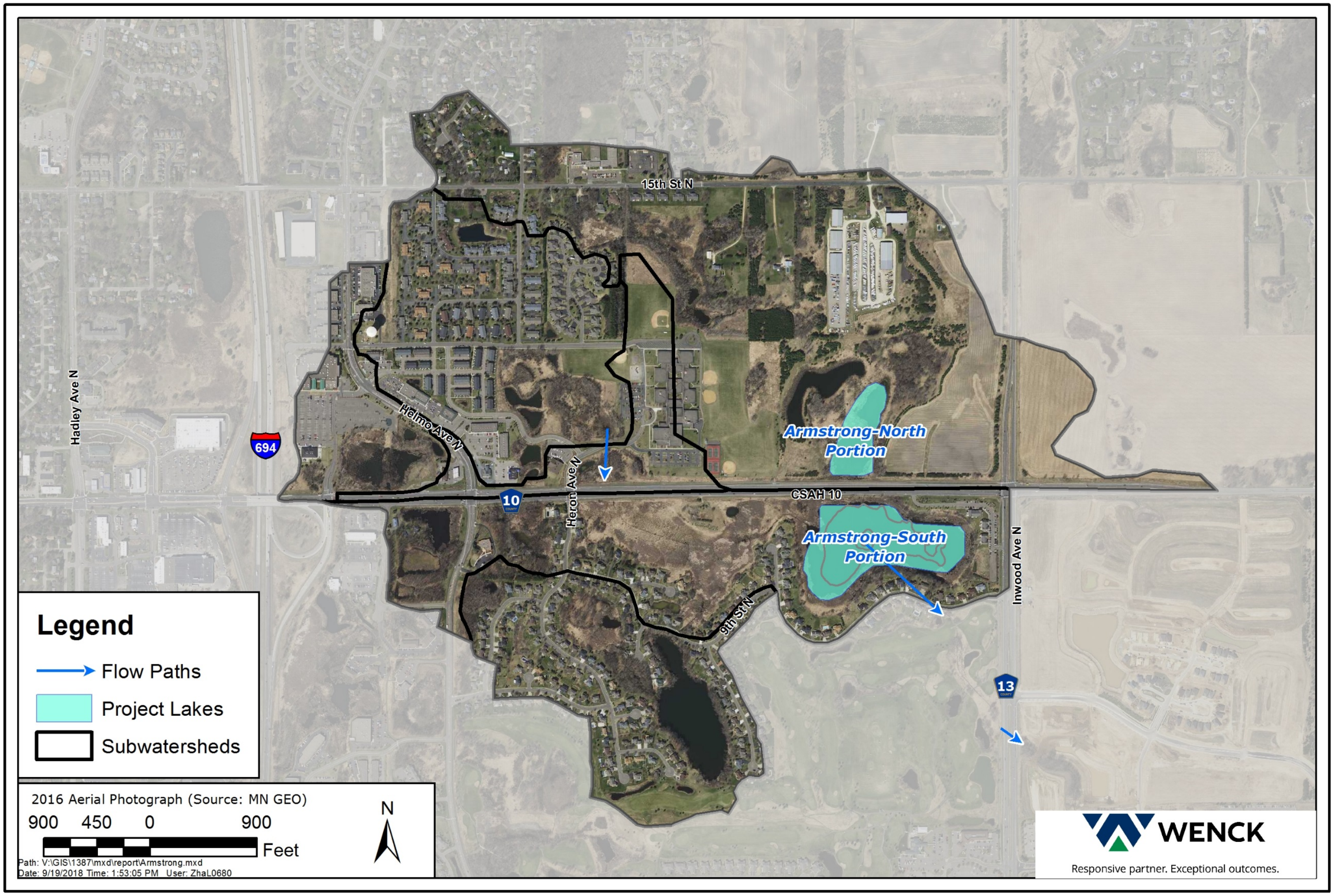


Figure 2-2. Armstrong Lake subwatersheds and general watersheds

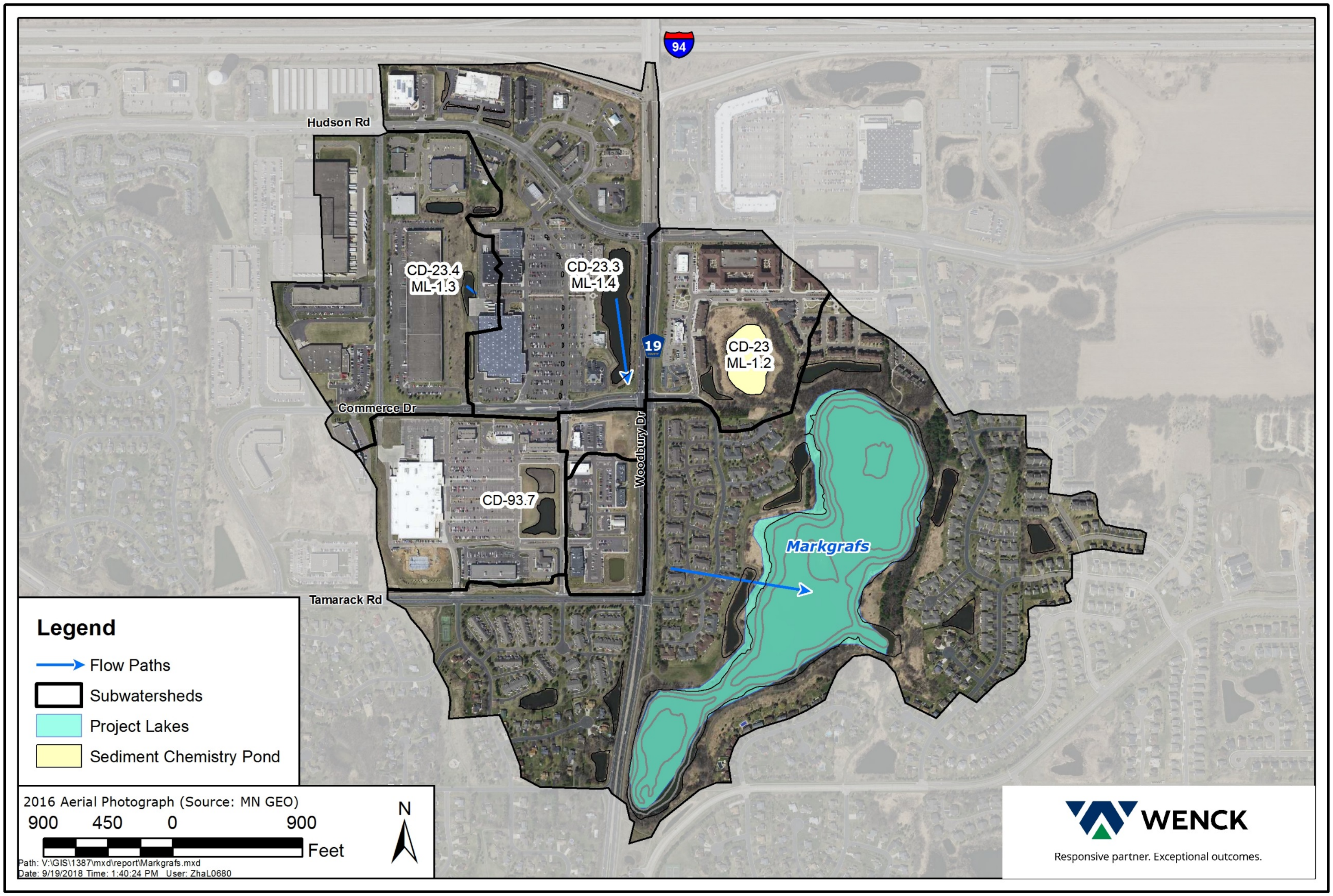


Figure 2-3. Markgrafs Lake subwatersheds and general flow direction.

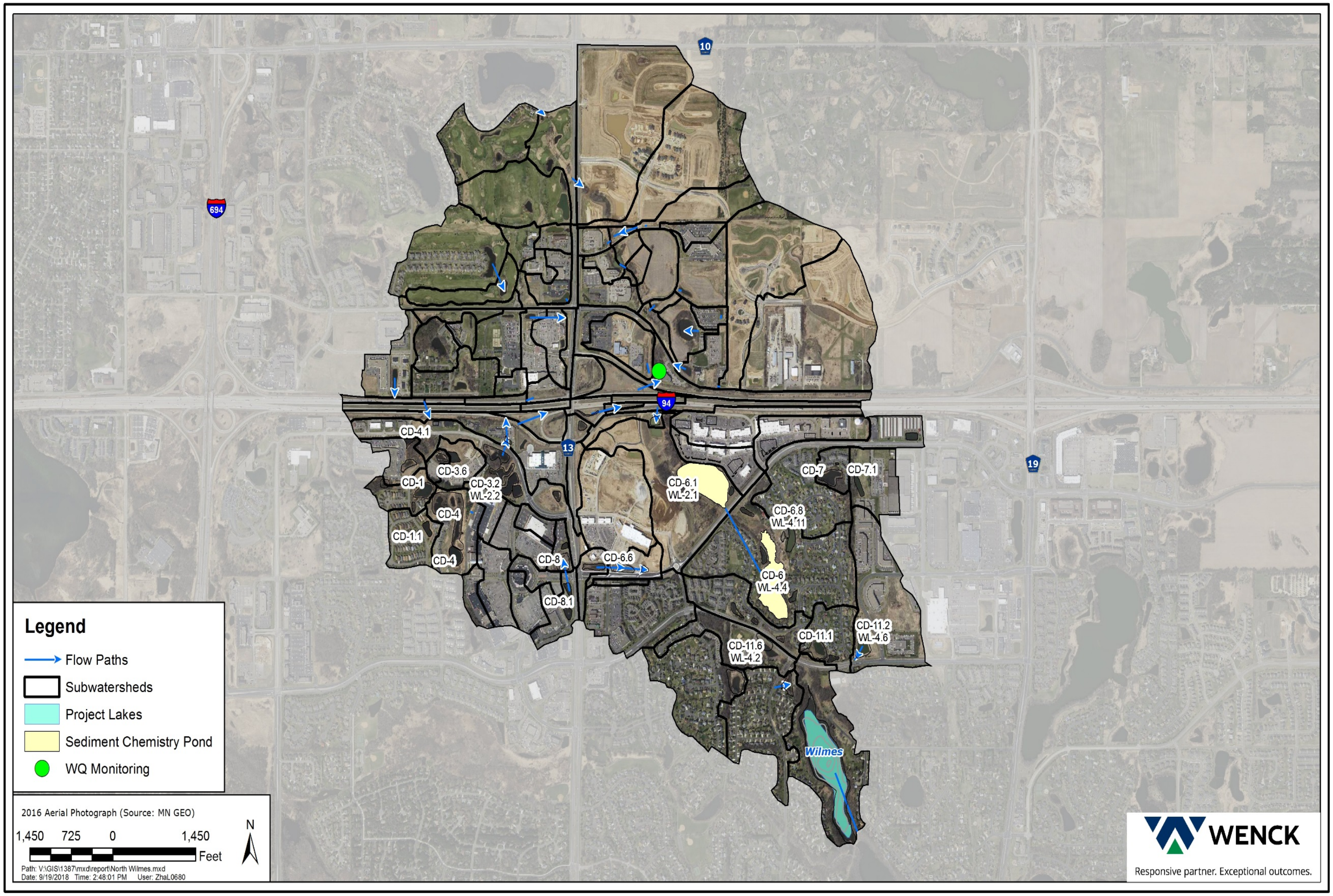


Figure 2-4. North Wilmes Lake subwatersheds and general flow direction.

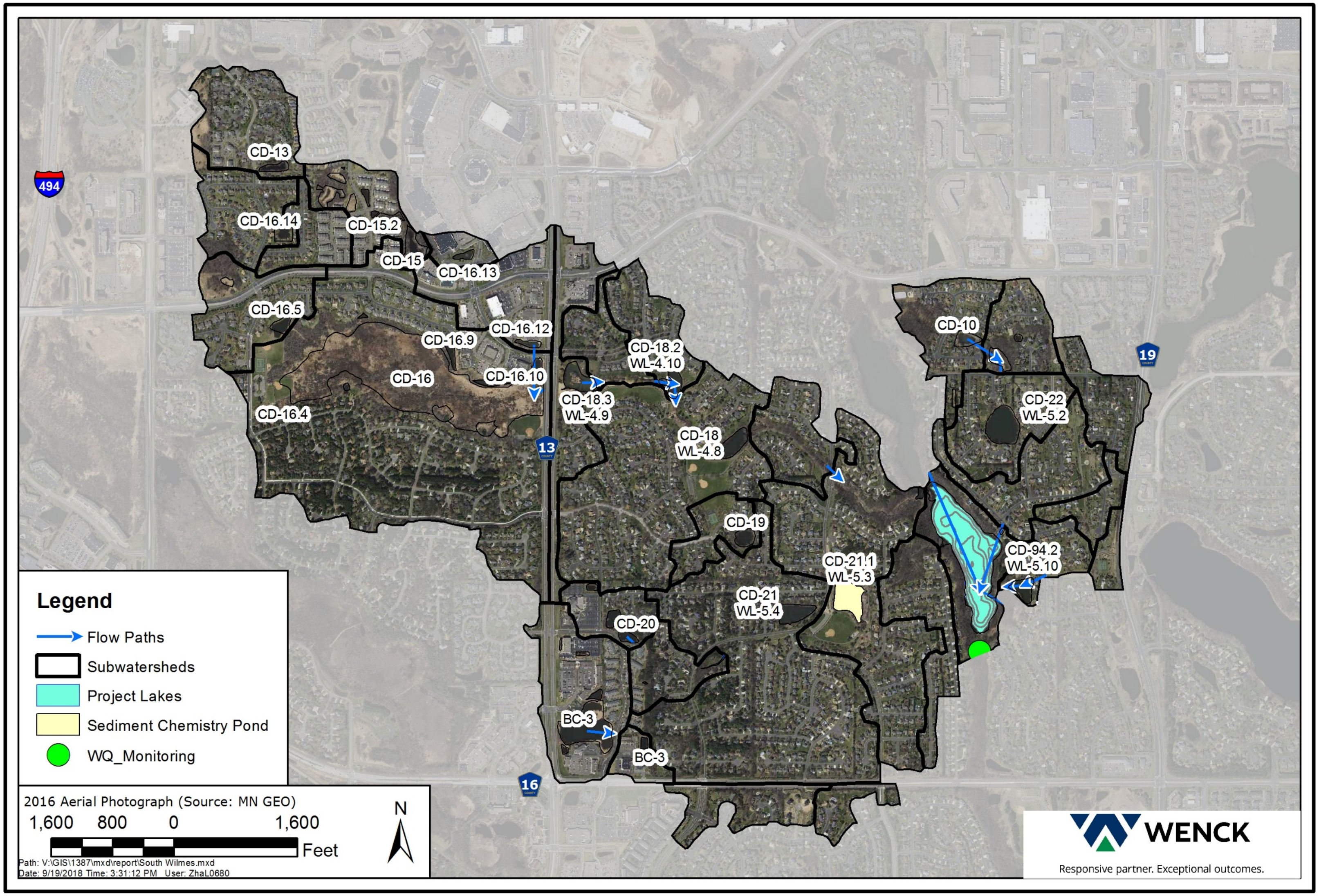


Figure 2-5. South Wilmes Lake subwatersheds and general flow direction.

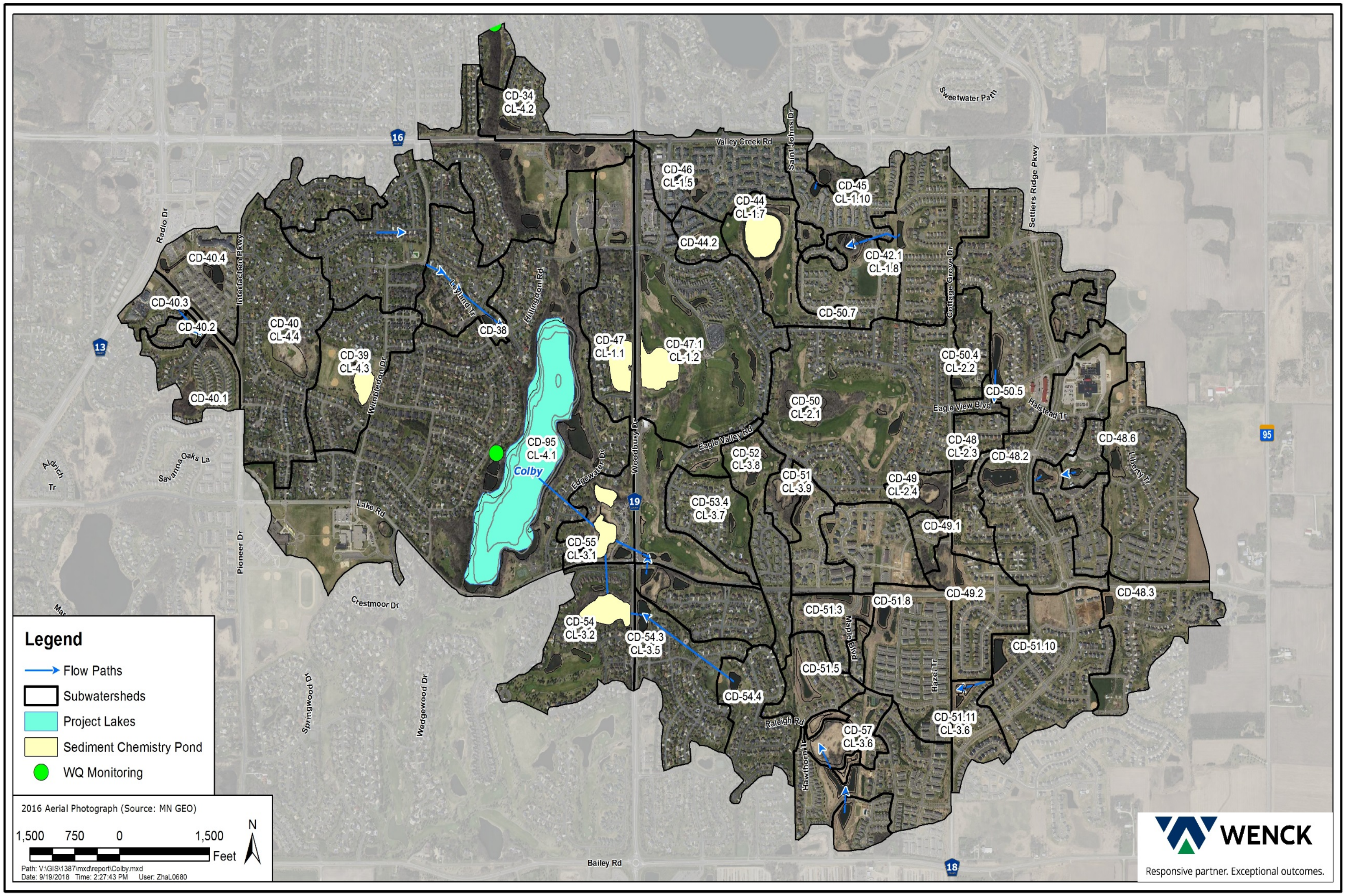


Figure 2-6. Colby Lake subwatersheds and general flow direction.

2.4.4 Colby Lake

Colby Lake (Public Water No. 82-0094-00) is a 69-acre lake with a max depth of 9 ft. Colby receives contributions from South Wilmes and it's 2,924 direct drainage area, of which 1075.3 acres are impervious (Figure 2-6).

2.4.5 Powers Lake

Powers Lake (Public Water No. 82-0092-00) is a 62-acre lake with a max depth of 40 ft and a modelled hydraulic residence time of 0.6 years (Figure 2-7). Powers Lake is the only deep lake in this study. Powers receives contributions from 1,257 acres, 484 acres of which are impervious.

2.4.6 La Lake

La Lake (Public Water No. 82-0097-00) is a 52-acre lake with a max depth of 8 ft and a modelled hydraulic residence time of 20 years (Figure 2-8). La receives contributions from a small watershed 64 acres, 3.5 acres of which are impervious.

2.4.7 Ravine Lake

Ravine Lake (Public Water No. 82-0087-00) is a 27-acre lake with a max depth of 16 ft and a modelled hydraulic residence time of 0.4 years (Figure 2-9). Ravine receives contributions a watershed of 2,191 acres, 664.9 acres of which are impervious.

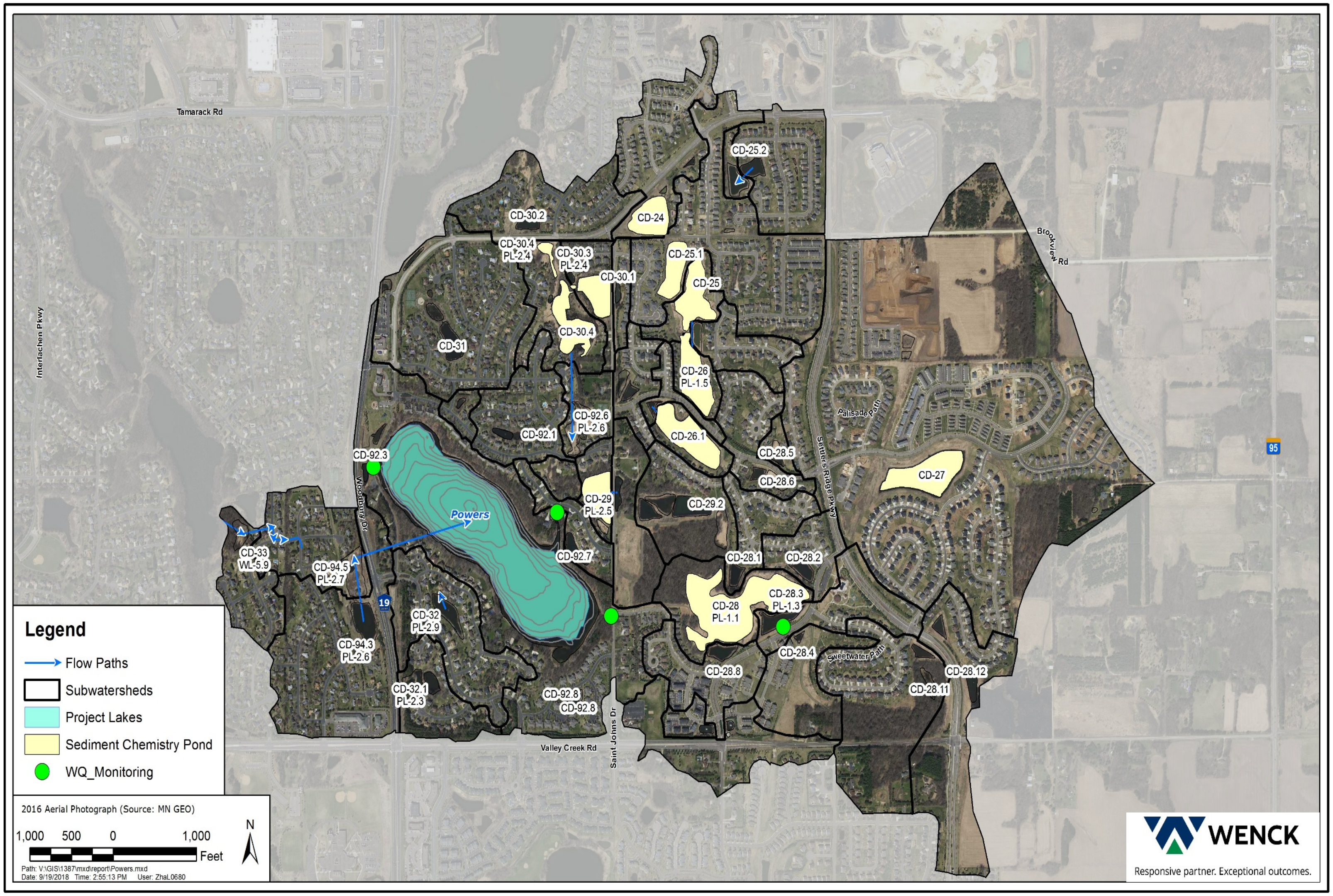


Figure 2-7. Powers Lake subwatersheds and general flow direction.

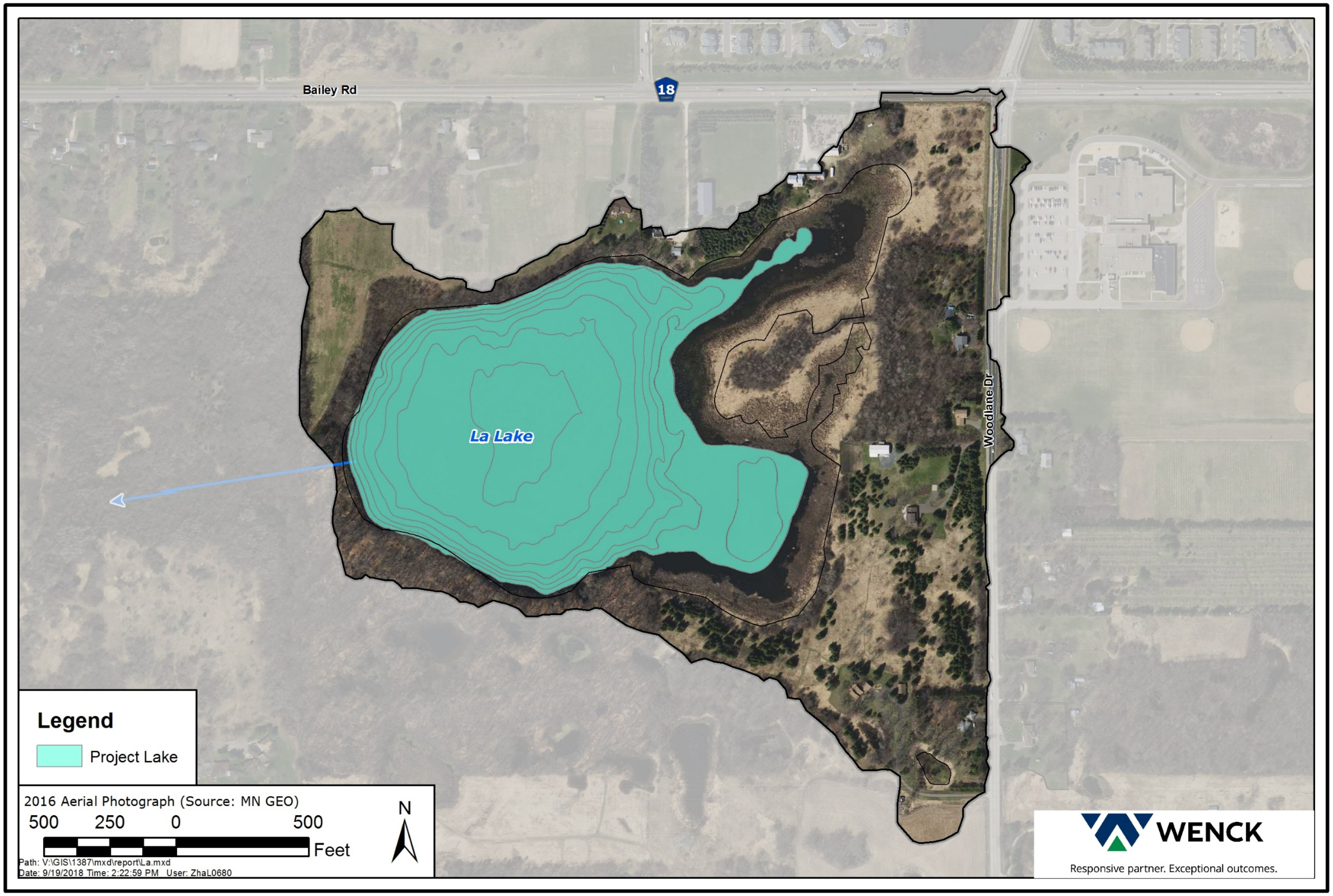


Figure 2-8. La Lake subwatersheds and general flow direction.

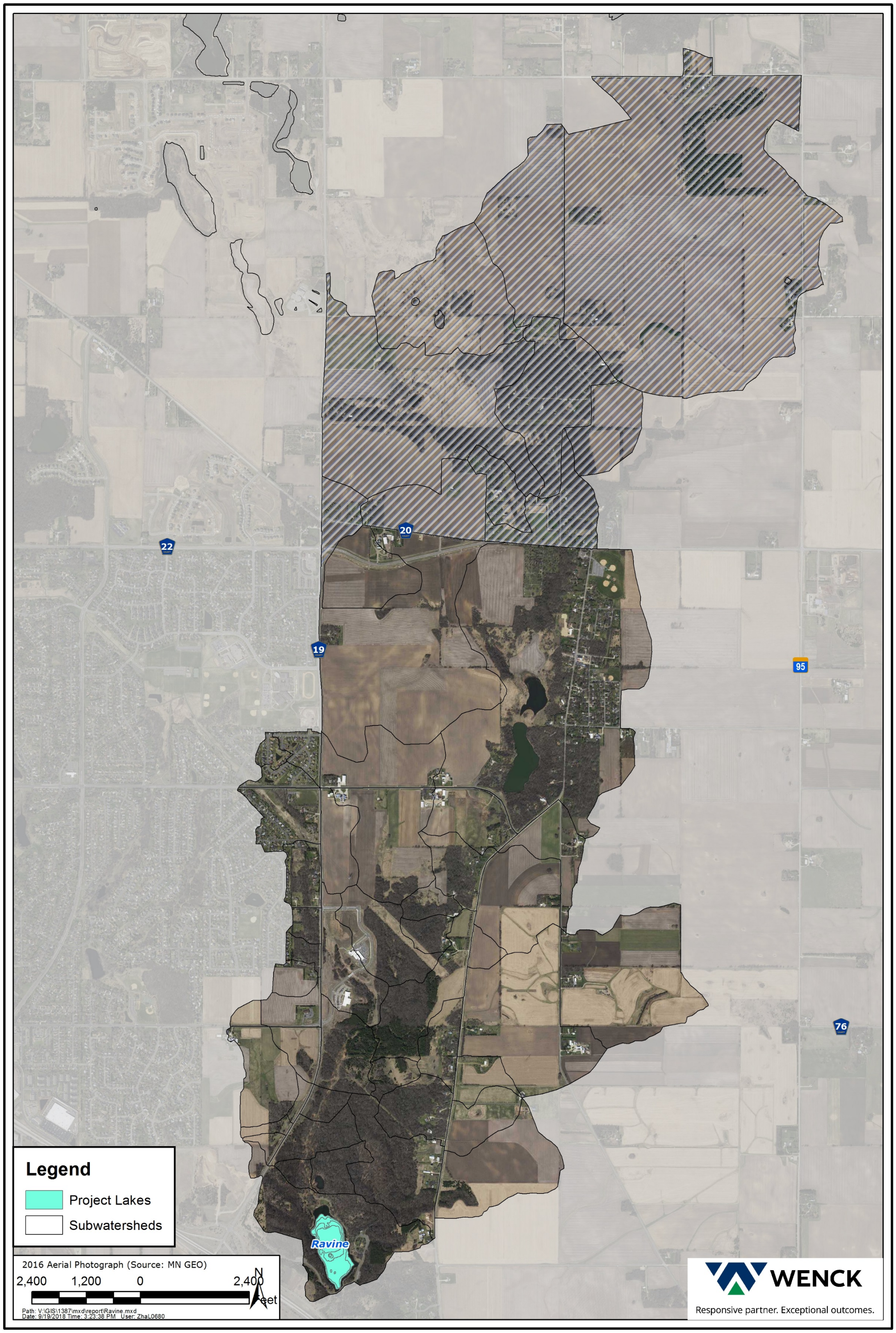


Figure 2-9. Ravine Lake subwatersheds and general flow direction.

2.5 LAND USE

Land use in the watershed is primarily residential and commercial land use typical of outer tier TCMA suburbs. Only Ravine Lake and La Lake have a relatively undeveloped watershed with 53% in agricultural use and 42% open space respectively (Figure 2-10).

Table 2-4. Land use percentage by type of use.

Lake	Total[1]	Right of Way	Residential	Water	Open Area	Retail/ Industrial	Agricultural
Armstrong	563	0.4%	29%	7%	35%	20%	8%
Colby	2,924	0%	65%	4%	25%	6%	0.3%
La	64	0%	10%	45%	42%	1%	2%
Markgrafs	425	2%	30%	11%	13%	44%	0%
Powers	1,257	0%	60%	6%	30%	2%	3%
Ravine	2,191	0.1%	9%	1%	28%	1%	60%
Wilmes	3,028	6%	31%	2%	38%	23%	0%

[1] Watershed area does not include upstream lakes.

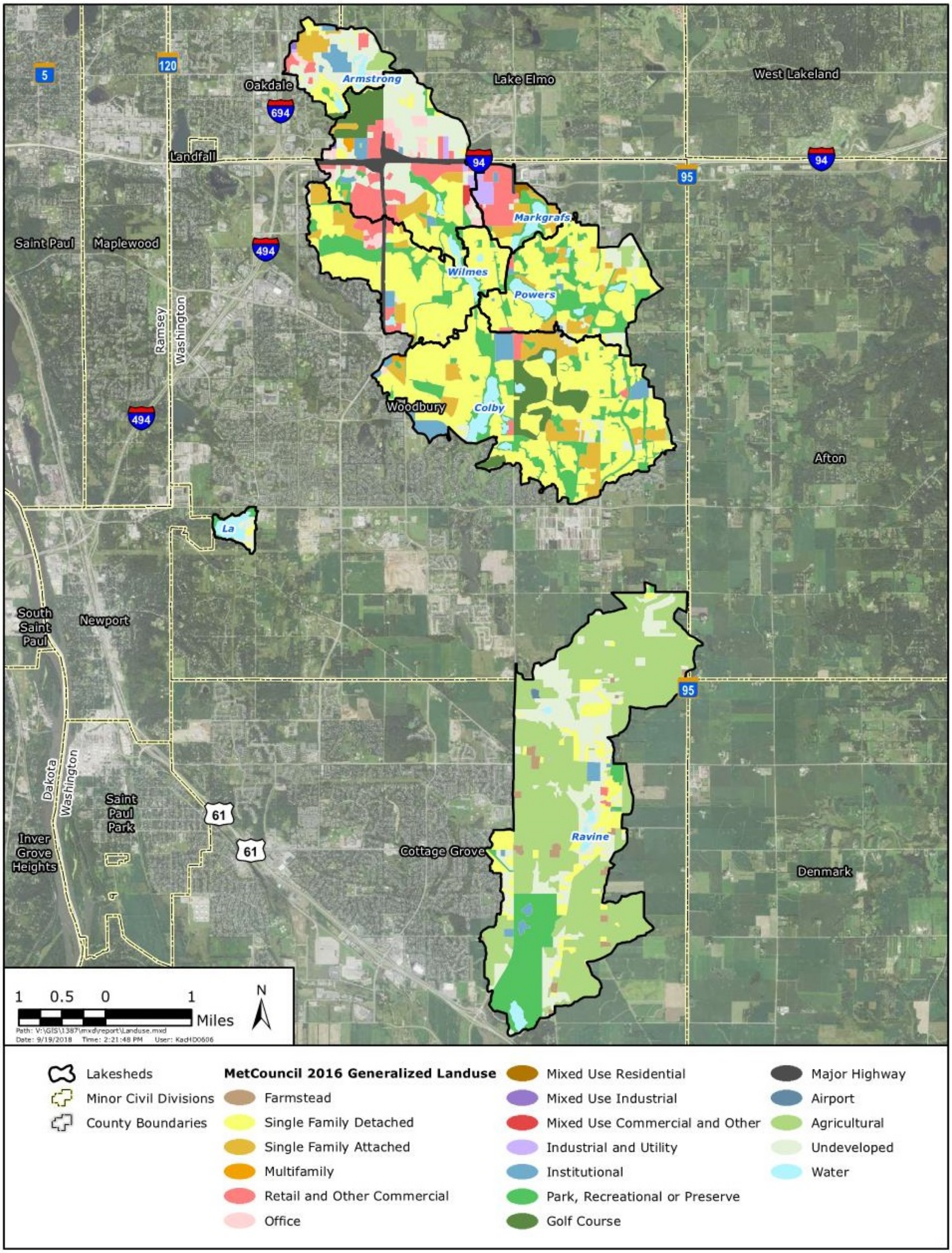


Figure 2-10. Landuse in each lakeshed.

2.6 SOILS AND GEOLOGY

The soil and geology of the watershed is outlined in the SWWD Watershed Management Plan October 2016. Soils in SWWD are all derived from glacial alluvium or till. Soil types that dominate the Mississippi River drainage area of the District are formed predominantly in glacial outwash under deciduous hardwood forest or prairie. These soils are well drained to excessively drained, medium textured to coarse textured soils.

2.7 GROUNDWATER

All residents in the SWWD rely on groundwater as their drinking water source. This is thanks to layers of bedrock, sands and gravels, and silt form the various aquifers lying beneath the District and are responsible for its characteristically high infiltration rates and recharge potential. Groundwater flows radially from the central upland regions of the county to the east, south, and west. Groundwater discharges through sand and gravel deposits to both the Mississippi River to the south and west and to the St. Croix River to the east.

According to the Washington County 2014-2024 Groundwater Plan, La, Markgrafs, and North and South Wilmes are all on perched aquifers. Perched lakes are lakes with bottoms above the regional water table and do not receive inflow from regional groundwater. Powers and Colby have groundwater recharge; however, these lakes are likely flow through lakes. Powers Lake only discharges through a lift station that operates infrequently. Therefore, water loss from the lake is likely through groundwater discharge or evapotranspiration. Groundwater quality can be impacted by the water quality in recharge lakes. Efforts to protect surface water quality will also ultimately protect groundwater quality.

Ravine is characterized as a Flow through lake. Flow through lakes are those for which recharge and discharge occur in different areas. These can be important recharge areas and are also very sensitive to changes in groundwater levels. Ravine has an unquantified contribution of groundwater interaction which has not been included in the lake response model and may be why the calibration factor is so high.

2.8 CLIMATOLOGICAL SUMMARY

The annual precipitation monotonically increased throughout the 5-year period, with the 5-year average coinciding with 2014 (Figure 2-11). The average annual precipitation between 2012 and 2016 was 34.8 inches.

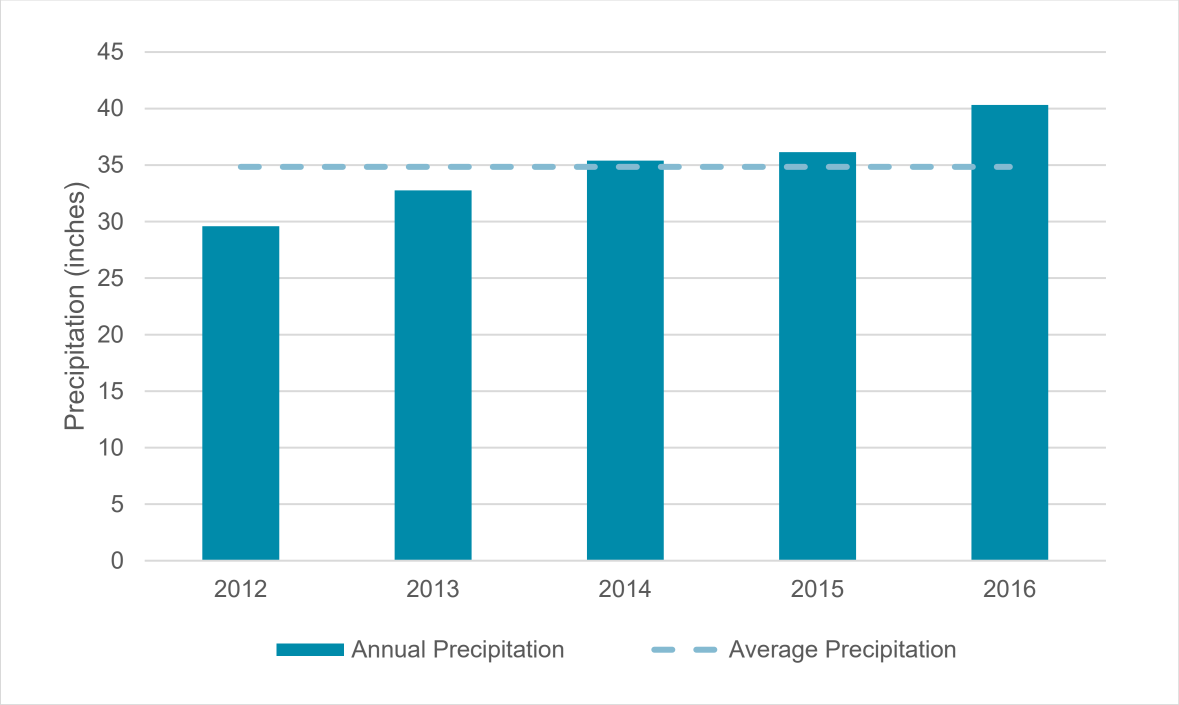


Figure 2-11. Annual and average precipitation recorded at the Minneapolis/St. Paul International Airport.

2.9 WATER QUALITY

Water quality in Minnesota lakes is often evaluated using three associated parameters: total phosphorus, chlorophyll-a, and Secchi depth. Total phosphorus is typically the limiting nutrient in Minnesota's lakes, meaning that algal growth will increase with increases in phosphorus. Chlorophyll-a is the primary pigment in aquatic algae and has been shown to have a direct correlation with algal biomass. Secchi depth is a physical measurement of water clarity. Increasing Secchi depths indicate less turbidity in the water column and increasing water quality. Conversely, rising total phosphorus and chlorophyll-a concentrations point to decreasing water quality and thus decreased water clarity. Measurements of these three parameters are interrelated and can be combined into an index that describes water quality.

2.9.1 Historical Water Quality Data

Lake water quality varies depending on annual precipitation, annual temperature, biotic population dynamics, and other factors. Annual summer averages from 2012 to 2016 demonstrated a broad range of water quality conditions in these lakes ranging from excellent water quality in Powers Lake to highly eutrophic conditions in Markgrafs and Colby Lake (Table 2-5). The annual water quality time series are presented in Appendix A.

Table 2-5. Shallow lake growing season averages for water quality parameters.

			In-Lake "Average" Condition (Calculated June - September)		
Lake Name	**Impairment (2018)**	**"Average" Condition Calculation Years**	**TP Concentration (µg/L)**	**Chl-*a* Concentration (µg/L)**	**Secchi Depth (m)**
Water Quality Standard for Shallow Lakes			**60**	**20**	**1.0**
Armstrong	N	2012-2016	70	10	0.7
Colby	Y	2012-2016	156	50	0.6
La	Y	2012-2016	68	22	1.4
Markgrafs	Y	2012-2016	125	22	0.5
Ravine	Y	2012-2015	76	60	1.7
North Wilmes	Y	2001-2012	75	30	1.2
South Wilmes	Y	2012-2015	73	28	0.8
Water Quality Standard for Deep Lakes			**40**	**14**	**1.4**
Powers	N	2012-2016	28	13	3

All of the shallow lakes in this study have summer average TP concentrations at or above the standard for the 16-year monitoring history (Figure 2-12). Powers Lake, the only deep lake in this study, had periodic peaks in 2006-2007 and 2011 which exceeded the standard. However, the long-term average for Powers Lake is well below state water quality standards and has met the standard since 2012.

As expected with high phosphorus concentrations, most of the shallow lakes are relatively productive with chlorophyll-a concentrations at or near the chlorophyll-a standard (Figure 2-13). Armstrong has quite low chlorophyll-a concentrations (10 µg/L) considering higher P concentrations. Secchi depth was poor in Armstrong suggesting that non-algal turbidity may be limiting algal production (Figure 2-14). Wilmes, Ravine and Colby lake have extremely high chlorophyll-a concentrations and likely have severe algal blooms late in the summer. However, North Wilmes and Ravine Lake still demonstrated excellent water clarity, however this may be due to colony forming algal species that allow light penetration but still are considered severe algal blooms.

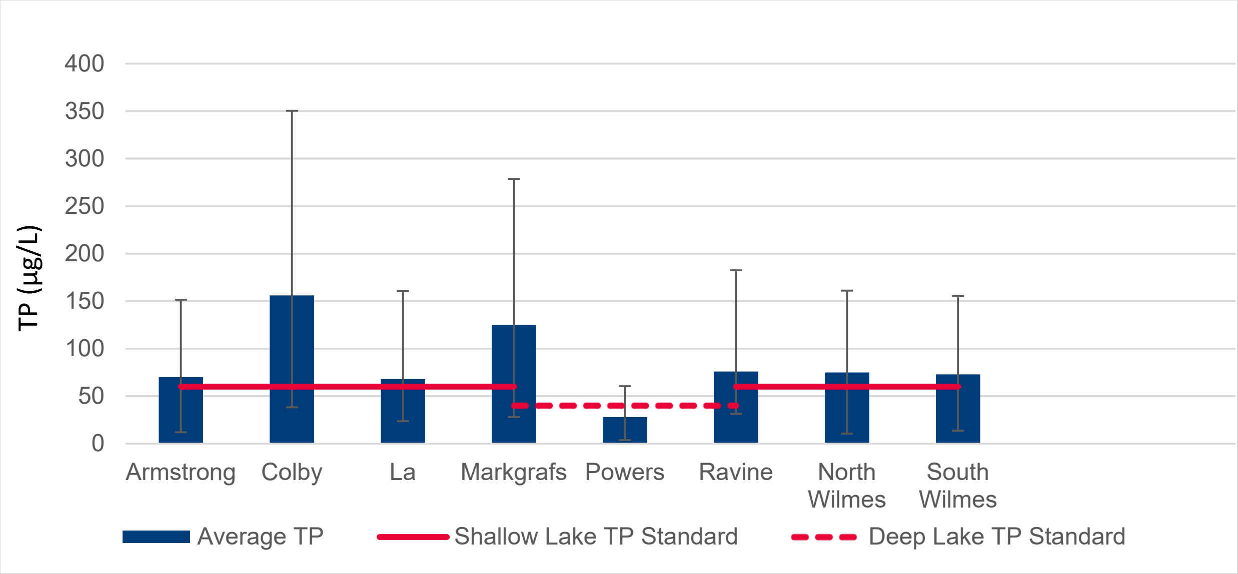


Figure 2-12. Annual summer average TP concentration and deep and shallow lake TP standards. Error bars represent the 95% confidence interval.

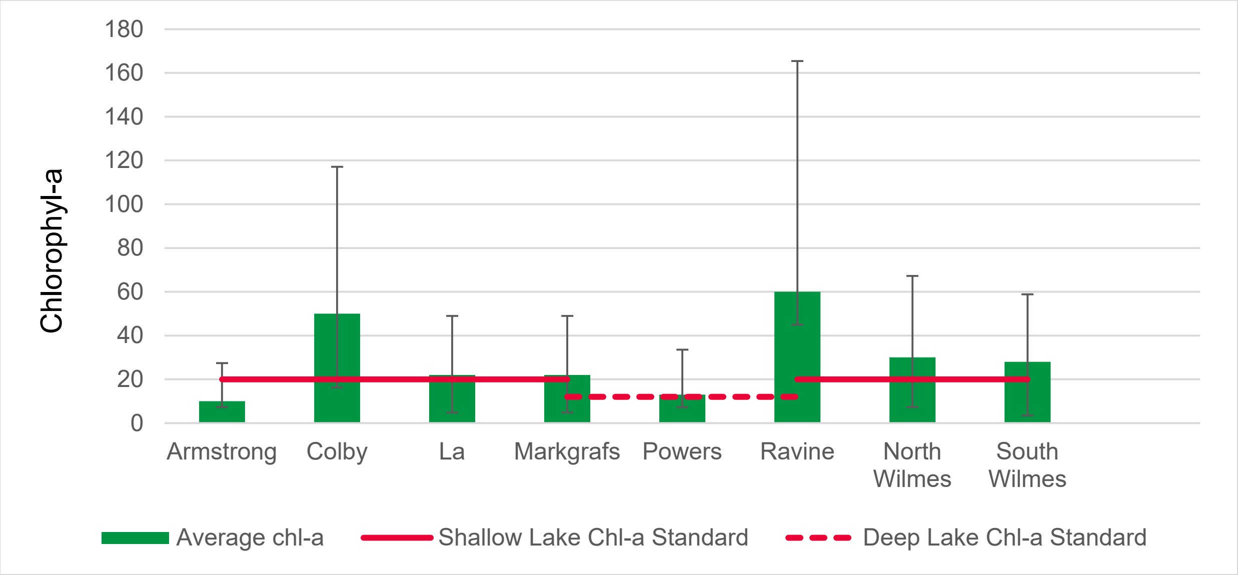


Figure 2-13. Annual summer average chl-a concentration and deep and shallow chl-a lake standards. Error bars represent the 95% confidence interval.

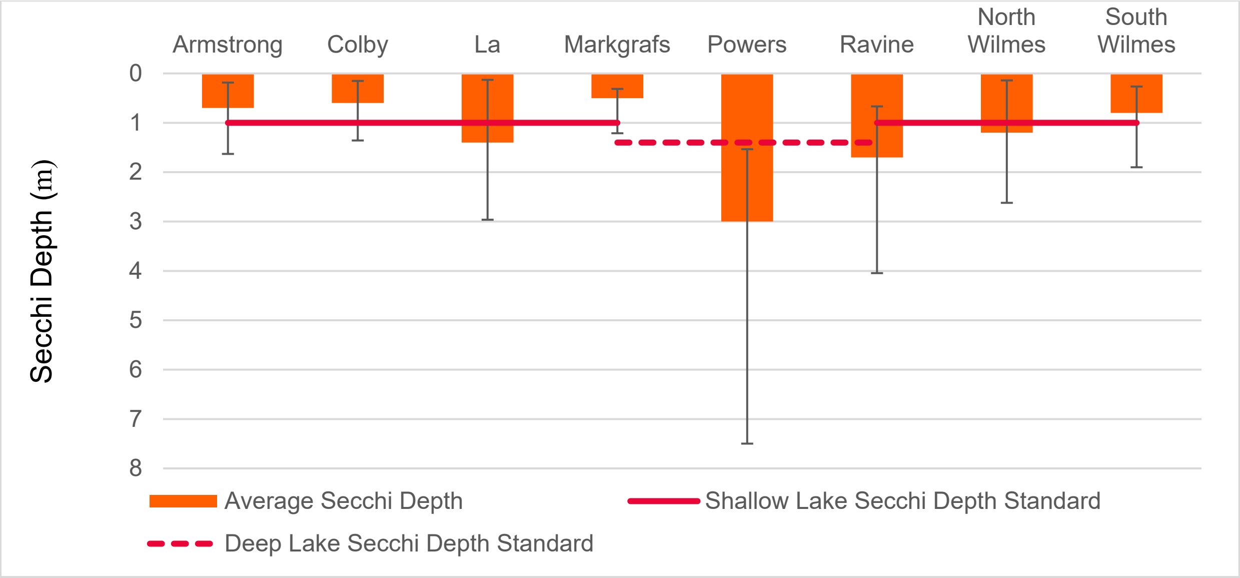


Figure 2-14. Annual summer average Secchi depth and deep and shallow lake Secchi depth standards. Error bars represent the 95% confidence interval.

2.10 FISHERIES AND AQUATIC VEGETATION

Biological conditions (fish, plants, zooplankton, and invertebrates) in shallow lakes play a critical role in maintaining water quality. The balance between top predators and their prey (panfish, minnows) can have a large effect on the size of the cladoceran population, an effective algae grazer. Likewise, the amount and type of vegetation can affect the fish and zooplankton balance, ultimately affecting the cladocerans population. Because all the lakes are highly dependent on biological conditions, fish and vegetation data were compiled for each of the assessment lakes. Freshwater Scientific Services conducted vegetation surveys on each of the lakes in the summer of 2015 (Freshwater Scientific Services 2015). Minnesota DNR files were reviewed for this study. Compiled fish data are provided in Appendix B. Fish and vegetation conditions in the lakes are summarized in Tables 2-6 and 2-7.

2.10.1 Fisheries

Fisheries play a direct role in controlling water clarity by affecting large zooplankton grazer abundance which can have a large influence on water clarity. An overabundance of zooplankton predators such as stunted panfish or fathead minnows can lead to increased algal blooms and a potential collapse of the submerged aquatic vegetation population. Several of the lakes in this study have long histories of fisheries management going back as far as the 1950s for several of these lakes.

Fishing the Neighborhood (FiN)

The lakes with the strongest fisheries management are Fishing in the Neighborhood (FiN) lakes including Colby, Powers and Ravine. FiN is a program run by the Minnesota Department of Natural Resources (DNR) aimed at increasing angling opportunities, public awareness and environmental stewardship within the seven-county Metro Region. As a result, each of these lakes has a DNR management plan and is regularly surveyed by the DNR (Table 2-6). In addition to fishing piers, two of the three FiN lakes, Colby and Powers, have shoreline parks containing amenities such as playgrounds, walking trails, tennis courts, picnic tables and grills. Ravine, the other FiN lake, has limited shore-fishing access other than a fishing station and fishing pier, but the DNR is planning to expand access. The FiN lakes are stocked with species such as bluegill sunfish, black crappie, channel catfish, walleye and largemouth bass (Table 2-6). Other species that are known to reside in these lakes include black bullhead, brown bullhead, green sunfish, pumpkinseed sunfish, hybrid sunfish, yellow perch, golden shiner, white sucker and northern pike (Table 2-6).

The Minnesota DNR routinely monitors fish communities in the District’s FiN lakes. These data were organized by trophic structure to evaluate the current conditions of the fish communities (Appendix A). Surveys in Colby Lake measured high numbers and biomass of black bullhead which likely contribute to the degradation of water quality of Colby Lake. Power’s Lake has maintained a relatively balanced fish community since the 1980s with few bullheads and large top predators. Ravine historically (2001) had a large bullhead population, but the lake has shifted to a more balanced panfish community. Other than Colby Lake, stocking appears to have maintained a healthy fish community in these lakes.

Fisheries Management in Other Lakes

Fisheries in Armstrong, La and Wilmes have never been surveyed by the DNR, although there are plans for La Lake to become a surveyed and managed lake in the future according to DNR East Metro Area Fisheries Supervisor TJ DeBates. DeBates said there are also plans for installation of a fishing pier in La Lake. Markgrafs, although it is not a FiN lake, has also had its fishery surveyed once (in 2008) by the DNR (Table 2-6). Wilmes Lake has been stocked with walleye and bluegill at least once (in 1997; Table 2-6).

Even lakes that have not been formally surveyed by the DNR have documented winter-kill events (Table 2-6). Winter kill events take place when dissolved oxygen in the water becomes too low for fish to survive and is often associated with eutrophic conditions. It is also worth noting that several of the lakes have been used in the past for walleye rearing, including Colby, La, Markgrafs and Ravine. Walleye rearing took place in several of these lakes as early as the 1970s.

Common Carp and Roughfish

None of the lakes have verified carp populations although not all lakes have been surveyed. Carp infestation in shallow lakes can degrade water quality and eliminate submerged aquatic vegetation which are critical for maintaining the clear lake state in shallow lakes.

Fathead Minnows

Fathead minnows are particularly effective at grazing large zooplankton grazers, which can lead to increased algal populations and nuisance algal blooms. None of the lakes have been monitored for fathead minnow populations.

Table 2-6. Summary of fisheries information in the seven lakes.

Lake	FiN	Fishing Access	Fish Surveys	Stocking	Fish species	Winter-kills	Carp
Armstrong	No	No	none	none	n/a	?	--
Colby[1]	Yes	Yes	2002, 2007, 2015	• bluegill sunfish • black crappie • channel catfish	• black bullhead • black crappie • bluegill sunfish • green sunfish • pumpkinseed sunfish • hybrid sunfish • channel catfish • yellow perch	Yes	No
La	No	No	none	none	n/a	No	--
Markgrafs	No	No	2008	none	• bluegill sunfish • black bullhead • yellow perch • golden shiner • white sucker	Yes	--
Powers	Yes	Yes	1977, 1982, 1984, 1992, 1997, 2007, 2012	None—management plans say potential plan is to stock walleye and largemouth bass	• walleye • northern pike • largemouth bass • bluegill sunfish • black crappie • pumpkinseed sunfish • hybrid sunfish • yellow perch • white sucker	Yes	No
Ravine	Yes	Yes	2001, 2006, 2011, 2016	• walleye • largemouth bass • black crappie	• walleye • bluegill sunfish • pumpkinseed sunfish • green sunfish • black crappie • yellow perch • largemouth bass • white bass • brown bullhead	Partial/ isolated winter-kills documented	No
Wilmes	No	No	none	Walleye and bluegill (1997)	n/a	Yes	--

[1] aeration occurred in 2014

2.10.2 Aquatic Vegetation

Aquatic plants are beneficial to lake ecosystems, providing spawning and cover for fish, habitat for macroinvertebrates, refuge for prey, and stabilization of sediments. However, in high abundance and density, they limit recreation activities, such as boating and swimming, and may reduce aesthetic values. Excess nutrients in lakes can lead to non-native, invasive aquatic plants taking over a lake. Some exotics can lead to special problems in lakes. For example, under the right conditions, Eurasian watermilfoil can reduce plant biodiversity in a lake when it grows in great densities and out-competes all the other plants. Ultimately, this can lead to a shift in the fish community because these high densities favor panfish over large game fish. Species such as Curly-leaf pondweed can cause very specific problems by changing the dynamics of internal phosphorus loading. Ultimately, there is a delicate balance within the aquatic plant community in any lake ecosystem.

Aquatic vegetation communities in these lakes are relatively healthy. Vegetative cover is relatively high, especially in littoral areas where several lakes have 100 percent or close to 100 percent of littoral areas vegetated (Table 2-7). Maximum depths of vegetative growth are also relatively deep, especially in Wilmes and Ravine, which has vegetation down to 11 and 15 feet, respectively (Table 2-7).

Curly-leaf Pondweed and Eurasian Watermilfoil

Curly-leaf pondweed and Eurasian watermilfoil are invasive and can easily take over a lake's aquatic macrophyte community. Curly-leaf pondweed presents a unique problem because it is believed to affect significantly the in-lake availability of phosphorus, contributing to the eutrophication problem. Curly-leaf pondweed begins growing in late fall, continues growing under the ice, and dies back relatively early in summer, releasing nutrients into the water column as it decomposes, possibly contributing to algal blooms. Curly-leaf pondweed can also out-compete desirable native plant species.

All lakes except Wilmes have vegetation communities with at least one non-native taxon (Table 2-7) with Eurasian watermilfoil and Curly-leaf pondweed being the most common non-native/invasive taxa. Both Powers and Colby Lakes have infestations of Eurasian watermilfoil. Around 2013, the City of Woodbury tried harvesting Eurasian milfoil from the west end of Powers Lake to provide better access for the canoe landing. Powers and Colby Lakes both also contain Curly-leaf pondweed, as do Markgrafs and Ravine (Table 2-7).

Table 2-7. Summary of aquatic vegetation information in the seven lakes.

Lake	% Lake Vegetated	% Littoral Area Vegetated	Max. depth of growth (ft.)	Floristic Quality Index	# Native taxa	# Non-native taxa	Curly-leaf pondweed?	Eurasian watermilfoil?
Armstrong	100%	100%	4.3	20.8	19	1	No	No
Colby	88%	100%	7.9	17.0	14	2	Yes	Yes
La	81%	81%	8.4	19.8	15	1	No	No
Markgrafs	62%	62%	6.8	15.0	13	1	Yes	No
Powers	46%	100%	20	13.9	9	3	Yes	Yes
Ravine	88%	96%	15.7	17.1	13	1	Yes	No
Wilmes	58%	69%	10.8	17.5	11	0	No	No

Aquatic Vegetation Floristic Quality Index

The Minnesota DNR (MnDNR) recently developed an Aquatic Vegetation Index of Biotic Integrity for lakes in Minnesota which allows health assessment of a lake's vegetation community. The MnDNR Lake Plant IBI is composed of two metrics. The first metric is taxa richness, or the estimated number of taxa (species) in a community. This metric is a useful tool to describe and compare aquatic macrophyte communities and it also reflects and detects changes in water quality conditions. The second metric is the Floristic Quality Index (FQI). This metric distinguishes those plant communities that may have similar species richness but differ in species composition. The MnDNR used lake plant survey data from 3,254 lakes corresponding with the natural distribution of lakes in Minnesota (Radomski and Perleberg 2012). Deep and shallow lakes were included in the development of the lake vegetation IBI using surveys collected between 1993 and 2010.

The FQI is an aquatic vegetation health index that incorporates aspects of species richness and the habitat specificity of each species identified. Species richness is simply the number of species found within a given location. The conservatism score (C-score) is a species-specific score assigned that relates a given species level of habitat specificity. It is a value that reflects the likelihood of finding a species in natural habitats, therefore the more habitat specific /rarer a species is the greater its C-score. Since the FQI incorporates both richness and a qualitative component to the species identified it provides greater level of detail than historic species richness only metrics. By assigning a C-score to a species allows differentiation in high quality versus low quality habitats that contain similar numbers of species. The FQI is computed by multiplying the mean C-score by the square root of species richness (Equation 1).

Equation 1. $FQI = \overline{C_{Score}} * \sqrt{No.of\ Species}$

The MnDNR used the Floristic Quality Index to develop impairment thresholds to relate the health of the vegetation community to eutrophication stress (Radomski and Perleberg 2012) using point intercept surveys. Statistical modeling found distinct breaks in FQI scores and species richness counts suggesting the need to establish thresholds for ecoregions and lake type (shallow vs. deep). The MnDNR defined exceptional lakes and those lakes exceeding the 95th percentile using a statewide database that was stratified by ecoregion and lake type (Table 2-8). The 10th percentile was selected to represent the degraded breakpoint. The threshold between poor and good represents the DNR's recommended impairment threshold for the assessment of the lake plant community (Paul Radomski pers. comm.).

Table 2-8. The lake plant IBI thresholds found within the NCHF (2B) Ecoregion.

Classification	FQI		Narrative Description
	Deep	Shallow	
Exceptional	>32.4	>26.0	High species diversity often comprised of native intolerant species. Near reference communities.
Good	18.7 - 32.4	17.9 - 26.0	The community is beginning to show signs of anthropogenic disturbance. Moderate species diversity and a mixed assemblage of tolerant and intolerant species.
Poor	13.0 - 18.6	7.6 - 17.8	The community shows obvious signs of anthropogenic disturbance. Low species diversity with a community often comprised of non-native and/or intolerant species
Degraded	≤13	≤7.5	Very low species diversity with a community comprised of non-native and/or intolerant species. Most disturbed communities.

Note: Deep lakes ≥15 feet maximum depth; shallow lakes < 15 feet maximum depth.

Floristic quality index (FQI) values for the SWWD lakes range from 13.9 to 20.8 (Figure 2-15). For shallow lakes, which all of these lakes are except Powers, FQI is considered good if above 17.9, while for deep lakes, FQI is considered good if above 18.7. Therefore, Powers has a fairly poor FQI, but otherwise these lakes have FQI values near or above the "good" threshold. Powers has a poor FQI in large part because its vegetation community is dominated by Eurasian watermilfoil.

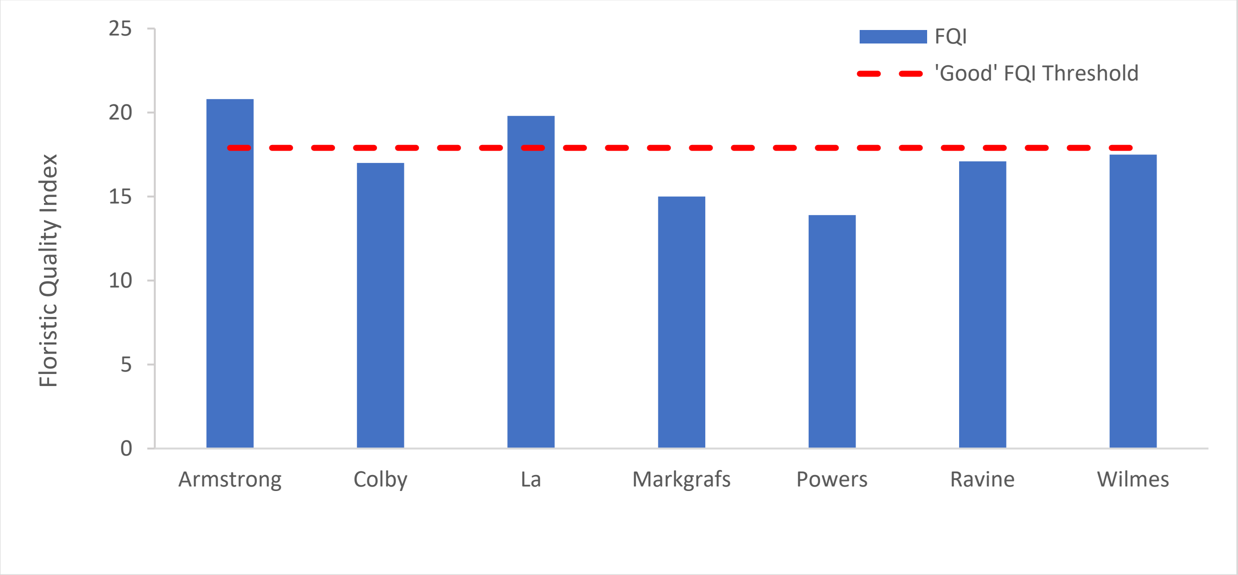


Figure 2-15. Floristic Quality Index (FQI) of the seven lakes as compared to threshold at which FQI is good (17.9).

3.0 Phosphorus Source Assessment

3.1 NUTRIENT SOURCES

A key component to developing a lake management plan is to understand the nutrient sources contributing to the impairment, specifically phosphorus. This section provides a brief description of the potential sources of phosphorus contributing to the lakes. The latter sections of this report discuss the major pollutant sources that have been quantified using collected monitoring data and water quality modeling. The information presented here and in the upcoming sections together will provide information necessary to target pollutant load reductions.

3.2 WATERSHED NUTRIENT LOADING

3.2.1 Model Approach

Water and phosphorus budgets were developed for most of these lakes in previous lake management studies to identify nutrient reductions for the lakes. These studies used XPSWMM and P8 to develop hydrology and nutrient loading and the Canfield-Bachmann model to determine lake response. This study updated those models to include new developments and new BMPs to reduce nutrient loading. Updates included:

1. New land use and impervious areas since the last models were completed
2. Calibration to a longer time period (8 years; 2010 through 2017) and more recently collected water quality and quantity data
3. Change in the lake response model from seasonal loads to annual loads and
4. Updated lake response models that include measured internal phosphorus release from the lakes

These changes and their impacts to the nutrient budgets are more detailed in the flowing Sections of this report.

3.2.2 XPSWMM Model Updates

The first step in developing watershed phosphorus loading to lakes is to quantify watershed hydrology. Water quality models developed for *The Water Quality Modeling Report: Armstrong Lake, Markgrafs Lake, and Wilmes Lake Report* in 2012 were based on previously developed XPSWMM models. These models were updated with new development and impervious areas (Table 3-1).

Table 3-1. Comparison of Total Area and Impervious Area for the updated and existing XPSWMM model.

	XPSWMM 2017		XPSWMM 2012	
Lakeshed	**Total Area (ac)**	**Impervious Area (ac)**	**Total Area (ac)**	**Impervious Area (ac)**
Armstrong	563	191	566	196
Colby	2,924	1,078	2,870	1,005
La	64	4	NA	NA
Markgrafs	425	277	410	220
Powers	1,257	484	1,260	431
Ravine	2,191	665	2,191	658
North Wilmes	2,413	1,043	2,419	840
South Wilmes	615	235	605	222

3.2.3 P8 Model Updates

P8 water quality models developed for *The Water Quality Modeling Report: Armstrong Lake, Markgrafs Lake, and Wilmes Lake Report* in 2012 served as the basis for the P8 models used in this study. The 2012 models were modified to match the 2017 XPSWMM model with following parameters:

- Naming convention
- Watershed areas
- Watershed percent impervious
- Device storage (bottom elevation, bottom area, permanent pool area, and flood pool area)
- Device outlet (type, size, and discharge coefficient)
- Routing

Additional watersheds and storage nodes were added as needed to each P8 model where previous watersheds were split into smaller subwatersheds or new areas drained to the existing watersheds.

3.2.4 Model Calibration

Four of the updated P8 models were calibrated to the District's monitoring stations (Tables 3-2 and 3-3). The Armstrong P8 model was calibrated to the MS-1 monitoring station, the Markgrafs and Wilmes P8 models were calibrated to the Wilmes outlet monitoring station, and the Powers P8 model was calibrated to the Powers East monitoring station. Wenck adjusted the ratio of indirectly connected impervious to directly connected impervious to match flow volumes at the monitoring locations. TP scale factors were then adjusted in P8 to match the loads given for each monitoring data (see Appendix C). Wenck calibrated flow and load values by using an average of all available data 2010 and later. The TP load for the Markgrafs and Wilmes Lake were not calibrated because the Wilmes Outlet is receiving contributions from unmodeled upstream lakes and watersheds, thus the TP concentrations would be inaccurate for calibration of our model. It should be noted that Wilmes was calibrate for flow.

Table 3-2. Water quantity calibration parameters.

Monitoring Station	Monitored Data	Existing Model			Updated Model		
	Volume (ac-ft)	Flow (ac-ft)	Volume Difference (ac-ft)	Volume Difference %	Flow (ac-ft)	Volume Difference (ac-ft)	Volume Difference %
MS-1	418	269	-149	-36%	384	-34	-8%
Powers East	336	146	-190	-56%	340	5	1%
Wilmes Outlet	1,773	1,481	-292	-16%	1,747	-26	-1%
	TP Load (lbs)	**TP Load (lbs)**	**TP Load Difference (lbs)**	**TP Load Difference %**	**TP Load (lbs)**	**TP Load Difference (lbs)**	**TP Load Difference %**
MS-1	293	87	-206	-70%	306	13	4%
Powers East	91	103	12	14%	90	-0.8	-1%

Table 3-3. Water quality calibration parameters.

Monitoring Station	Monitored Data	Existing Model			Updated Model		
	TP Load (lbs)	TP Load (lbs)	TP Load Difference (lbs)	TP Load Difference %	TP Load (lbs)	TP Load Difference (lbs)	TP Load Difference %
MS-1	293	87	-206	-70%	306	13	4%
Powers East	91	103	12	14%	90	-0.8	-1%

The Colby P8 model was calibrated to monitoring data. Initial runs of the updated model indicated that influent TP load was low when compared to the in-lake monitoring data. The TP scale factor was increased from the initial 0.9 to 1.5 to match the monitoring data.

The final model, Ravine, kept the same assumptions as the existing conditions model since monitoring data was only available for one year (2017) at the time of this study in this watershed. Additionally, there was not an updated XPSWMM model provided for the Ravine P8. The only modification made to this model was to add additional impervious area added by the recent construction around the City Hall building.

A new P8 model was created for La Lake. This was a relatively small model that consists of only one watershed and one storage device. This model was not calibrated, as there are no monitoring stations in this watershed.

3.2.5 Pond Sediment Chemistry and Water Quality

Phosphorus Pools and Fluxes in Stormwater Ponds

Pond sediments, under certain environmental conditions, can release phosphorus to overlying waters and become a source of phosphorus in watersheds. Typically, this occurs when pond sediments become anoxic (DO <2.0 mg/L) and there is a large concentration of releasable phosphorus or redox-P. Three fractions of sediment phosphorus make up redox-P including iron bound P, loosely bound P, and labile organic P. Pond sediment chemistry can provide a clue for the potential for pond sediments to be a source of watershed phosphorus loading. Ponds that have a large pool of redox-P (releasable P) have a greater potential to contribute P to stormwater and increases eutrophication in downstream waters. In Minnesota Lakes, redox-P concentrations greater than 0.2 mg/L typically demonstrate P release. However, recent evidence in stormwater ponds suggests that the labile P pool may have stronger influence on P release than in lakes. For the purposes of this report, any redox-P value greater than 0.5 µg/g is considered to have a high risk of contributing P to stormwater. Further, ponds with labile P fractions greater than 0.3 µg/g were also considered to be a high-risk pond.

While high redox and labile P pools in sediments may represent a high risk of contributing P to stormwater, prolonged anoxia is also necessary to drive sediment phosphorus release. However, measuring anoxia in ponds is time and labor intensive and short periods of anoxia can be missed unless expensive continuous monitoring equipment is deployed. The City of Woodbury monitored DO in late July and late August in 26 ponds in 2017 (City of Woodbury, 2018). Unfortunately, only a few of these monitored ponds were the same as ponds measured for sediment chemistry in this study. Sixteen of the 26 ponds demonstrated anoxia above the sediments with some anoxia as shallow as a half of meter. Further, four ponds had surface and bottom TP measurements with two showing elevated TP near the pond sediments. Pond 92.1 had concentrations of 362 µg/L near the sediments as compared to 115 µg/L at the surface. A pond (CD-92) in the southeast drainage of Wilmes Lake showed concentrations of 340 µg/L near the sediments as compared to 61 µg/L at the surface. The other two ponds had minimal differences between surface as bottom TP concentrations. However, these conditions suggest that internal loading from pond sediments is likely occurring in these watersheds and may be contributing P to downstream waters. Further investigation is needed to determine the frequency and magnitude of P loading from pond sediments.

Because this is an emerging issue and the scientific understanding of these processes is relatively young, sediment P pools was used to assess the risk of major ponds in the watershed to contribute P to stormwater. Ponds that have high redox P (>0.3 µg/g) or labile P (>0.3 µg/g) concentrations were considered at risk for contributing to downstream eutrophication. These ponds warrant further analysis and monitoring to quantify P flux.

Powers Lake Watershed

Sediment chemistry was measured in 9 ponds in the Powers Lake watershed to determine the potential pools of releasable phosphorus from pond sediments (Figure 3-1). Mobile-P (redox P plus labile P) concentrations ranged from 0.4 to 0.7 mg/g, moderate concentrations when compared to lake sediments (Bischoff and James, unpublished data). Sediment thickness, the layer of new sediment over the original bottom as measured by visual observation, ranged between 2 and 5 centimeters. Overall, the ponds did not demonstrate large pools of phosphorus in surficial sediments and the sediment thickness was relatively thin. However, our experience in lake sediments suggest that these concentrations can contribute P to overlying water during anoxic conditions.

Twelve ponds were monitored in the Powers Lake watershed with summer average surface TP concentrations ranging from 43 to 161 µg/L. Eight of the twelve demonstrated anoxia in July and August with one pond showing elevated TP in bottom water. However, surface concentrations were relatively low compared to other stormwater pond surveys in the Twin

Cities Metropolitan Region where TP concentrations often exceeded 1 mg/L (Riley Purgatory Bluff Creek Watershed District, 2014).

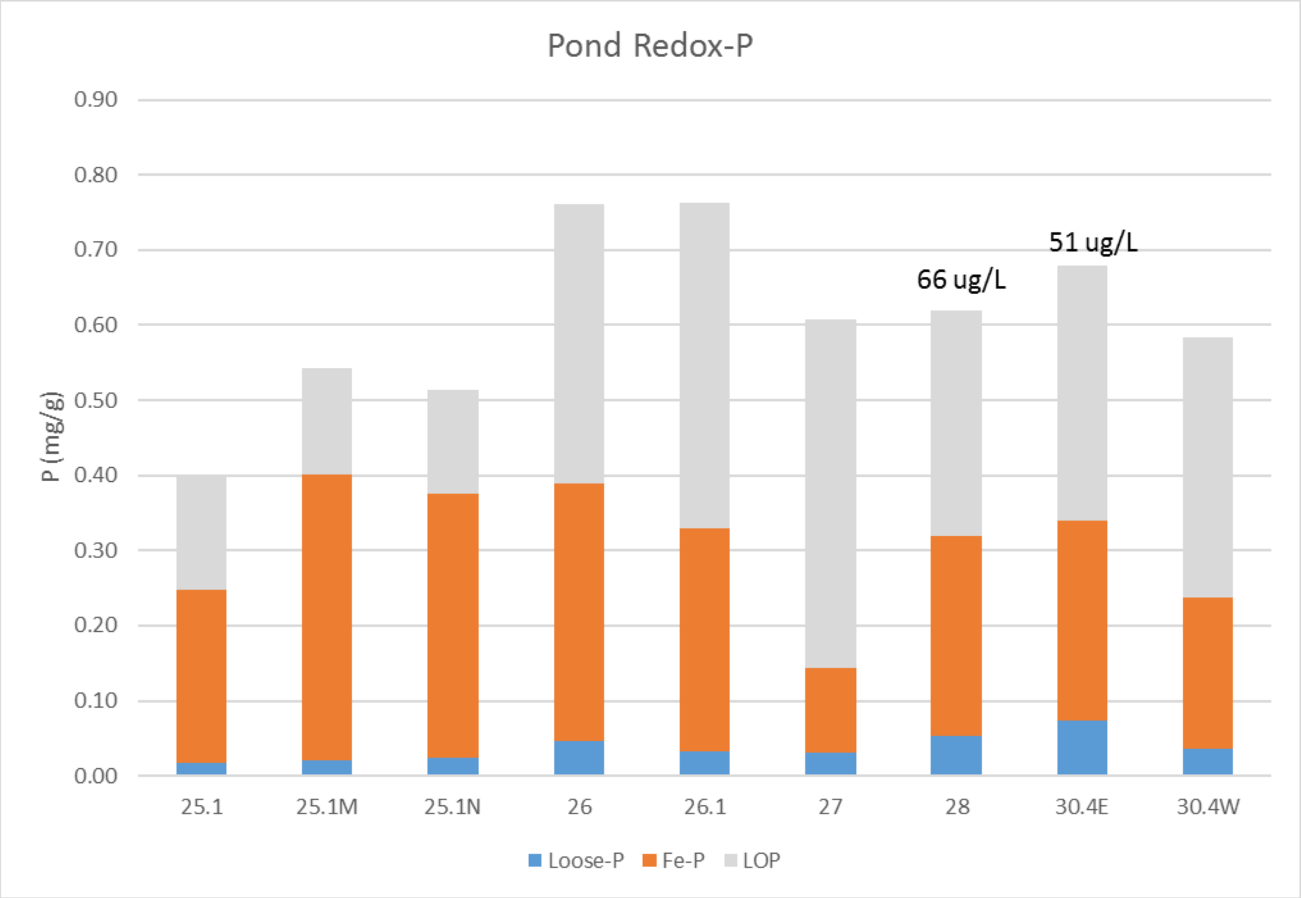


Figure 3-1. Surficial sediment phosphorus fractions in select stormwater ponds in the Powers Lake watershed.
Loose-P is loosely bound P, Fe-P is iron bound P, and LOP is labile organic P. Concentrations above the bars is summer average TP for 2017 (N=5).

Colby Lake Watershed

Sediment chemistry was measured in 5 ponds in the Colby Lake watershed to determine the potential pools of releasable phosphorus from pond sediments (Figure 3-2). Redox-P concentrations ranged from 0.05 to 0.7 mg/g. No pond water quality data are available for the Colby Lake Watershed.

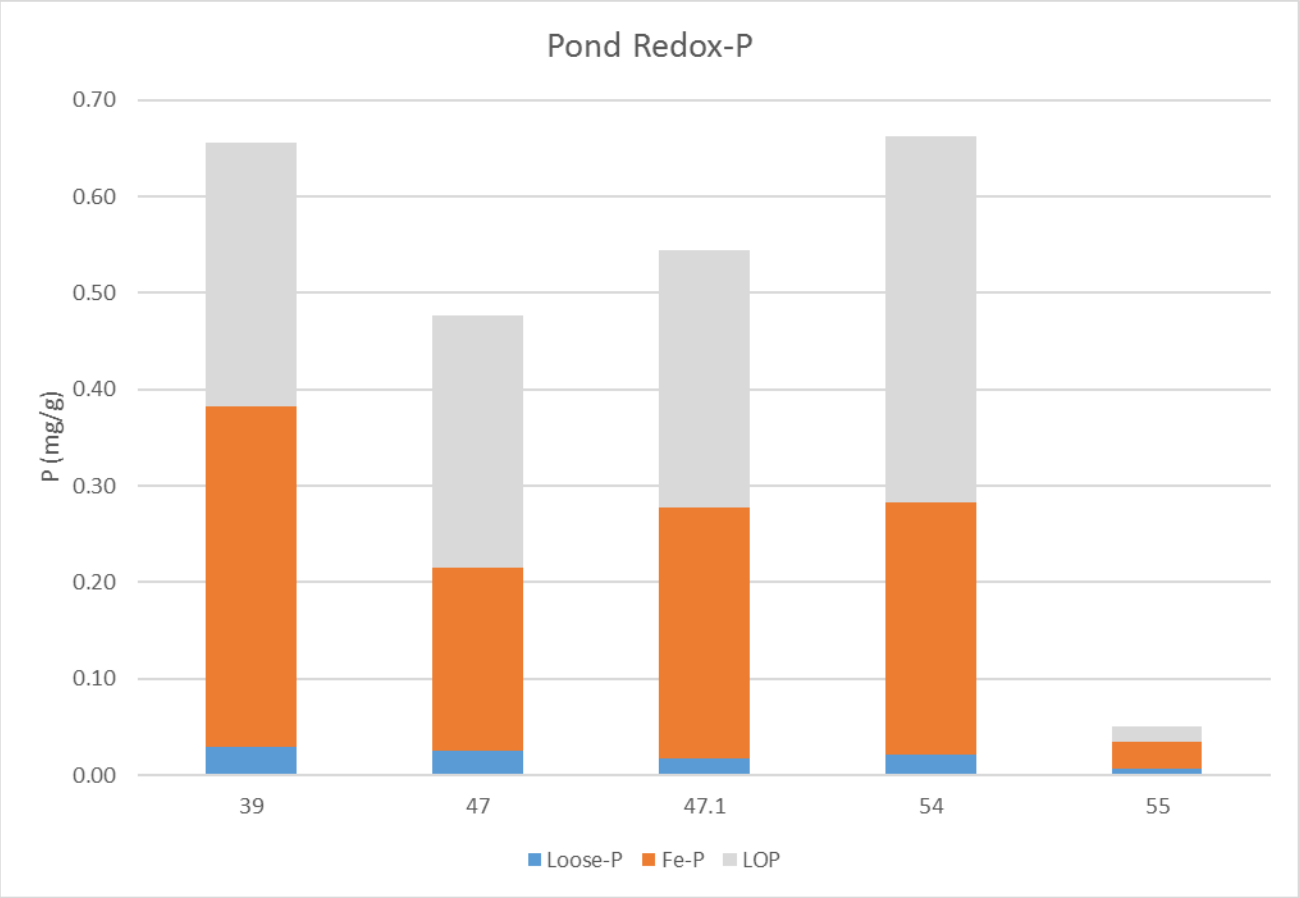


Figure 3-2. Surficial sediment phosphorus fractions in select stormwater ponds in the Colby Lake watershed.
Loose-P is loosely bound P, Fe-P is iron bound P, and LOP is labile organic P.

Wilmes Lake Watershed

Sediment chemistry was measured in 6 ponds in the Wilmes Lake watershed to determine the potential pools of releasable phosphorus from pond sediments (Figure 3-3). Redox-P concentrations ranged from 0.4 to 1.4 mg/g with most of the ponds less than 0.5 µg/g in mobile P. Pond 6 had the highest concentration of mobile P in the sediment, representing a high risk to release p to surface waters. However, measure P concentrations in the water column were moderate suggesting the pond may not be releasing significant amounts for P from the sediments. Further investigation is warranted. The remaining ponds only demonstrated a moderate to low risk and are not likely contributing to large quantities of P to surface waters.

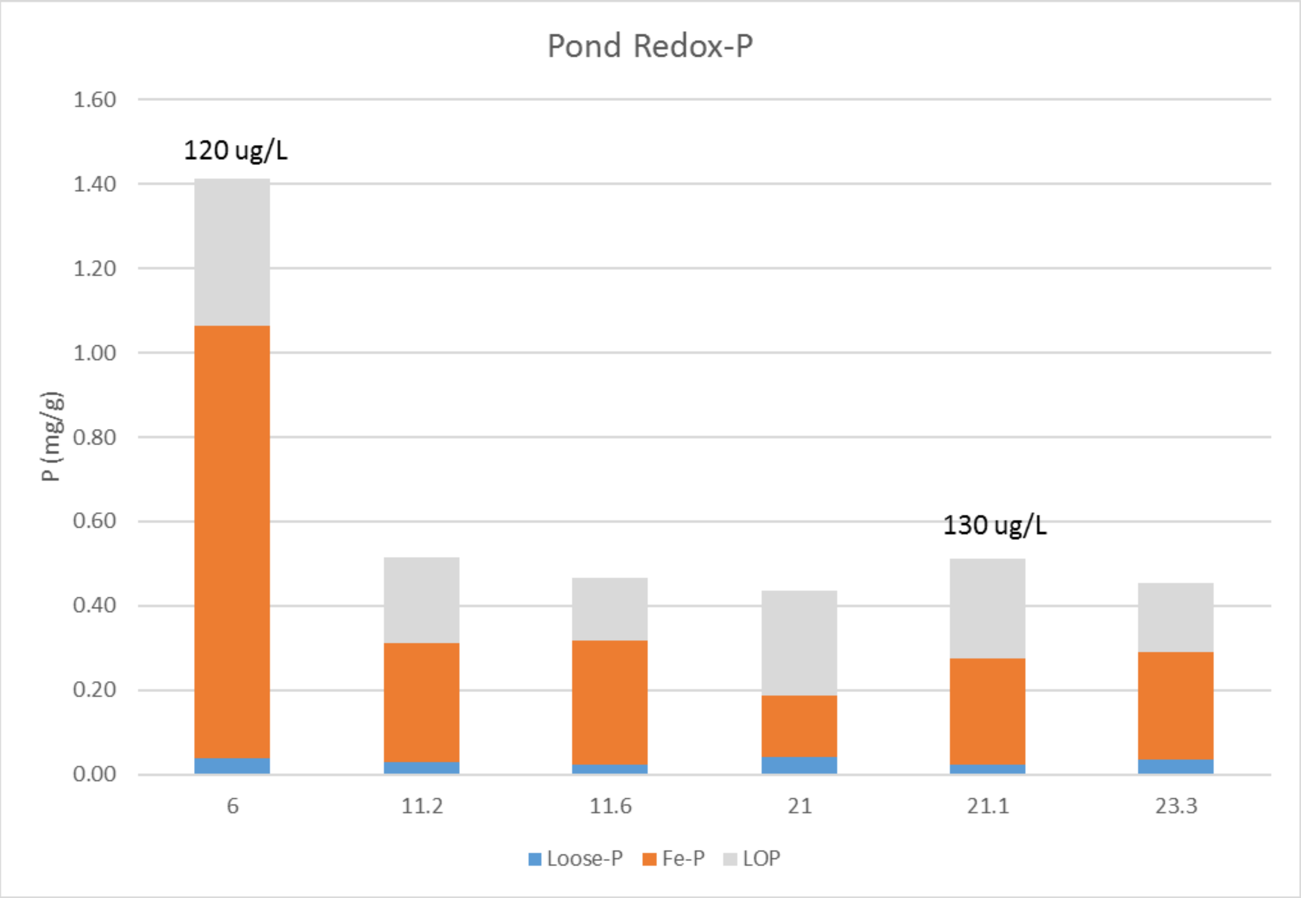


Figure 3-3. Surficial sediment phosphorus fractions in select stormwater ponds in the North and South Wilmes Lake watershed.
Loose-P is loosely bound P, Fe-P is iron bound P, and LOP is labile organic P.
Concentrations above the bars is summer average TP for 2017 (N=5).

3.3 INTERNAL PHOSPHORUS LOADING

Internal phosphorus loading from lake sediments has been demonstrated to be an important part of the phosphorus budgets. Internal loading is typically the result of organic sediment releasing phosphorus to the water column. This often occurs when anoxic conditions are present, meaning that the water in and above the sediment is devoid of oxygen.

Shallow lakes, like most of the lakes presented here, often demonstrate short periods of anoxia due to instability of stratification, which can last a few days or even a few hours, that are often missed by periodic field measurements. Thus, the following equation was used to estimate the anoxic factor for all shallow lakes in this TMDL study (Nürnberg 2005):

$$AF_{shallow} = -35.4 + 44.2 \log (TP) + 0.95\ z/A^{0.5}$$

Where TP is the average summer phosphorus concentration of the lake, z is the mean depth (m) and A is the lake surface area (km2).

To calculate total internal load for a lake, the anoxic factor (days) is multiplied by an estimated or measured phosphorus release rate (mg/m2/day). Release rates were obtained by collecting sediment cores in the field and incubating them in the lab under anoxic conditions to measure phosphorus release over time (Table 3-4). The vertical sediment chemistry profiles for each core is presented in Appendix D.

Table 3-4. Sediment release rates (aerobic and anaerobic), anoxic factors, and annual internal loads for each neighborhood lake.

Lake	Anaerobic Release Rate ($mg/m^2/day$)	Average Anoxic Factor[1] (days)	Average Annual Internal Load (lbs/yr)
Armstrong	1.7	50.1	14
Colby	10.7	65	427
La	1.7	54.5	42
Markgrafs	5.1	65.3	141
Ravine	12.3	52.6	154
Powers	5.1	63.8[2]	181
North Wilmes	12	55.1	112
South Wilmes	12.9	53.2	125

[1] The shallow lake anoxic factor from Nurnberg 2005 was used for the shallow lakes
[2] Measured from dissolved oxygen profiles since Powers Lake is a deep, stratified lake

3.4 ATMOSPHERIC LOADING

A study conducted for the MPCA, “Detailed Assessment of Phosphorus Sources to Minnesota Watersheds” (Barr Engineering, 2004), estimated the atmospheric inputs of phosphorus from deposition for different regions of Minnesota. The rates vary based on the precipitation received in a given year. Precipitation received during 2005-2011 was within that study’s average range (25” to 38”). That study’s annual atmospheric deposition rate of 26.8 kg/km^2 for average precipitation years was used to calculate annual atmospheric deposition load for these lakes.

3.5 UPSTREAM LAKES

Some of the lakes addressed in this study have upstream lakes that discharge either directly or indirectly into the assessment lake. Meeting water quality standards in the downstream lakes is contingent on water quality improvements in the proposed impaired upstream lakes. For these situations, outflow loads from the upstream lake were routed directly into the downstream lake and were estimated using monitored water quality.

4.0 Nutrient Budgets and Lake Response

4.1 APPROACH

To develop the required phosphorus load reductions for each of the lakes, a lake response model was developed. Calibrated models were then used to determine appropriate reductions from each source. Following is a description of the development of the model and load reductions.

4.2 BATHTUB MODEL (LAKE RESPONSE)

Lake response to nutrient loading was modeled using BATHTUB and the extensive data set available for the study lakes. BATHTUB is a series of empirical eutrophication models that predict the response to phosphorus inputs for morphologically complex lakes and reservoirs (Walker 1999). Several models (subroutines) are available for use within the BATHTUB model, and the Canfield-Bachmann model was used to predict the lake response to total phosphorus loads.

The Canfield-Bachmann model (Canfield and Bachmann 1981) estimates the lake phosphorus sedimentation rate, which is needed to predict the relationship between in-lake phosphorus concentrations and phosphorus load inputs. The phosphorus sedimentation rate is an estimate of net phosphorus loss from the water column through sedimentation to the lake bottom and is used in concert with lake-specific characteristics, such as annual phosphorus loading, mean depth, and hydraulic flushing rate, to predict in-lake phosphorus concentrations. These model predictions are compared to measured data to evaluate how well the model describes the lake system.

Once a model is well calibrated, the resulting relationship between phosphorus load and in-lake water quality is used to determine the assimilative capacity. Construction, calibration, and results of the BATHTUB model are presented in Appendix E.

4.3 NUTRIENT BUDGETS

Nutrient budgets were developed for each of the lakes using watershed loading from P8, internal load measurements, and estimates of atmospheric loading. Lake response models were then calibrated to in-lake monitoring data by adjusting the sedimentation rate in the Canfield-Bachmann model.

Target loads were determined by changing the internal and watershed loads in BATHTUB to achieve a final in-lake TP concentration of 60 μg/L. The target internal load was determined first, by changing the release rates from the measured release rate to 1 [mg/m^2-day]. After the release rate was reduced and the target internal load is determined, the target watershed load was determined by reducing the watershed load to achieve the desired in-lake TP concentration.

The margin of safety, MOS, represents the values based on the upper bound of the 95% confidence interval. Monte Carlo simulation was used to estimate upper boundary of the 95% confidence interval on a few parameters: watershed total inflow (ac-ft), watershed TP loading (lbs/yr), sediment phosphorus release rate mm/d/m^2), and anoxic factor (d).

Watershed total inflow and watershed TP loading were obtained from the P8 model. Bootstrapping method was used to randomly select 3 values from the result and calculate the mean, and this procedure was repeated 10,000 times. Empirical CDF was generated to calculate 95% confidence level. Both histograms appeared to be skewed normal distribution. Sediment phosphorus release rate was measured for some of the lakes. Mean and standard deviation of the release rate were provided. Monte Carlo simulation was used to generate 10,000 random numbers from the distribution defined by mean and standard deviation. Normal distribution was assumed for both data set. Empirical CDF was generated to calculated 95% confidence level.

4.3.1 Markgrafs Lake

Phosphorus loading to Markgrafs was an even split between internal load and watershed loading (Table 4-1 and Figure 4-1). To meet water quality standards, Markgrafs Lake requires an approximate 209-pound reduction in phosphorus loading. It should be noted that there is a fairly large error term around this load reduction with the 95% confidence interval suggesting a reduction range of 93 to 325 pounds, the high representing almost all of the loading. Just over half of this reduction can be achieved through internal load reductions and can achieve the lower bound of the 95% confidence interval. This suggests that an internal load reduction may be sufficient to bring the lake into compliance with water quality standards. Once the internal load project is completed, the remaining reductions would come from the watershed if needed.

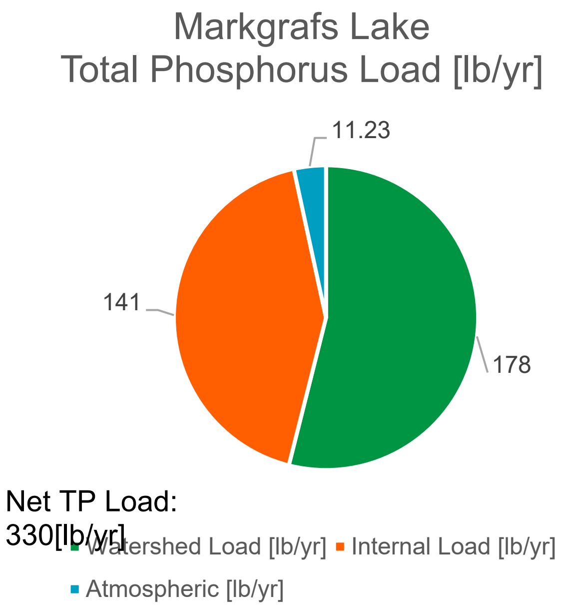


Figure 4-1. Total Phosphorus load - Markgrafs Lake

Table 4-1. TP load allocation for Markgrafs Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	-	-	-	-	-
Watershed Load	178	82	96	54%	28
Internal Load	141	27	114	81%	88
Atmospheric Load	11	11	-	-	-
Total	330	121	209	63%	116

4.3.2 Powers Lake

Loading to Powers Lake is predominantly from the watershed representing 77% of the phosphorus loading to the lake (Table 4-2 and Figure 4-2). While Powers Lake currently meets water quality standards, water load reductions could be pursued in the watershed to protect water quality in the lake since the lake has exceeded the standard in the past five years. Since internal loading is such a small proportion of the overall load, we do not recommend pursuing an internal load reduction project at this time.

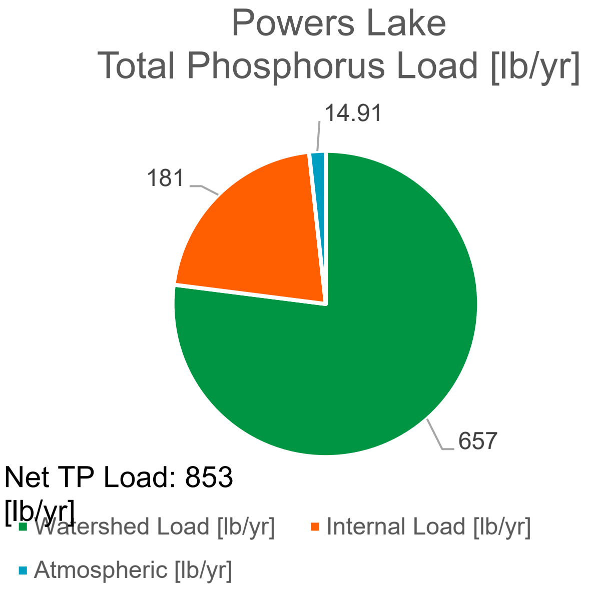


Figure 4-2. Total Phosphorus load - Powers Lake

Table 4-2. TP load allocation for Powers Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	-	-	-	-	-
Watershed Load	657	657	-	-	-
Internal Load	181	181	-	-	-
Atmospheric Load	15	15	-	-	-
Total	853	853	-	-	-

4.3.3 Armstrong, Wilmes and Colby Lake

Four basins make up the multi-lake system, i.e. Armstrong, North Wilmes, South Wilmes, and Colby. The contribution from upstream lakes compounds as we move down the chain, with Colby Lake and South Wilmes receiving the most TP load from upstream lakes.

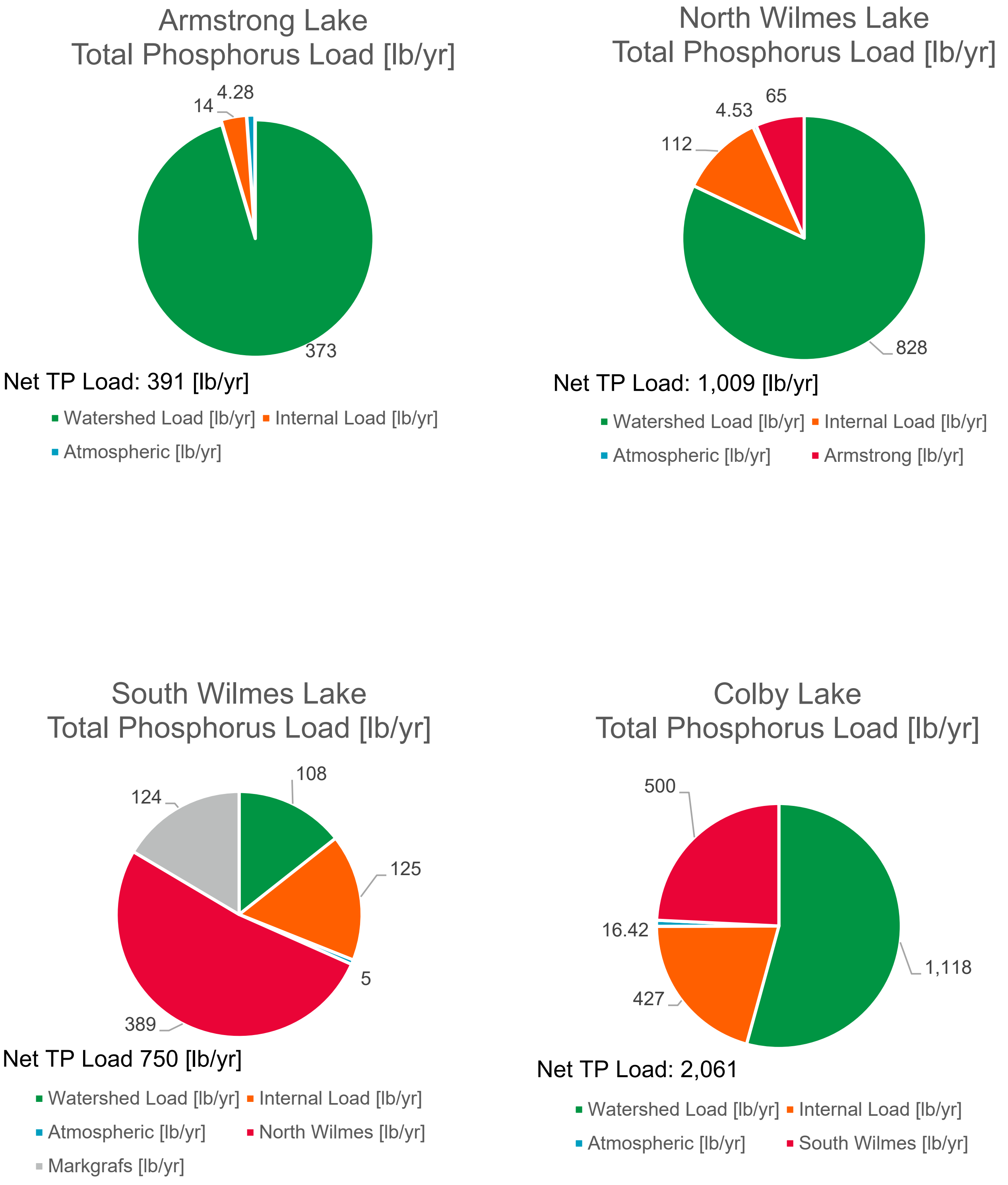


Figure 4-3. Total Phosphorus load – Armstrong, North Wilmes, South Wilmes, and Colby Lakes

Armstrong sits at the top of the chain has very little internal loading with most of its phosphorus load coming from the watershed (Table 4-3 and Figure 4-3). The 95% confidence interval around the load reductions are quite large ranging from zero to 194 pounds P reduction. Implementation of BMPs should be completed adaptively with continued lake monitoring to measure response from BMP installation.

Table 4-3. TP load allocation for Armstrong Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	-	-	-	-	-
Watershed Load	373	290	83	22%	88
Internal Load	14	8	6	43%	4
Atmospheric Load	4	4	-	-	-
Total	391	302	89	23%	105

For North and South Wilmes, most of the phosphorus load comes through North Wilmes including drainage from Armstrong Lake. North Wilmes Lake is predominantly driven by watershed loading, representing over 82% of the phosphorus load to the lake (Table 4-4). The target watershed phosphorus load range for lake is 467 to 886 pounds per year. Current loading is within the 95% confidence interval range suggesting an incremental approach to watershed and internal phosphorus load reductions.

Table 4-4. TP load allocation for North Wilmes Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	65	55	10	15%	20
Watershed Load	828	675	153	18%	208
Internal Load	112	9	103	92%	49
Atmospheric Load	5	5	-	-	-
Total	1,009	744	265	26%	272

Water quality in South Wilmes Lake is primarily driven by phosphorus coming from North Wilmes Lake. Because South Wilmes Lake is so heavily influenced by North Wilmes Lake, we recommend focusing on reducing watershed phosphorus loading to North Wilmes Lake. Internal phosphorus loading represents 17% of the overall P loading to South Wilmes Lake and may offer a cost-effective way of reducing phosphorus loading if the lake continues to demonstrate poor water quality once North Wilmes and Markgrafs Lake is meeting water quality standards (Table 4-5).

Table 4-5. TP load allocation for South Wilmes Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	513	432	81	16%	35
Watershed Load	108	108	27*	25%	65
Internal Load	125	125	-	-	-
Atmospheric Load	5	5	-	-	-
Total	750	642	108	14%	100

*Watershed reductions were chosen because of existing retrofit analysis, alternatively the water quality goal can be achieved by internal load reduction only, see section 5.4**.**

Colby lake is the final lake in the chain and receives input directly from South Wilmes Lake. Colby lake has the highest net load with the most contribution from the watershed and internal loading as compared with the other lakes in this study (Table 4-6). Watershed loading represents more than half of the P load to the lake with upstream lakes and internal loading at 24% and 21% respectively. Since water quality is so poor in Colby Lake, large reductions in both watershed P loading and internal loading will be required.

Table 4-6. TP load allocation for Colby Lake.

	Existing TP Load (lb/yr)	Target Load (lb/yr)	Load Reduction		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	500	402	98	20%	131
Watershed Load	1,118	300	818	73%	272
Internal Load	427	40	387	91%	163
Atmospheric Load	16	16	-	-	-
Total	2,061	758	1,303	63%	566

4.3.4 La Lake

La Lake has a very small, undeveloped watershed that provides minimal P loading to the lake (Figure 4-4 and Table 4-7). The majority of P loading to La Lake is from lake sediments, representing 70% of the P load to the lake. Phosphorus reduction efforts should focus on internal phosphorus loading.

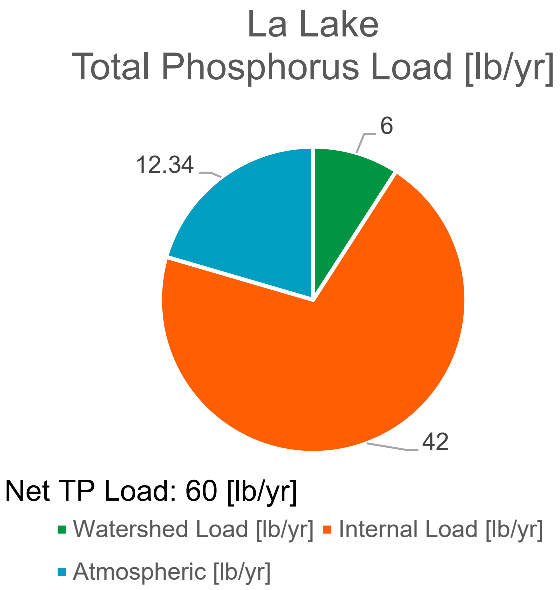


Figure 4-4. Total Phosphorus load - La Lake

Table 4-7. TP load allocation for La Lake.

	Existing TP Load (lb/yr)	**Target Load** (lb/yr)	**Load Reduction**		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	-	-	-	-	-
Watershed Load	6	6	-	0%	2
Internal Load	42	25	17	40%	16
Atmospheric Load	12	12	-	-	-
Total	60	43	17	28%	18

4.3.5 Ravine Lake

Ravine Lake is quite small (27 acres) with a very large watershed (2,191 acres) which provides large nutrient loads to the lake (Figure 4-5 and Table 4-8). Watershed phosphorus loading represents over half of the phosphorus loading to the lake with internal loading representing 38% of the phosphorus load. It should also be noted that anecdotal evidence suggests there is a strong groundwater influence in Ravine Lake that may provide phosphorus loading to the lake. Since investigating the phosphorus load from groundwater to Ravine Lake was outside the scope of this project, further investigation is warranted. Ravine Lake demonstrates severe algal blooms in the summer even with moderate total phosphorus concentrations suggesting an imbalance in the lake ecology.

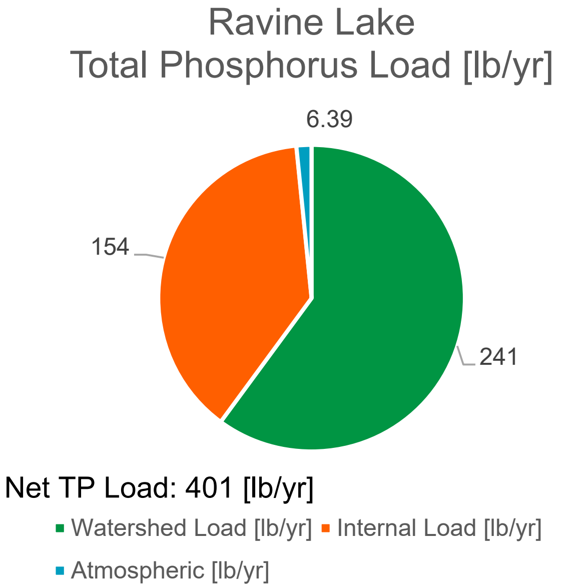


Figure 4-5. Total Phosphorus load - Ravine Lake

Table 4-8. TP load allocation for Ravine Lake.

	Existing TP Load (lb/yr)	**Target Load** (lb/yr)	**Load Reduction**		
			(lb/yr)	%	MOS (lb/yr)
Upstream Lakes Load	-	-	-	-	-
Watershed Load	241	241	-	100%	59
Internal Load	154	13	141	92%	48
Atmospheric Load	6	6	-	-	-
Total	401	260	141	35%	107

5.0 Implementation Plan

5.1 IMPLEMENTATION PLAN SUMMARY

Recommended management activities for each of the lakes include a mix of internal and external (watershed) nutrient reduction projects, fisheries management, aquatic vegetation management and shoreline management. Following is a summary of the potential management activities including associated costs. Costs were completed for an expected 30-year life cycle.

5.2 ADAPTIVE MANAGEMENT

Implementation will be conducted using adaptive management principles (Figure 5-1). Adaptive management is essentially a phased approach where a strategy is identified and implemented in the first cycle. After implementation of that phase has been completed, progress toward meeting the goals is assessed. A new strategy is then formulated to continue making progress toward meeting the goals. These steps are continually repeated until established goals are met. This process allows for future technological advances that may alter the course of actions. Continued monitoring and "course corrections" responding to monitoring results are the most appropriate strategies for attaining the water quality goals of this management plan.

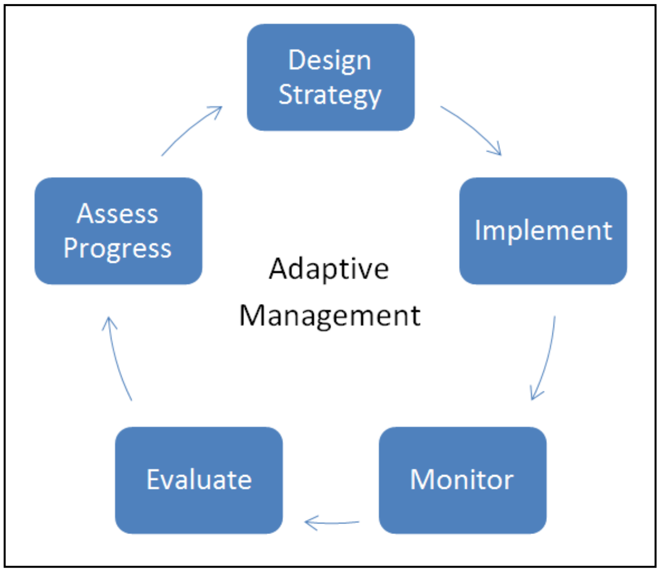


Figure 5-1. Adaptive management.

5.3 WATERSHED LOAD REDUCTIONS

The goal of this project was to update the nutrient budgets for the lakes and identify in-lake management opportunities to enhance water quality and lake conditions. While the focus of this report was on in-lake management, the District has been actively developing watershed retrofit studies to identify opportunities to reduce phosphorus loading. These studies were used as the basis for identifying watershed load reductions. However, this study does include a preliminary analysis of internal loading in stormwater ponds to determine if this currently unquantified source of phosphorus should be addressed.

5.3.1 Relationship to Previous Plans

Previous lake management plans used seasonal loading to develop the phosphorus budgets for each of the lakes. This report outlines the necessary reductions as annual load reductions since the selected lake response model is an annual model and BMP reductions are typically presented as annual numbers. However, both approaches address the same planning goal to provide a magnitude of effort required to improve water quality in the lakes. To that end, previous estimates were compared to current estimates to provide some context for previous studies and goals (Table 5-1).

Table 5-1. Previous study load reduction targets and current load reduction targets.

Lake	Prior Studies			Current Study			
	TP Load (lb/season)	TP Reduction (lb/season)	TP % reduction	TP Load (lb/yr)	TP Reduction (lb/yr)	TP Reduction[1] (lb/season)	TP % reduction
Armstrong	101	11	11%	391	89	30	23%
Colby	683	331	48%	2,061	1,303	436	63%
La	--	--	--	60	17	6	28%
Markgrafs	139	106	76%	330	209	70	63%
Ravine	137	18	13%	401	141	47	35%
Powers	90	--	--	853	--	--	--
North Wilmes	245	108	44%	1,009	265	89	26%
South Wilmes	278	26	10%	750	108	36	14%

[1] Seasonal load reductions were estimated by proportioning the seasonal load from the annual load (33%).

5.3.2 Watershed BMP Implementation

Four of the seven lakes required significant watershed load reductions from the watershed to meet state water quality standards (Table 5-2). Several of the lakes require a larger load reduction than was deemed achievable in the District's retrofit analysis. For example, Colby requires an 436-pound reduction in watershed loading seasonally but the retrofit analysis only identified 148 pounds of reduction through stormwater retrofits. The results were similar for North Wilmes where target reductions were 89 pounds of P with only 36 pounds of reduction opportunities identified. Armstrong, La, and Ravine do not currently have completed retrofit analyses.

Reductions in phosphorus loading from the watersheds beyond the current retrofit analyses will be challenging and will require additional analyses to determine where additional reductions may be achievable. These projects should be implemented using adaptive management where the initial projects are implemented, and the lake response is measured. Many of the lakes have a relatively large uncertainty in attainment of the standards that require adaptive management. For example, the MOS around the Colby Lake watershed load is 272 pounds suggesting that a target annual watershed load reduction range should be 609 to 1,090 pounds P (203 to 363 pounds seasonally). While it is unlikely that the watershed reduction will need to be over 1,000 pounds annually which is almost all of the watershed load, targeting the low end of the range and then monitoring the lake is a good adaptive management approach.

Table 5-2. Target watershed phosphorus load reductions and stormwater retrofit goals.

Lake	Target Watershed Load Reduction (lbs/season)	Target Watershed Load Reduction Range (lbs/season)	Proposed Watershed Load Reduction[4] (lbs)	Project Cost	Cost Efficiency ($/lb/yr)
Armstrong[1]	30	0 - 57	-	-	-
Colby	436	182 - 363	148	$4,098,123	$923
La[1]	6	--	-	-	-
Markgrafs[1]	70	23 - 41	-	-	-
Powers[2]	47	--	35.8	$187,693	$175
Ravine[1]	--	0-20	-	-	-
North Wilmes	89	0 - 120	35.8	$1,909,581	$9,664
South Wilmes	36	0 - 21	34	$944,871	$10,079

[1] No retrofit analysis [2] Lake is not impaired [4] Based on previously developed stormwater retrofit analyses

5.3.3 Stormwater Pond Management

The P8 urban catchment model used in this study focuses on particulate P and settling on stormwater ponds. Recent evidence suggests that stormwater pond sediments can be a source of phosphorus to surface waters. Pond sediments measured in this study suggests that there is a significant pool of P available for release from stormwater pond sediments. Further, pond monitoring demonstrated frequent and large anoxic areas in many of the ponds with several ponds showing high bottom water TP concentrations indicative of sediment P release in ponds. However, most of the ponds monitored by the City of Woodbury had moderate average surface TP concentrations. It should be noted that pond TP concentrations will be highly episodic with routine flushing from storm events and that current monitoring only occurred monthly in the ponds.

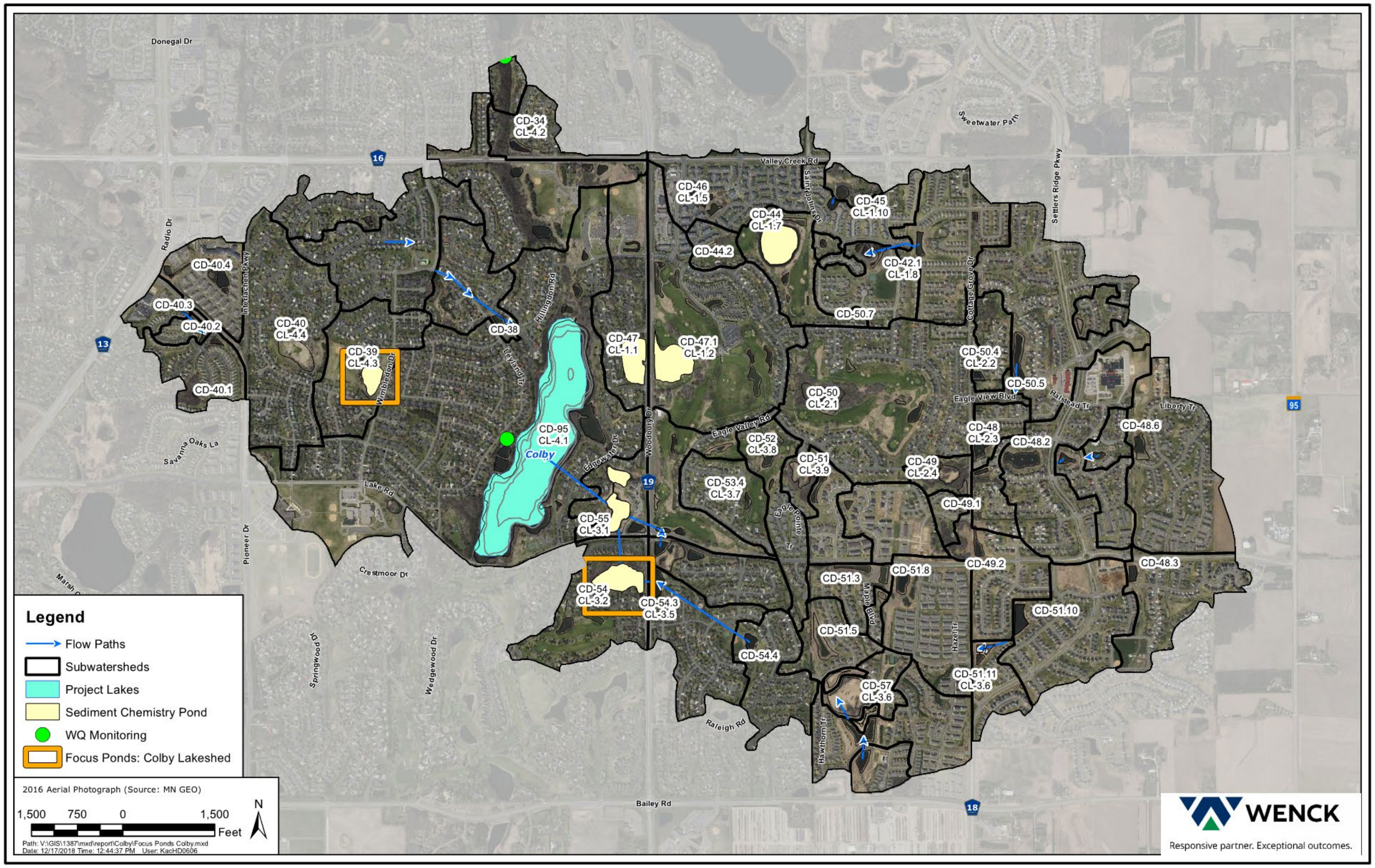
Based on the evidence developed in this report, further investigation of pond sediment loading is warranted. The investigation should focus on key watersheds with large watershed loads including Colby, Powers, and North Wilmes Lake (Figures 5-2 through 5-4). These lakes demonstrated poor water quality, have a large number of ponds, and demonstrate large watershed loads. The study should investigate sediment P release through lab measurements, frequent DO measurements, and bottom phosphorus concentrations. The following ponds could be further investigated to determine if internal load reductions will impact watershed P loading:

Colby Lake
- CD-39
- CD-54

North and South Wilmes Lake
- CD-6

Powers Lake
- CD-26

- CD-26.1



2016 Aerial Photograph (Source: MN GEO)

Path: V:\GIS\1387\mxd\report\Colby\Focus Ponds Colby.mxd
Date: 12/17/2018 Time: 12:44:37 PM User: KacHD0606

Figure 5-2. Colby Lake Stormwater Ponds.

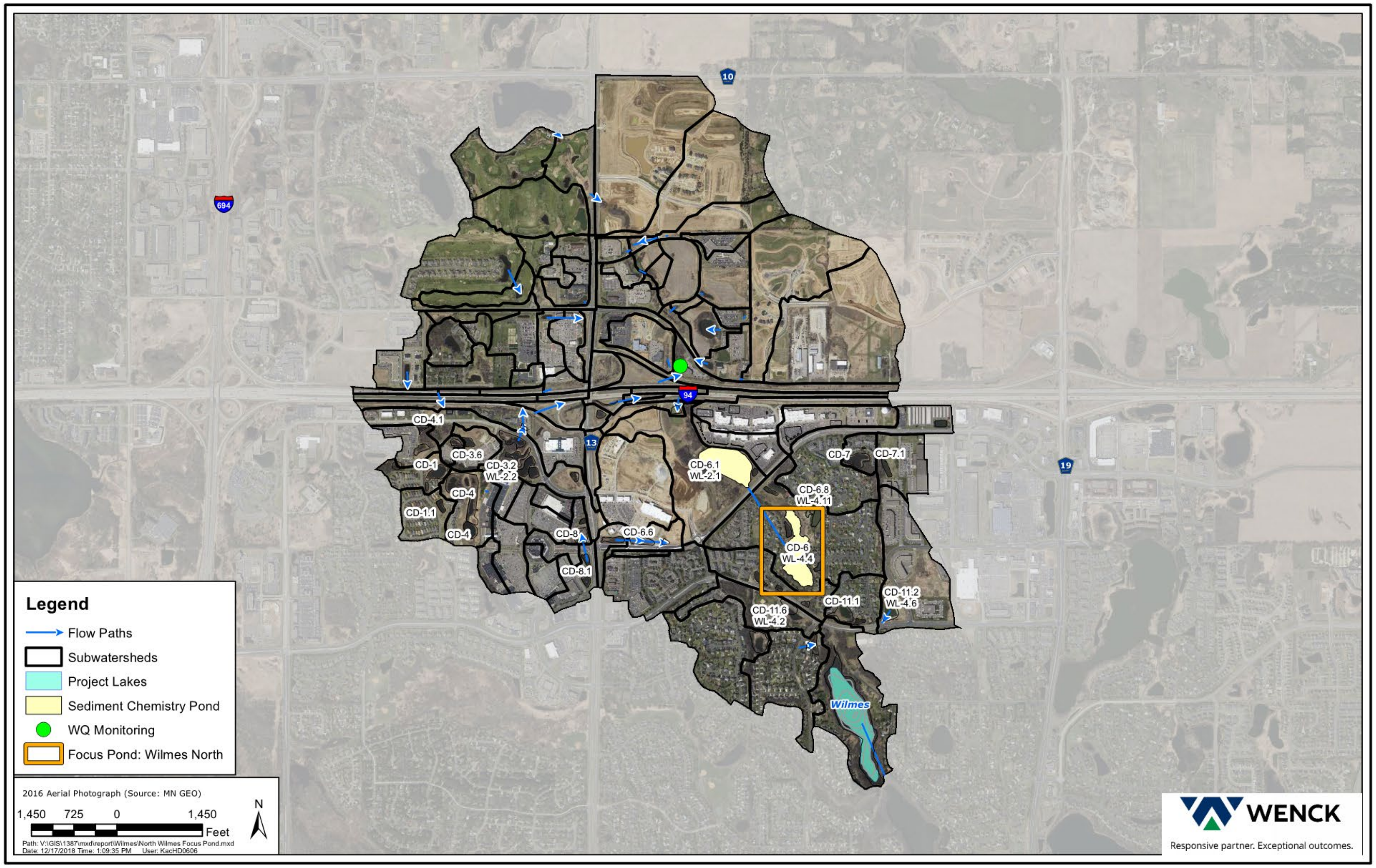


Figure 5-3. Wilmes Stormwater Ponds.

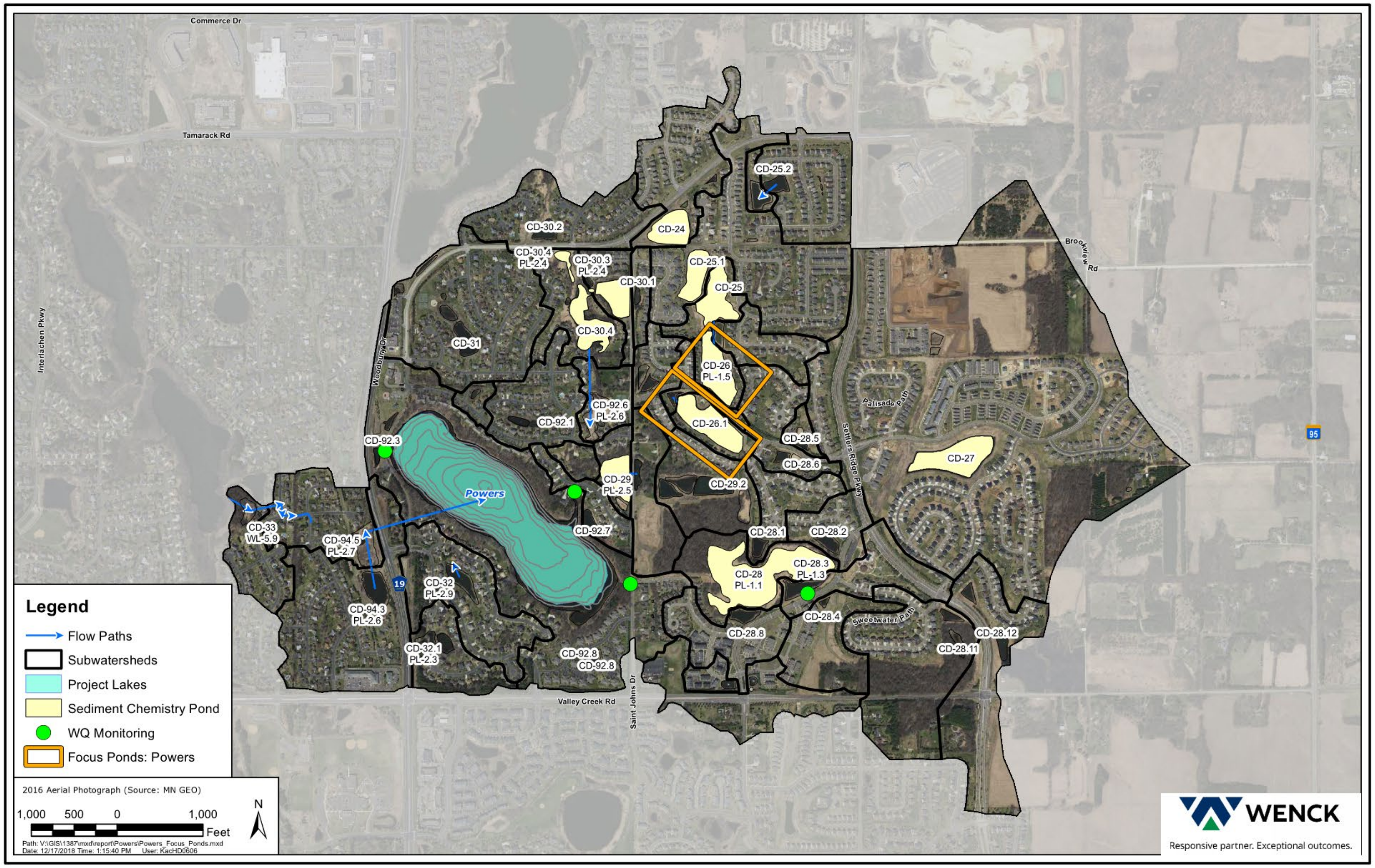


Figure 5-4. Powers Stormwater Ponds.

5.4 INTERNAL PHOSPHORUS LOAD REDUCTIONS

Five lakes were identified as having internal P loading large enough to recommend alum applications as viable options for lake phosphorus management. Over half of each of these lakes' TP budgets is from internal phosphorus loading.

Sediment cores from each lake were collected and analyzed for redox-bound phosphorus (redox-p) to estimate the amount of alum needed to adsorb redox-sensitive phosphorus. Sediment redox-p concentrations were then converted to an aluminum-to-phosphorus ratio large enough to adsorb 90% of the available sediment redox-p ($Al:P_{90\%}$) using an empirical relationship developed by James and Bischoff (2015). The alum dose per area (m^2) was calculated by multiplying $Al:P_{90\%}$ ratio by the redox-p in the uppermost 10 cm of each lake.

The unit area alum dose (Al g/m^2) can then be multiplied by the dosing area to determine the mass of aluminum needed. For these cost estimates, a buffered alum solution was included as a conservative assurance because it is currently unknown whether alum applications would cause pH to decrease temporarily to unacceptable levels. Buffered alum solutions generally include aluminum sulfate and sodium aluminate, which cost an estimated $2.00 and $5.00 per gallon, respectively. An assumed 2:1 aluminum sulfate-to-sodium aluminate ratio would be used in the treatments.

Assuming the aforementioned, the cost for each initial alum treatment is outlined in Table 5-2. Although alum is a proven method for substantially reducing internal loading from lake sediments, such treatments can degrade over time. The combination of sedimentation and alum structural changes may require an additional treatment during its estimated 30-year life cycle. Thus, a second but reduced alum application is included in each cost estimate to ensure long-term limits of phosphorus release from sediments.

The longevity of the alum treatments was estimated using the phosphorus sedimentation term in the lake response model. The amount of time (years) to replace inactivated phosphorus was estimated using the sedimentation term for both existing conditions and conditions once all other watershed reductions are accomplished (Table 5-2). Th expected longevity under current conditions was relatively low for all of the lakes (4 to 9 years) suggesting that the focus for P reductions should remain on the watershed in the near term. However, all of the lakes demonstrated a reasonable longevity when watershed reductions are completed. Only Wilmes Lake had an expected longevity less than 10 years even when meeting water quality goals because Wilmes has a large watershed and high sedimentation rate. It is important to note that these estimates are based on a lake response model and only represent an estimate of the longevity.

Table 5-3. Alum treatment cost estimates for lakes with significant internal phosphorus loads.

Lake	Target Internal Load Reduction (lb)	Present Value Cost	Project Cost	Cost Efficiency ($/lb/yr)	Existing Estimated Longevity[1] (yr)	Goal Estimated Longevity[2] (yr)
Colby	387	$280,529	$432,666	$37	5	21
La	17	$245,213	$336,788	$660	34	46

Lake	Target Internal Load Reduction (lb)	Present Value Cost	Project Cost	Cost Efficiency ($/lb/yr)	Existing Estimated Longevity[1] (yr)	Goal Estimated Longevity[2] (yr)
Markgrafs	114	$177,347	$257,221	$75	4	12
Ravine	141	$365,039	$522,783	$124	9	14
North Wilmes	103	$126,157	$184,794	$60	3	4
South Wilmes*	115	$100,195	$148,060	$43	4	7

[1] Estimated time to replace total mass of inactivated redox phosphorus
[2] Estimated time to replace total mass of inactivated redox phosphorus adjusted with the target loads
*Alternative treatment option to achieve South Wilmes water quality goals without watershed load reductions.

5.5 AQUATIC VEGETATION MANAGEMENT AND MONITORING

Submerged aquatic vegetation is critical in maintaining the clear water state in the shallow lakes of this study. Most of the lakes have stable plant populations but are dominated by one or two species including Coontail and Canadian waterweed. While this condition supports clear water, it doesn’t support the breadth of wildlife and fish that would be expected with submerged vegetation. Managing a shallow urban lake for plant diversity is poorly understood, however, and most efforts use mechanical removal or herbicides to support recreation or minimize invasive species.

The vegetation management goal of these lakes ideally is to maintain broad lake coverage, manage invasive species such as Curly-leaf pondweed, and increase diversity where possible through nutrient and water level management and via changes in sediment chemistry ultimately (Table 5-3). Ideally, the shallow lakes will have a healthy and diverse vegetation community throughout the lake. However, a target of 85% coverage is a good goal to maintain healthy conditions.

Table 5-4. Submerged aquatic vegetation management activities for the neighborhood lakes.

Lake	Management Action	CLP? EWM?	Carp?	Vegetation Condition	Estimated Cost
Armstrong	• Routine Monitoring	No No	No	• High floristic quality index score • Dominated by Coontail	$4,000 biannually
Colby	• Routine Monitoring • CLP and EWM Control	Yes Yes	No	• Poor floristic quality index score • Dominated by Elodea • Poor water clarity likely limiting plants to shallow areas • Curly-Leaf pondweed and Eurasian watermilfoil present	$4,000 biannually $10,000 annually for control
La	• Routine Monitoring	No No	No	• High floristic quality index score	$4,000 biannually
Markgrafs	• Routine Monitoring • CLP Control	Yes No	No	• Dominated by Elodea • Poor vegetation coverage (62% of lake) • Poor floristic quality index score • Curly-Leaf pondweed and Eurasian watermilfoil present	$4,000 biannually $7,000 annually for control
Powers[1]	• Routine Monitoring • CLP and EWM Control	Yes Yes	No	• Dominated by Coontail • Curly-Leaf pondweed and Eurasian watermilfoil present • Littoral area 100% vegetated	$4,000 biannually $10,000 annually for control
Ravine	• Routine Monitoring • CLP Control	Yes No	No	• Dominated by Coontail • Curly-Leaf pondweed present • Poor floristic quality index score	$4,000 biannually $7,000 annually for control
North Wilmes **South Wilmes**	• Routine Monitoring •	No No	No	• Dominated by Flat-stem pondweed • Poor floristic quality index score • Only 69% of littoral area vegetated	$4,000 biannually
All Lakes	• Roughfish control • Carp prevention • Invasive species prevention	--	--	• Almost all the lakes have healthy submerged aquatic vegetation communities but limited diversity • Invasive species present in watershed and spread should be controlled	$5,000 annually

5.5.1 Diversity Management

Almost all of the lakes are dominated by Coontail or Elodea, which is typical of nutrient enriched, urban lakes with relatively stable water elevations. Even though it is a native species, Coontail can dominate a lake by extensively matting the surface. Coontail management is currently poorly understood, and the only effective tools are physical removal and herbicide treatments. None of the lakes currently have Coontail at chronic, extensive levels with most of the lakes only having small areas where vegetation was growing to the surface. Increasing plant diversity in these lakes is likely tied to nutrient management and changes in sediment chemistry. In the short term, nutrient management is the best approach for aquatic vegetation diversity in these lakes. However, it may be difficult to achieve a diverse population without whole lake drawdown.

5.5.2 Curly-leaf Pondweed Control

Curly-leaf pondweed is a non-native plant that can have negative impacts on lake water quality and recreation if the population reaches extensive levels (high density, breaks the surface). It establishes under the ice, giving it a competitive advantage over native vegetation after spring temperatures warm. When Curly-leaf pondweed dies in midsummer, the plant's TP is released into the water. However, its overall contribution to internal phosphorus loading is poorly understood. Many lakes without Curly-leaf pondweed demonstrate the same increase in summer TP suggesting that other factors may be contributing to P release at this period.

Many studies and projects throughout the country over the years have focused on Curly-leaf pondweed and its effective management. However, both are poorly understood. At a minimum, any attempts to control this plant would begin with relatively simple monitoring of its extent and density in early season. Further determinations of what, if any, actions to take and when are not as simple, however. As with other lake plants, typical controls include chemical treatment and physical removal, but iron added to sediment and lake drawdowns before winter have also been done. Even with these challenges, Curly-leaf pondweed should be managed to minimize its impact on both the submerged aquatic vegetation community and water quality.

5.5.3 Assess and Manage Filamentous Algae

Filamentous algae start their life cycle on the sediments and are typically driven by internal phosphorus release. Filamentous algae may be monitored and assessed, but there is no quantitative distinction of when a filamentous algae bloom is a nuisance, and most shallow lakes have filamentous algae, especially in very shallow areas. A basic point intercept evaluation of mat coverage may provide a repeatable assessment strategy. However, simple observations throughout the year are often adequate for determining the extent of lake filamentous algae.

Filamentous algae can be quite difficult to control, with very few options for limiting the growth. Algae management efforts that focus on internal phosphorus release from the sediments, from where the majority of nutrients for filamentous algae come, may be the most effective strategy in the long term. Physical removal of algae mats is an option; however, this would be an ongoing activity that would require an annual budget for city staff time to coordinate and implement. Based on local evidence, alum additions to these lakes will reduce filamentous algae blooms.

5.5.4 Invasive Species Prevention

The prevention of invasive species is critical to maintaining a healthy biological community in the lakes. Invasive species such as Eurasian water milfoil, hydrilla, flowering rush, and purple loosestrife can reduce the diversity of the plant community and choke out native species. Prevention is much less expensive than control in the long term, so education about these species, how they spread, and what individual lake users can do is critical in preventing their introduction.

5.6 FISHERIES MANAGEMENT

5.6.1 Fisheries Management and Monitoring

Fisheries management is critical in maintaining clear water conditions in shallow lakes. Ideally, the fish community is balanced between top predators and panfish populations, lacks stunting in the panfish community, and has low numbers of fathead minnows and rough fish. The lakes also lack carp populations or if carp are present, they are managed to maintain low densities of carp. Following is a description of fish management activities to be considered for these shallow lakes in Eagan (Table 5-4).

5.6.2 Fathead Minnow Management

Fathead minnows can negatively affect water quality in shallow lakes by exerting heavy grazing pressure on large zooplankton. Large zooplankton help support clear water through efficient grazing of algal populations. There are a number of ways to manage fathead minnows in shallow lakes, including stocking top predators (e.g., walleye, bass, and northern pike). However, shallow lakes are not long-term habitat for fish such as walleye because they lack suitable spawning areas and tend to winter kill. Aeration may contribute to fathead minnow survival secondarily to its intended purpose of supporting game fish populations. It is also possible, but not reliable, that winterkills will reduce fathead minnow populations in some years.

5.6.3 Bullhead, Carp, and Roughfish Management

Bullheads and carp contribute to poor water clarity by stirring up sediments and uprooting submerged aquatic vegetation. None of the lakes are known to have carp populations, and ideally their introduction will continue to be prevented. Also, Colby Lake’s sizeable bullhead population should be reduced or managed. Options include physical removal using seine nets, chemical removal using rotenone, or stocking top predators such as channel catfish or walleye. Colby has recently been stocked with channel catfish.

Table 5-5. Fisheries management activities for the study lakes.

Lake	Management Action	Fisheries Condition	Estimated Cost
Armstrong	• Monitor fish community	• No fish survey available	$10,000 per survey
Colby	• Work with DNR on management plan • Manage roughfish density	• FiN Lake • Stocked with panfish and channel catfish • Large bullhead population	$10,000 biannually for roughfish control
La	• Monitor fish community	• No fish survey available	$10,000 per survey
Markgrafs	• Manage fish survival through aeration •	• Winterkills	$5,000 annually
Powers[1]	• Work with DNR on management plan • Manage fish survival through aeration	• FiN Lake • Winterkills	$5,000 annually
Ravine	• Work with DNR on management plan • Manage roughfish density	• FiN Lake • Stocked with walleye, largemouth bass, and black crappie • Historical dominance by bullheads	$10,000 biannually for roughfish control
North Wilmes	• Monitor fish community • Manage fish survival through aeration	• Winterkills • No fish survey available	$10,000 per survey $5,000 annually
South Wilmes[2]			
All Lakes	• Prevent carp infestation	• No carp are currently documented in the study lakes	$5,000 annually

5.6.4 Fish Monitoring

Regular monitoring of the fish community by the Minnesota DNR and/or the District will continue to provide information to evaluate any changes that may need to be addressed, including fishery balance, rough fish (especially carp), and decline in numbers or biomass. Ideally each lake will be surveyed once every five years, according to DNR standard protocol.

5.6.5 Invasive Species Prevention

Invasive species such as carp, zebra and Quagga mussels, rusty crayfish, New Zealand Mud snail, Chinese and Banded Mystery Snail, and spiny water fleas can have significant negative effects on the biological communities in lakes. Prevention is much less expensive than control in the long term, so education about these species, how they spread, and what individual lake users can do is critical in preventing their introduction to the lakes.

6.0 References

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Washington Conservation District *Colby Lake Stormwater Retrofit Assessment* http://www.swwdmn.org/wp-content/uploads/2016/03/COLBY-Assessment-Report.pdf

Washington Conservation District *Powers Lake Stormwater Retrofit Assessment* http://www.swwdmn.org/pdf/watershedplan/Library/PowersSRA.pdf

Appendix A

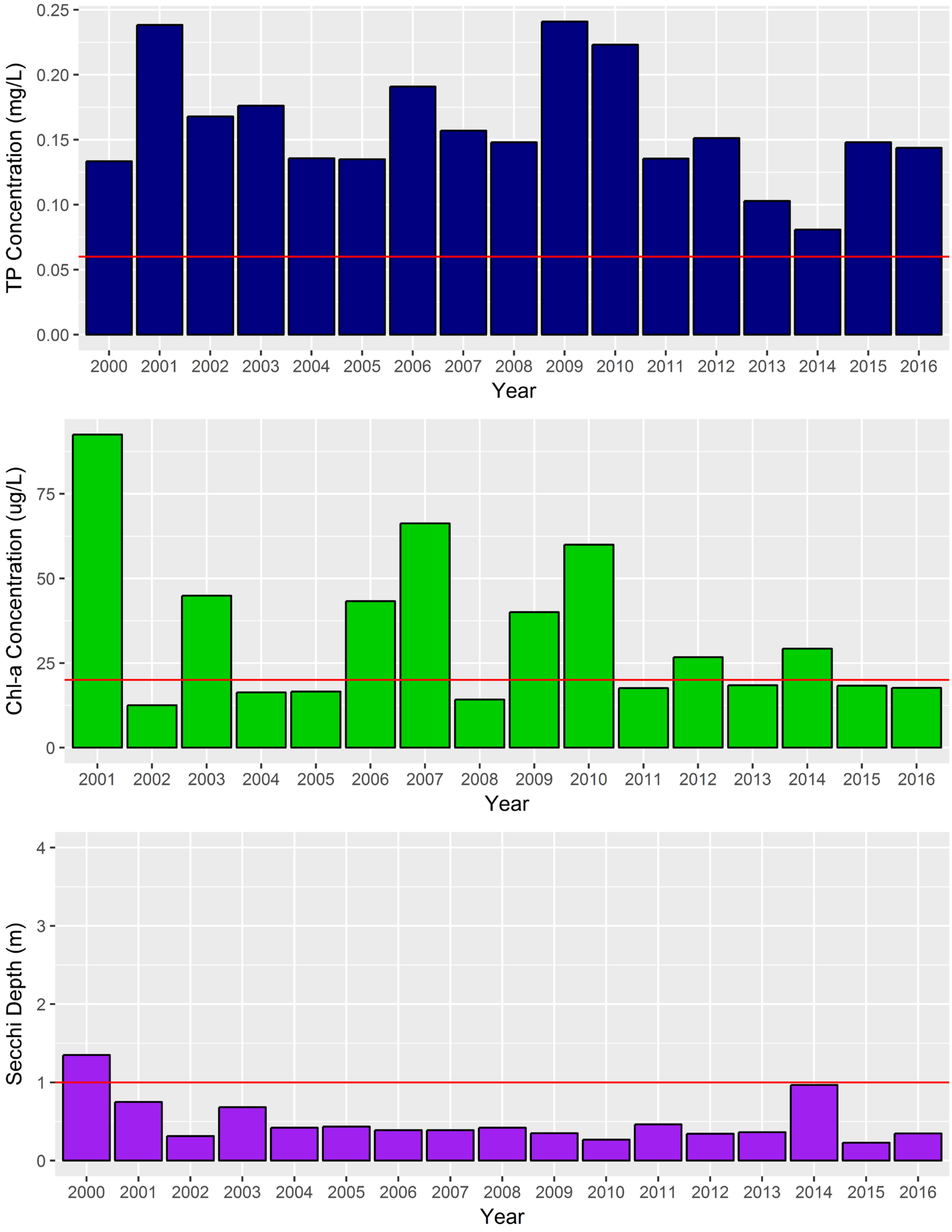


Figure A1: Armstrong Water Quality Time Series

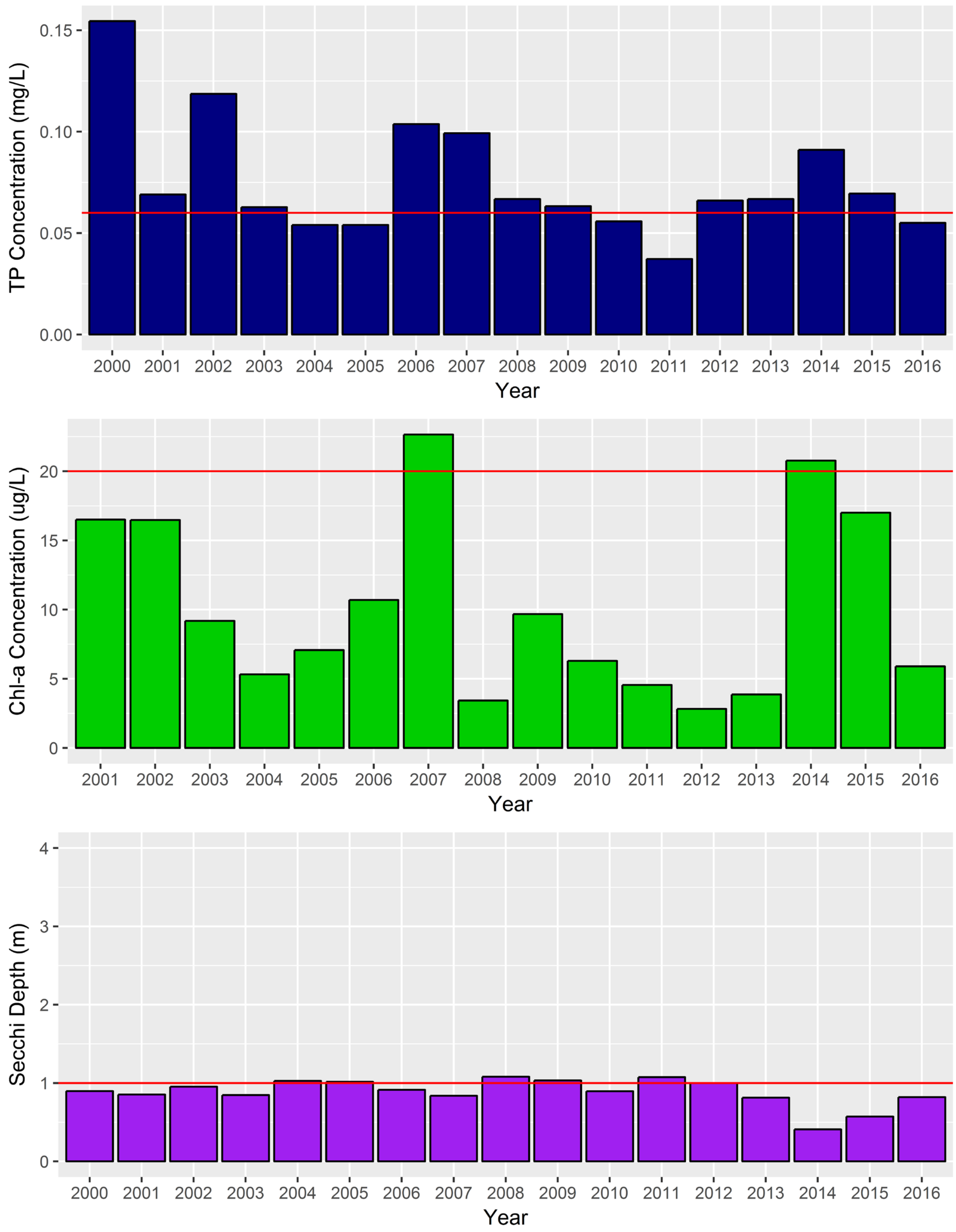


Figure A2: Colby Water Quality Time Series

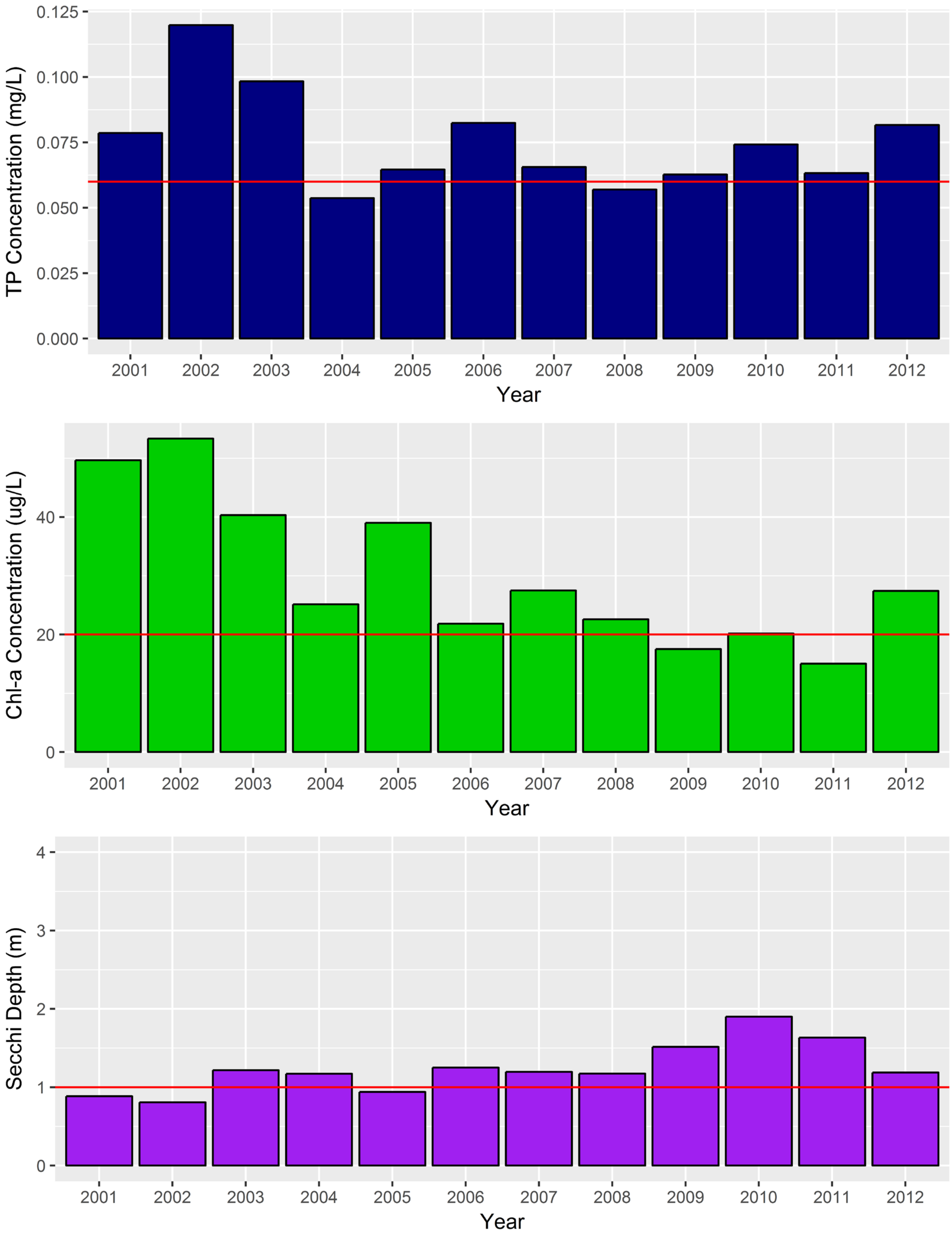


Figure A3: La Water Quality Times Series

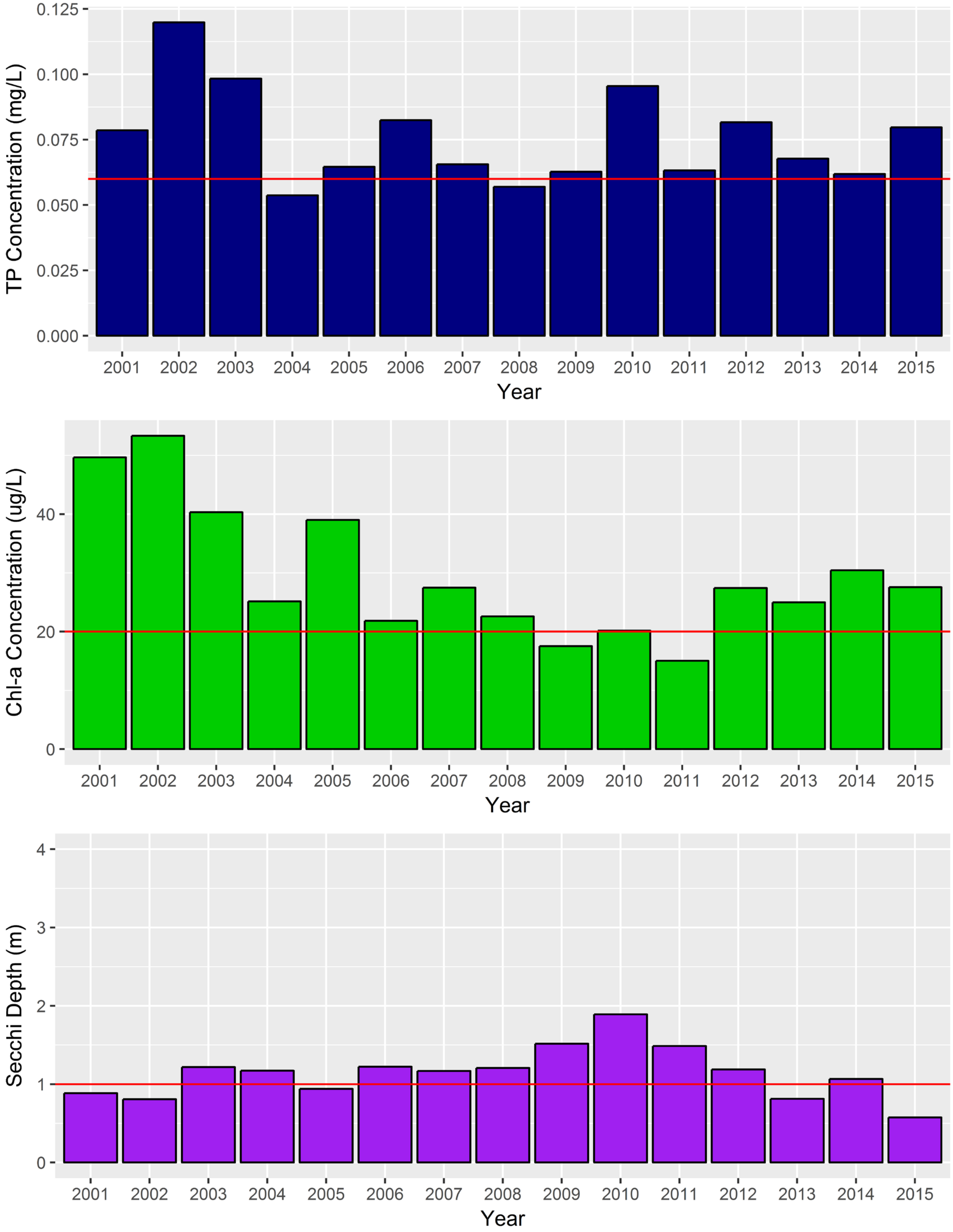


Figure A4: Markgrafs Water Quality Time Series

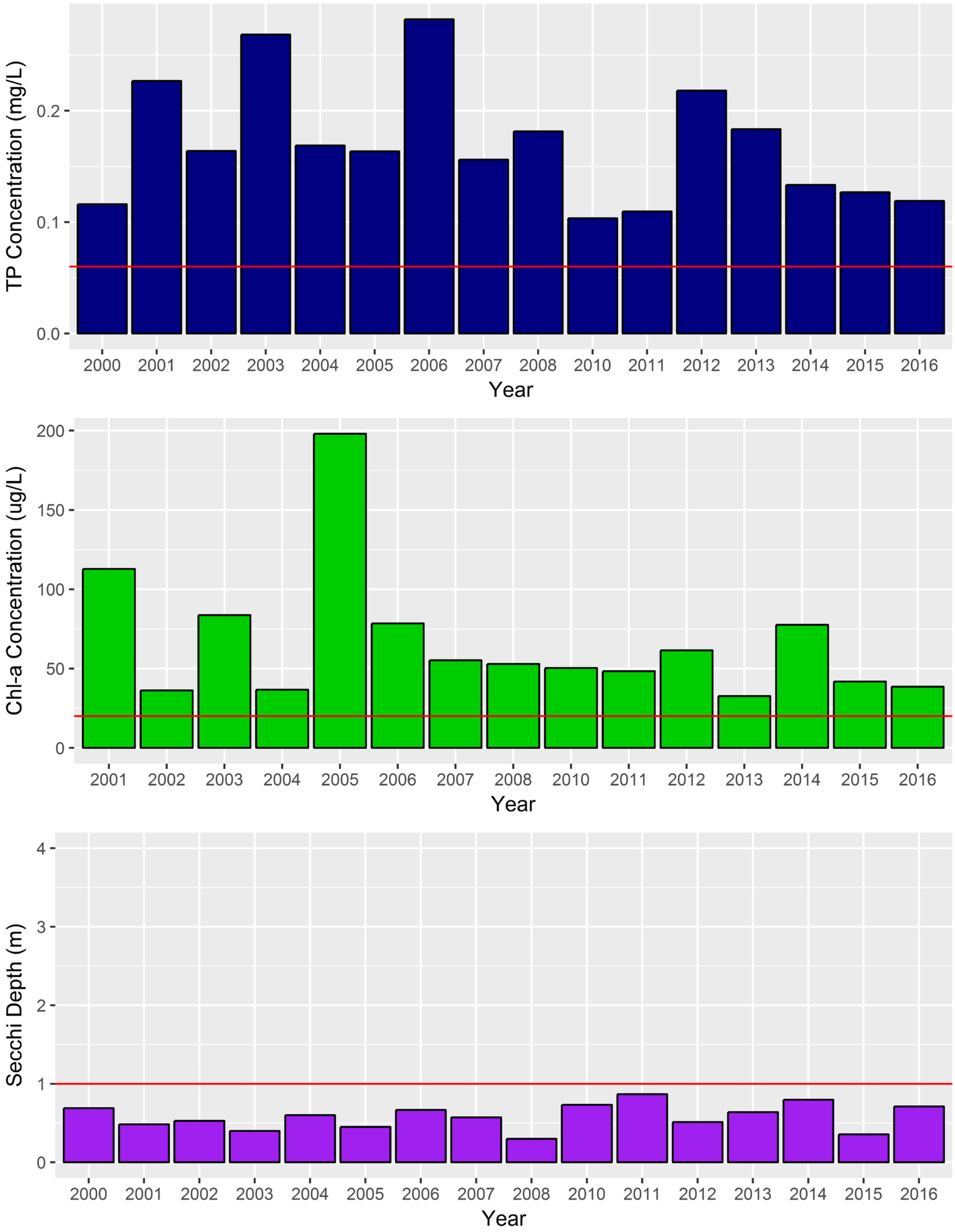


Figure A5: Powers Water Quality Time Series

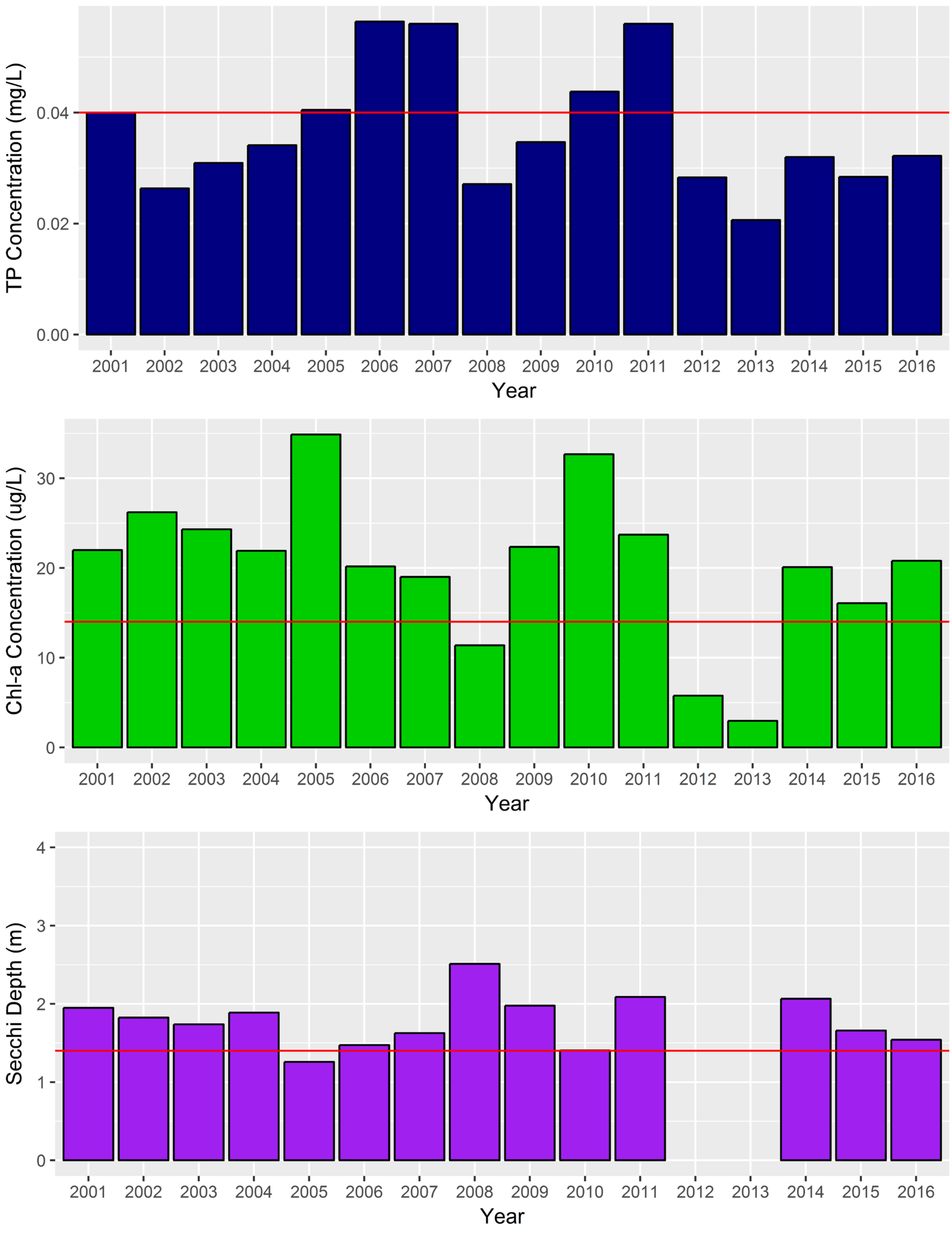


Figure A6: Ravine Water Quality Time Series

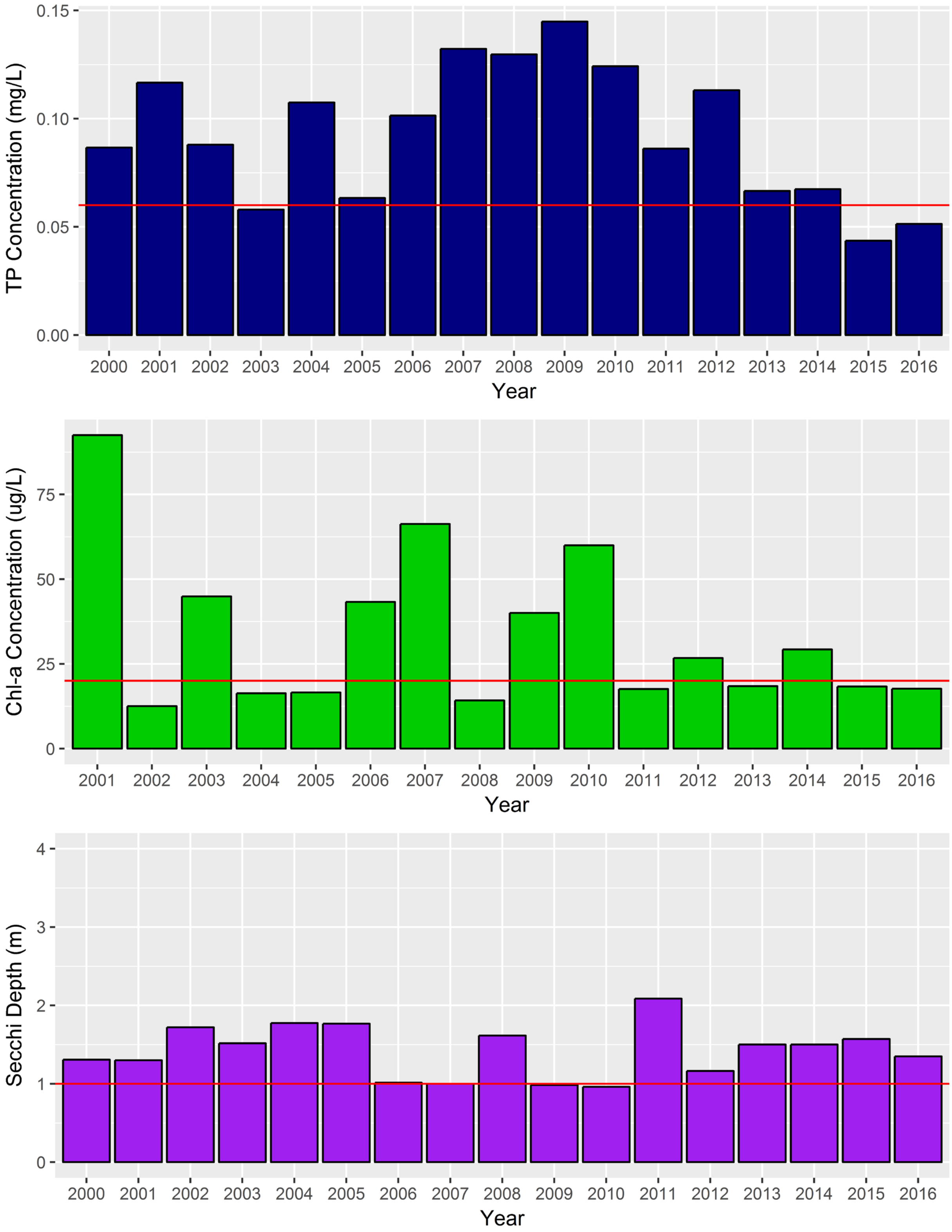


Figure A7: North Wilmes Water Quality Time Series

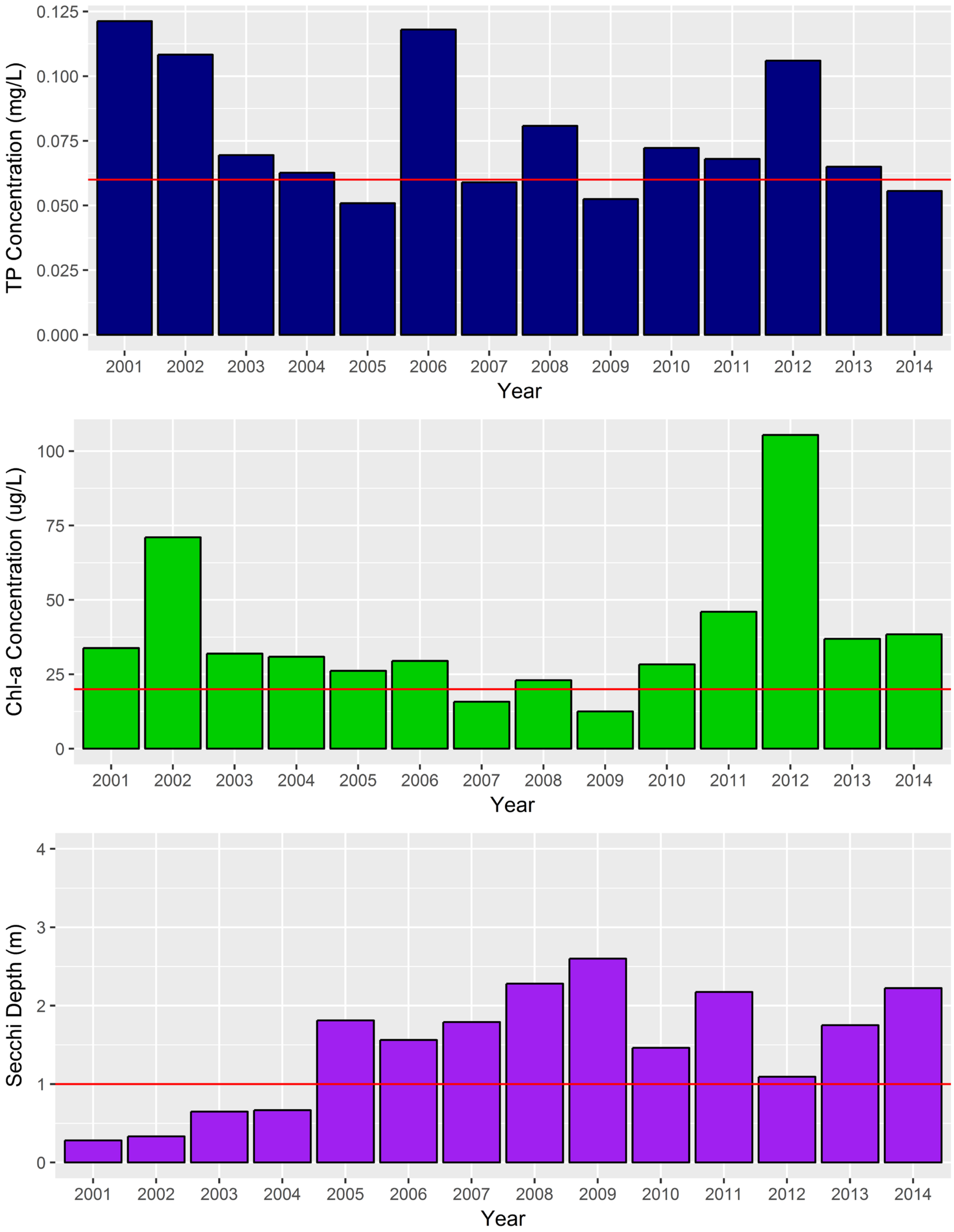
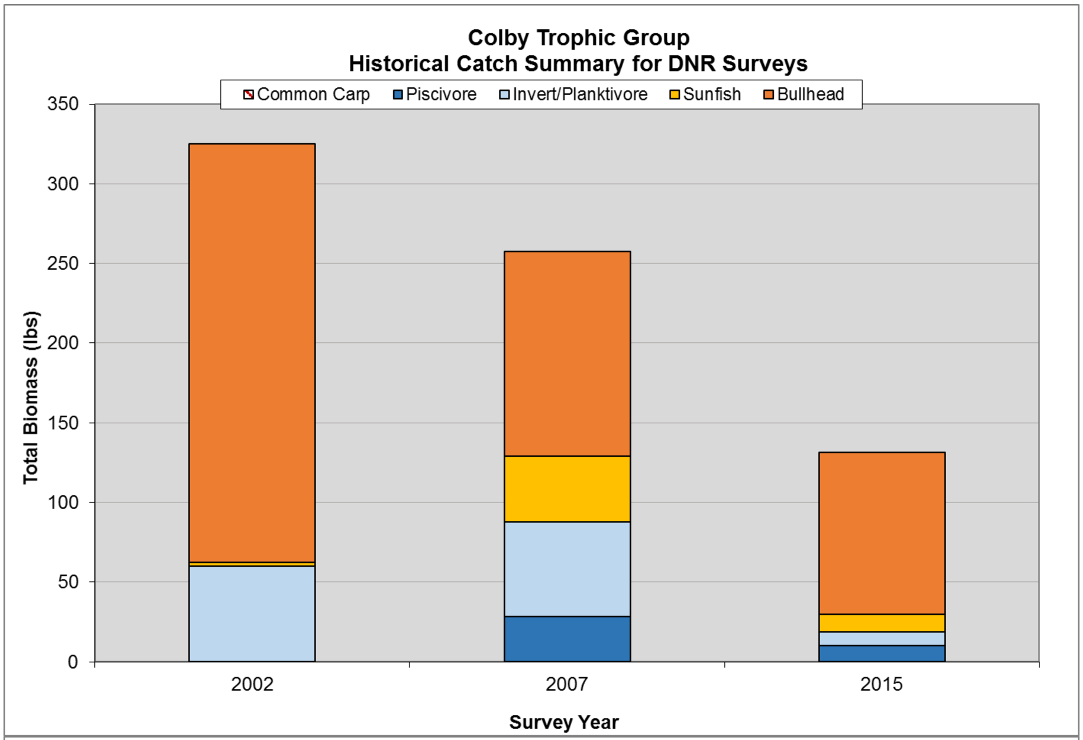
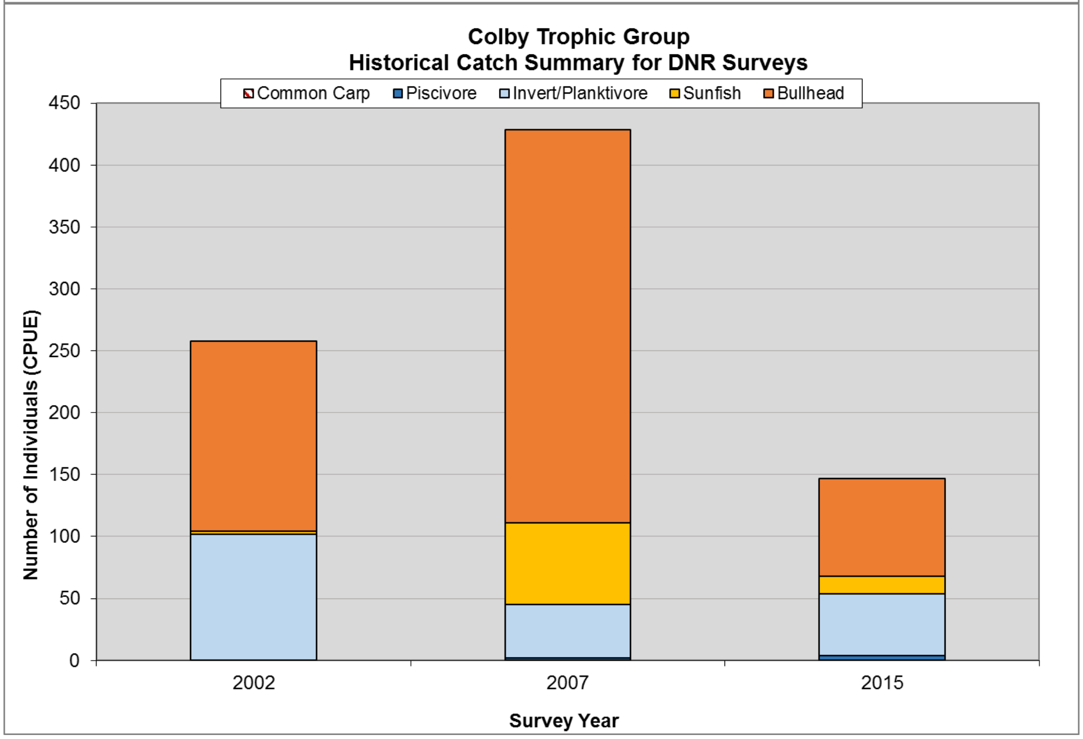
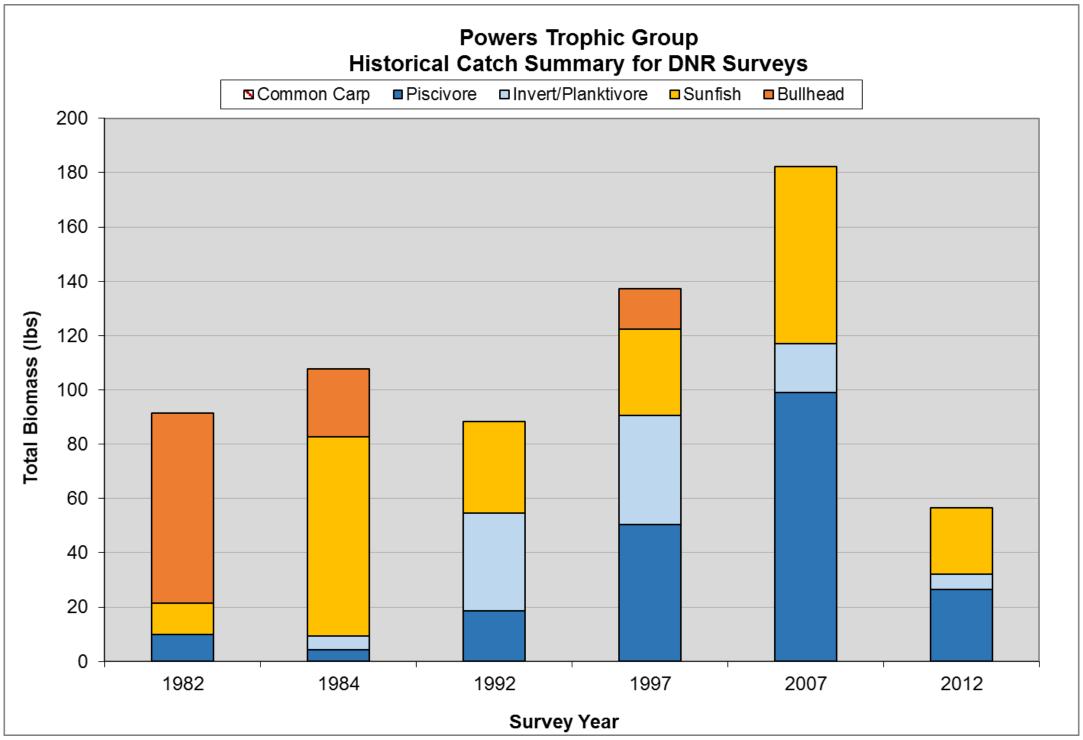
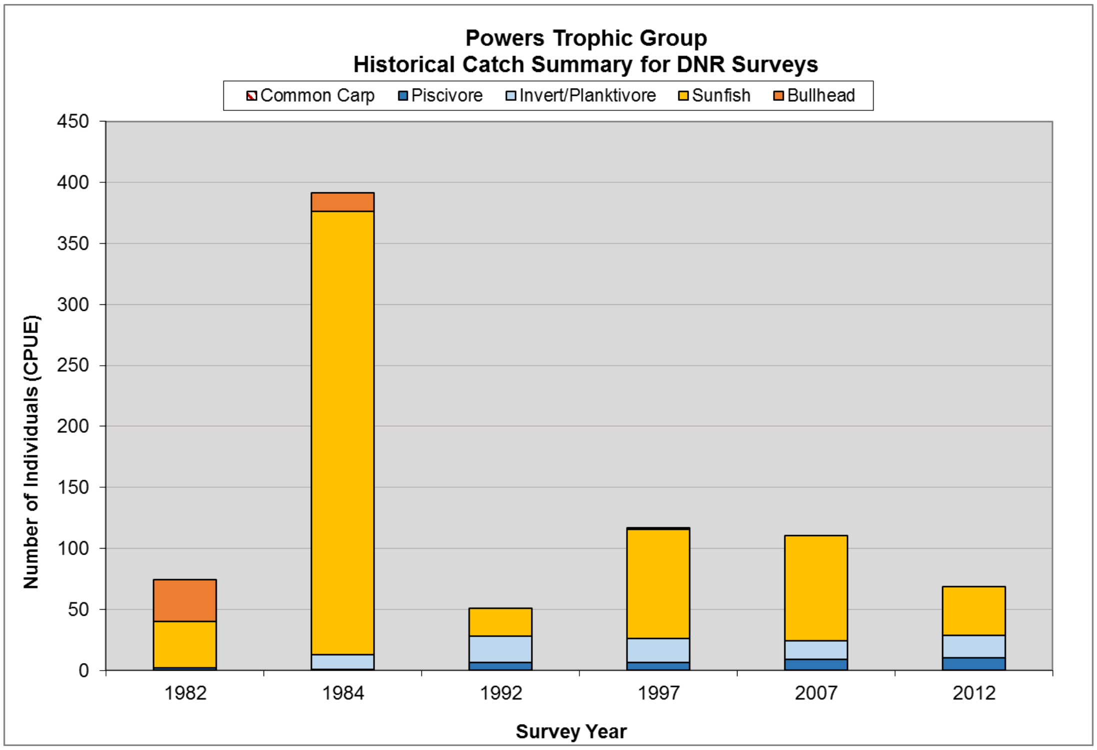


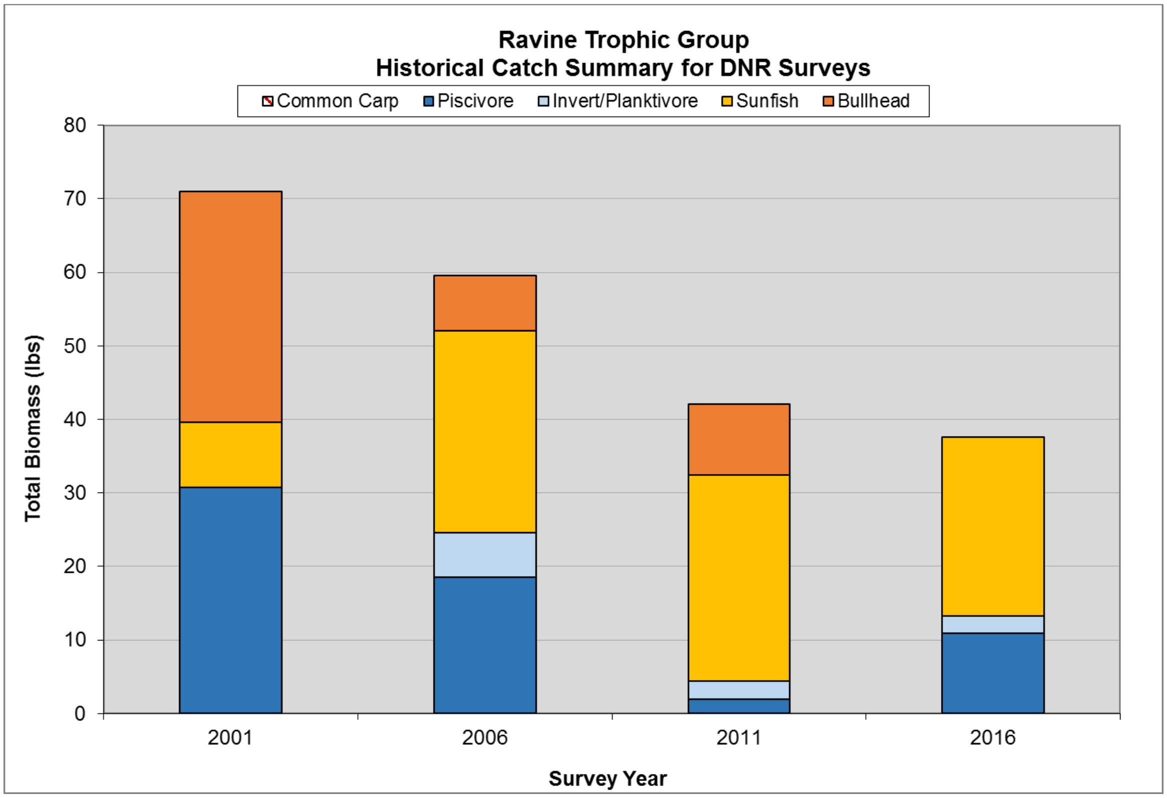
Figure A8: South Wilmes Water Quality Time Series

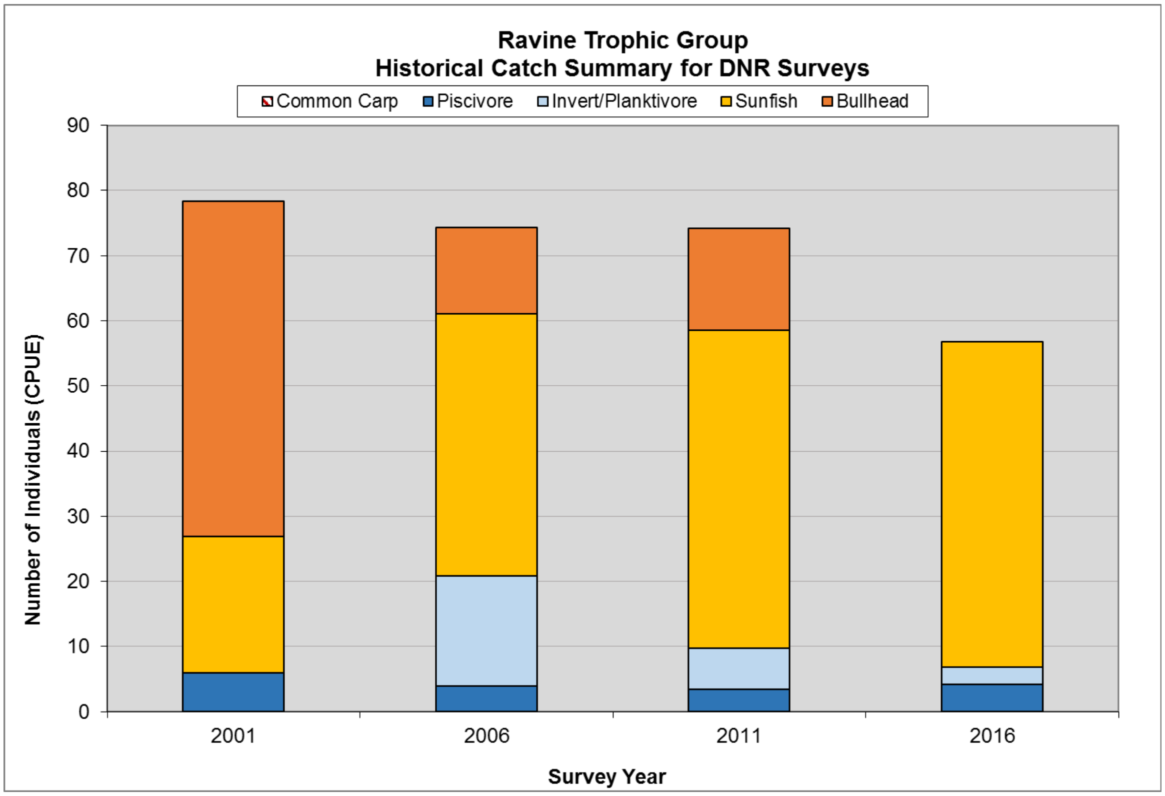

Colby Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Total Biomass (lbs)
350
300
250
200
150
100
50
0
2002
2007
2015
Survey Year


Colby Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Number of Individuals (CPUE)
450
400
350
300
250
200
150
100
50
0
2002
2007
2015
Survey Year


Powers Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Total Biomass (lbs)
0
20
40
60
80
100
120
140
160
180
200
1982
1984
1992
1997
2007
2012
Survey Year


Powers Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Number of Individuals (CPUE)
0
50
100
150
200
250
300
350
400
450
1982
1984
1992
1997
2007
2012
Survey Year

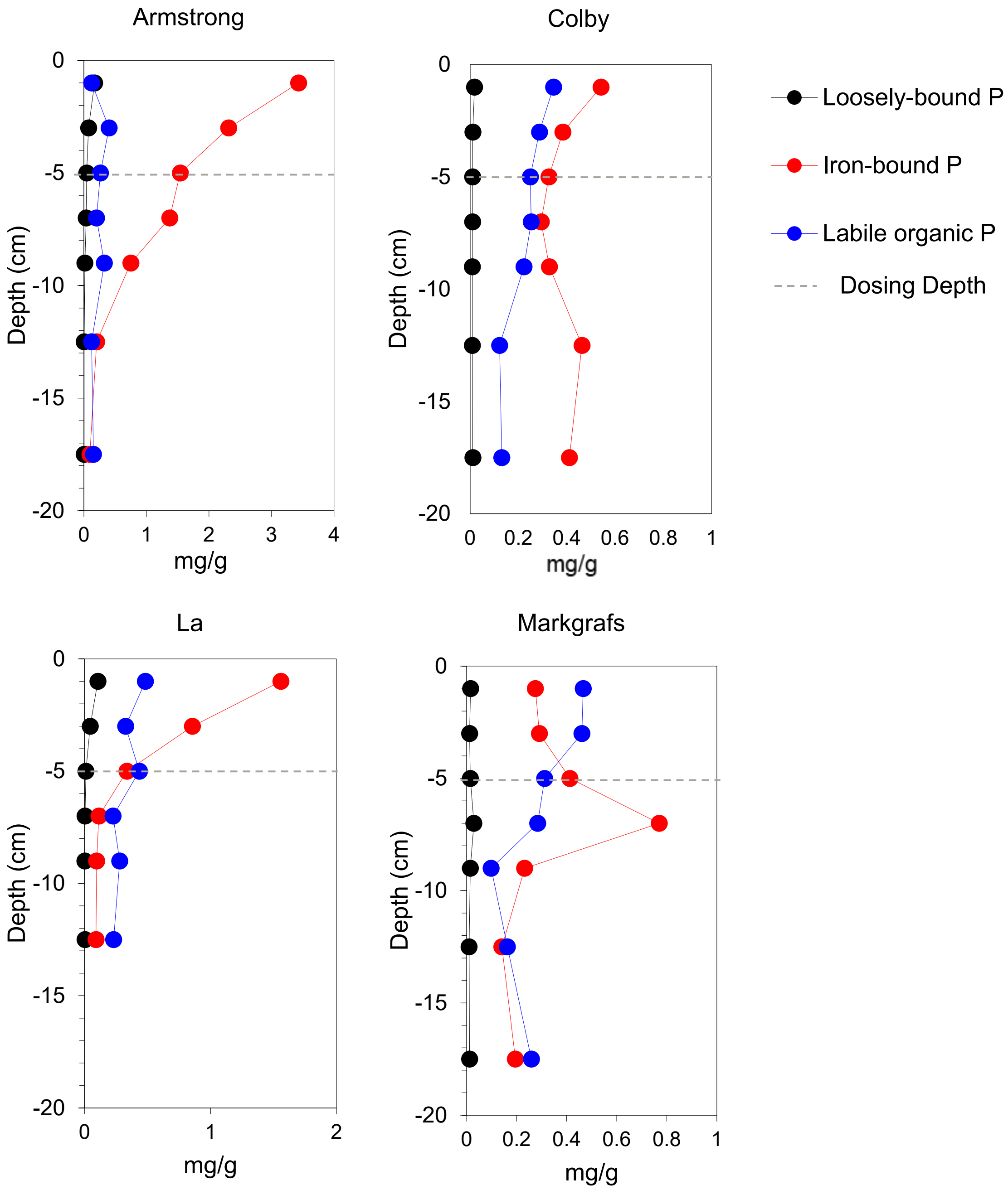

Ravine Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Total Biomass (lbs)
80
70
60
50
40
30
20
10
0
2001
2006
2011
2016
Survey Year


Ravine Trophic Group
Historical Catch Summary for DNR Surveys
Common Carp
Piscivore
Invert/Planktivore
Sunfish
Bullhead
Number of Individuals (CPUE)
90
80
70
60
50
40
30
20
10
0
2001
2006
2011
2016
Survey Year

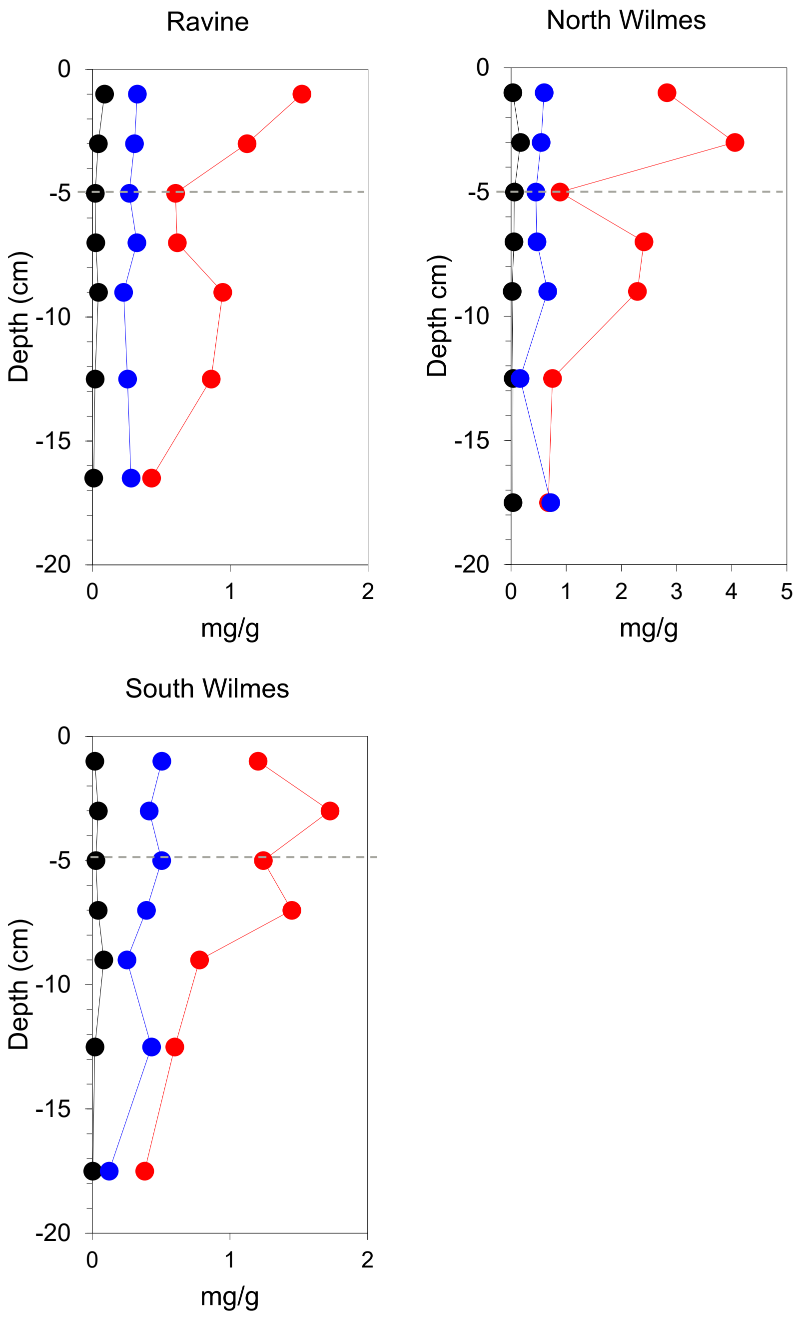
Appendix C

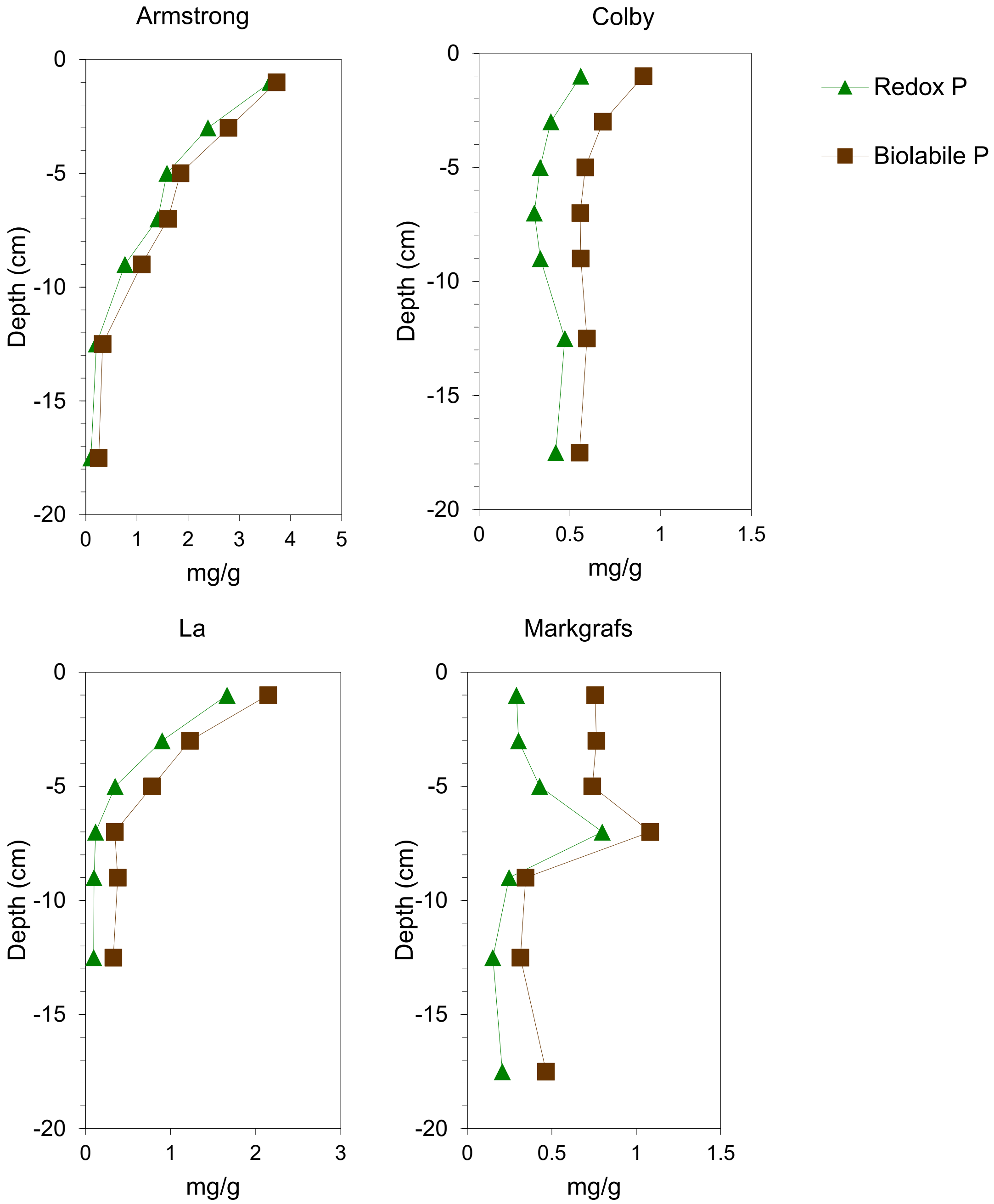
Watershed	P8 Parameter	Existing	Updated	Modified
Armstrong	TP Scale Factor	0.9	2.25	Yes
	Indirectly Connected/Directly Connected Ratio	50/50	45/55	Yes
Colby	TP Scale Factor	0.9	1.5	Yes
	Indirectly Connected/Directly Connected Ratio	50/50	50/50	No
Markgrafs	TP Scale Factor	0.9	0.9	No
	Indirectly Connected/Directly Connected Ratio	50/50	75/25	Yes
Powers	TP Scale Factor	1.1	0.89	Yes
	Indirectly Connected/Directly Connected Ratio	80/20	24/76	Yes
Ravine	TP Scale Factor	1	1	No
	Indirectly Connected/Directly Connected Ratio	30/70	30/70	No
Wilmes	TP Scale Factor	0.9	0.9	No
	Indirectly Connected/Directly Connected Ratio	50/50	75/25	Yes
La Lake	TP Scale Factor	NA	1	NA
	Indirectly Connected/Directly Connected Ratio	NA	100/0	NA

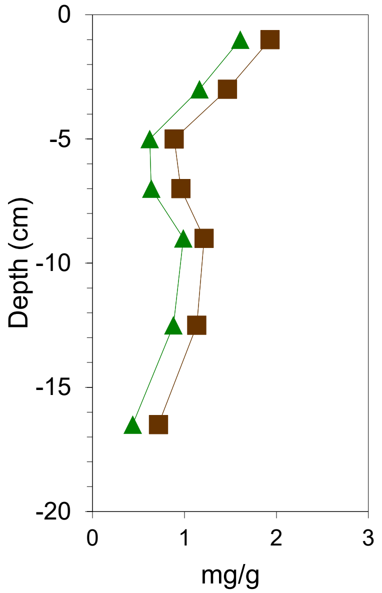
Appendix D

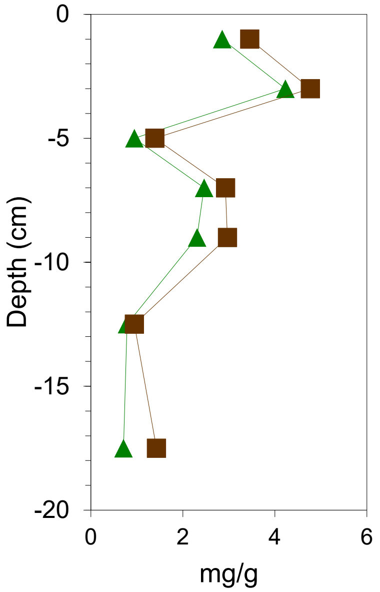


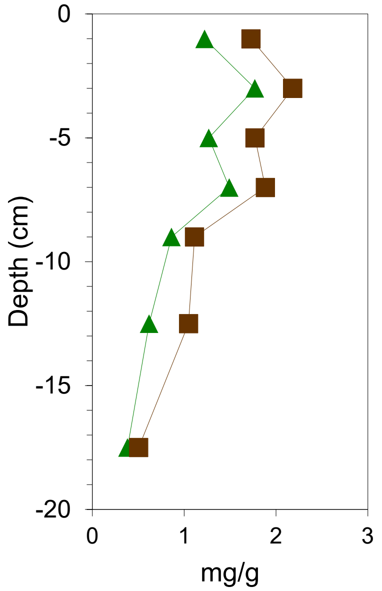
Armstrong
Colby
La
Markgrafs
Depth (cm)
0
-5
-10
-15
-20
mg/g
0
1
2
3
4
0
0.2
0.4
0.6
0.8
1
0
1
2
Loosely-bound P
Iron-bound P
Labile organic P
Dosing Depth

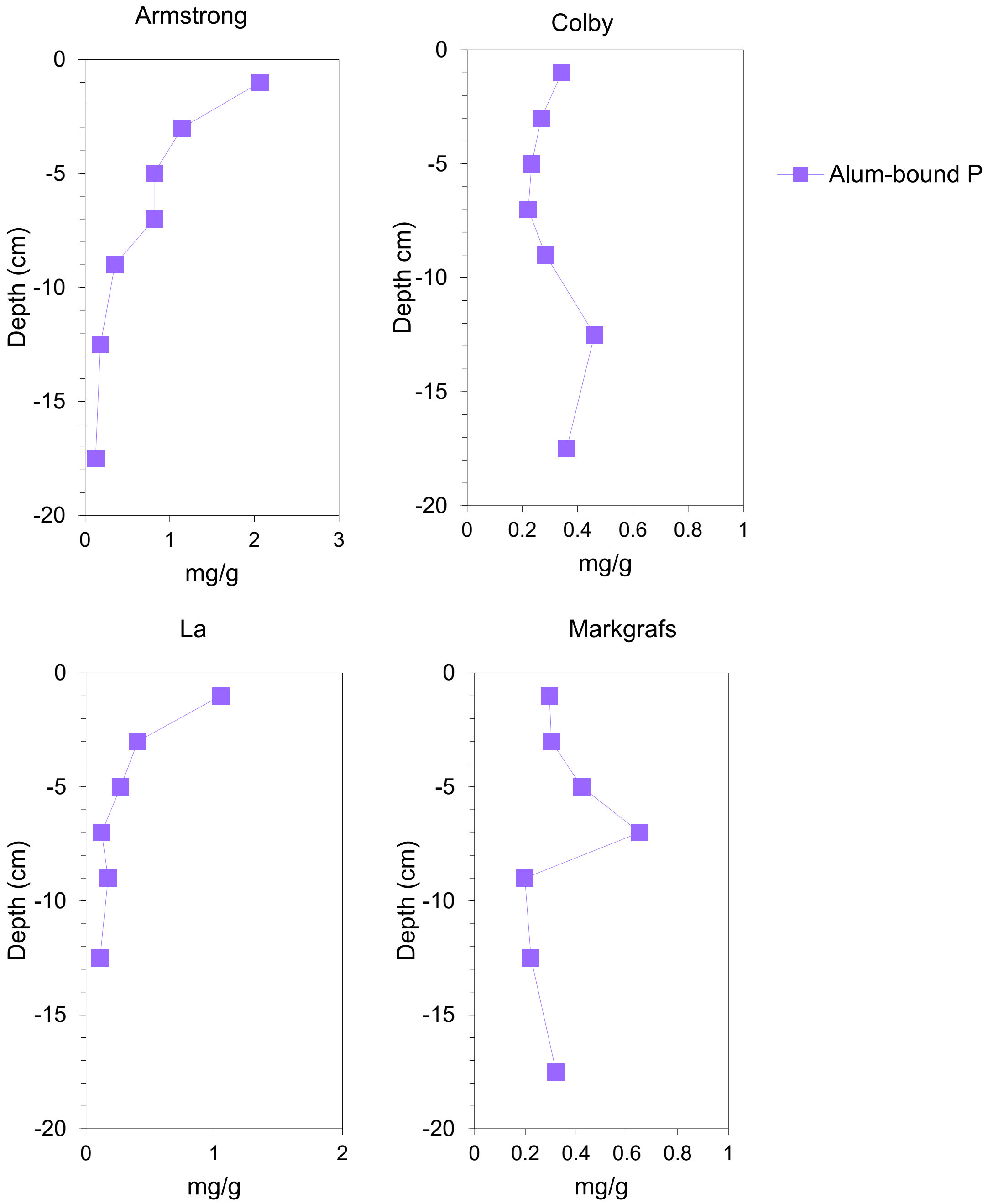

Ravine
North Wilmes
South Wilmes
Depth (cm)
Depth cm)
0
-5
-10
-15
-20
mg/g
0
1
2
3
4
5

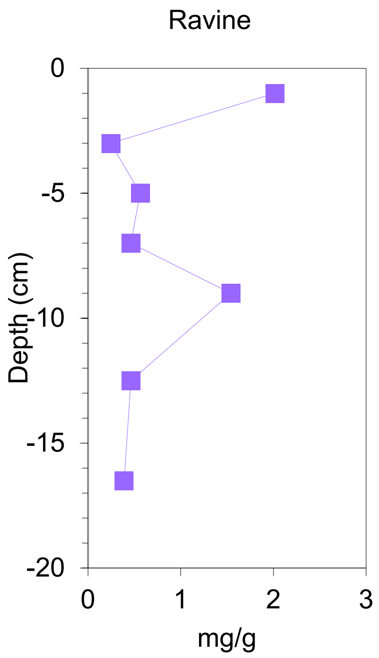

Armstrong
Colby
La
Markgrafs
Redox P
Biolabile P
Depth (cm)
mg/g
0
-5
-10
-15
-20
0
1
2
3
4
5
0
0.5
1
1.5
0
1
2
3

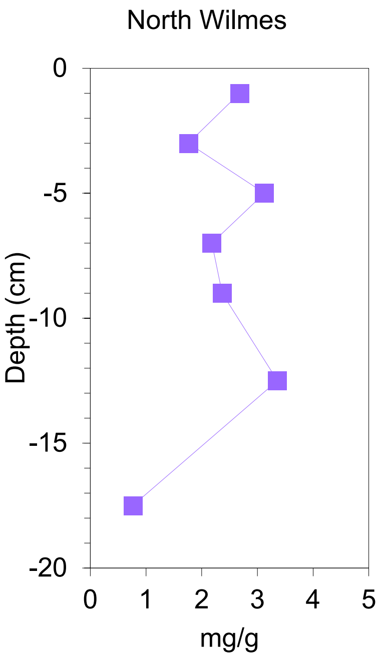

Ravine

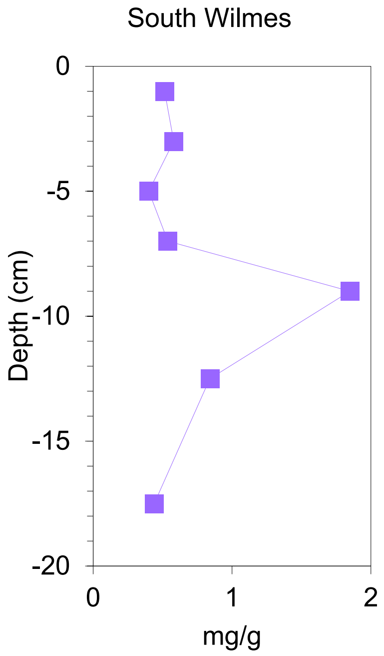

North Wilmes

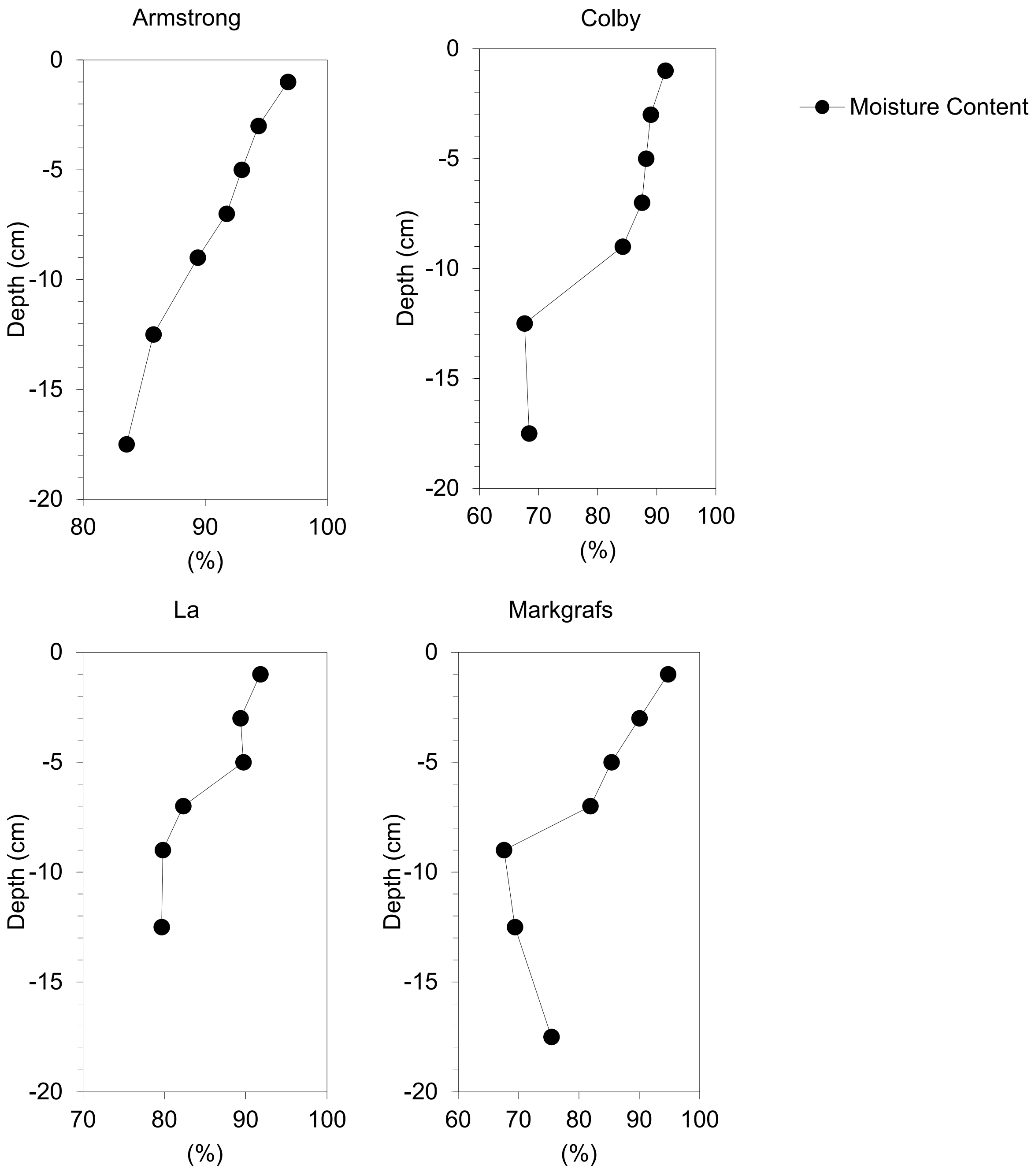

South Wilmes

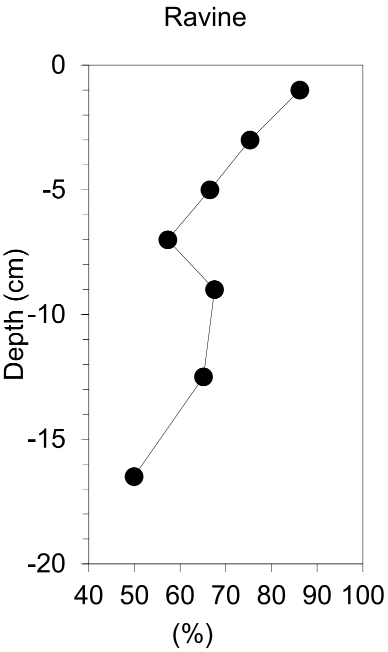

Armstrong
Colby
La
Markgrafs
Alum-bound P
Depth (cm)
0
-5
-10
-15
-20
mg/g
0
1
2
3
0
0.2
0.4
0.6
0.8
1
0
1
2

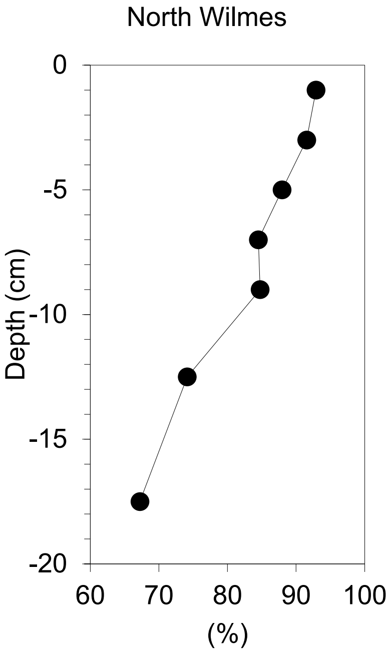

Ravine

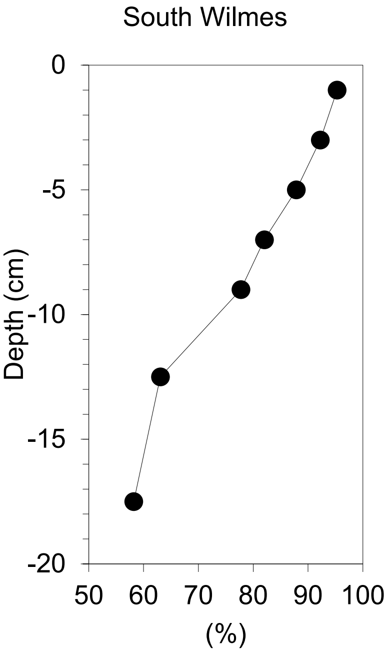

North Wilmes

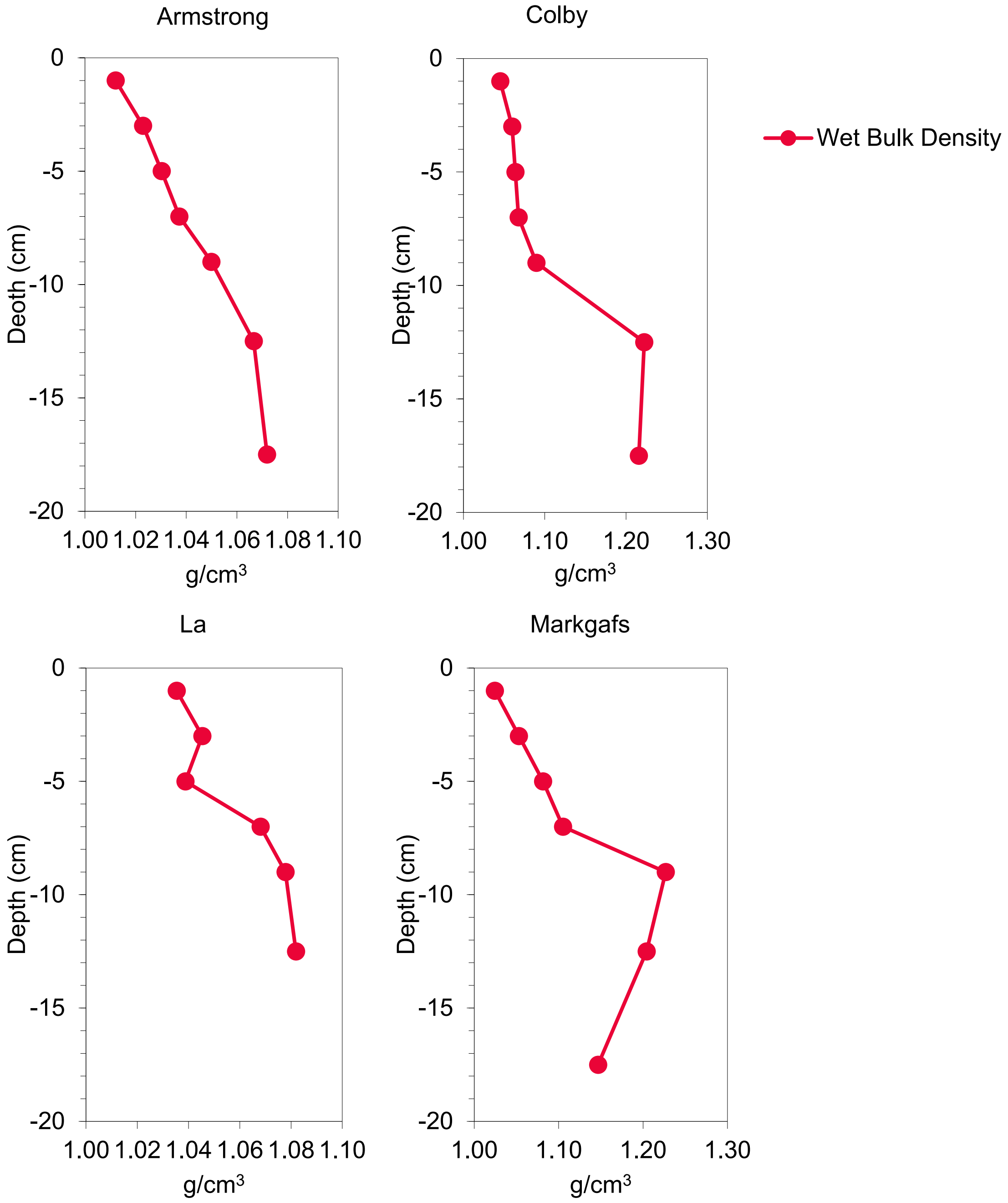

South Wilmes

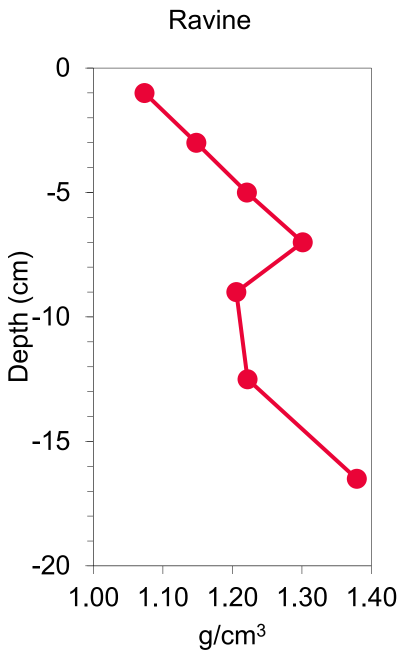

Armstrong
Colby
La
Markgrafs
Moisture Content
Depth (cm)
(%)
0
-5
-10
-15
-20
60
70
80
90
100


Ravine
Depth (cm)
0
-5
-10
-15
-20
40
50
60
70
80
90
100
(%)

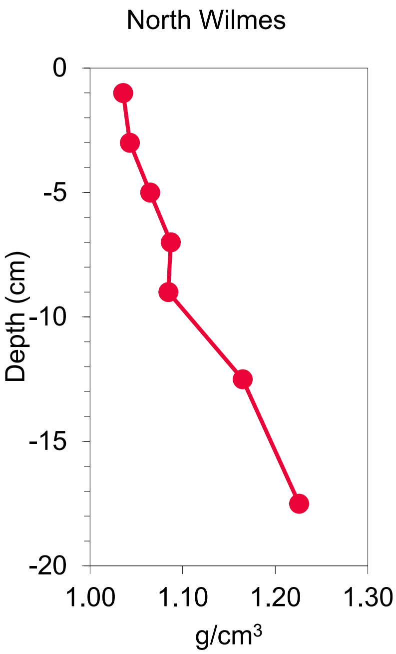

North Wilmes
Depth (cm)
0
-5
-10
-15
-20
60
70
80
90
100
(%)


South Wilmes
Depth (cm)
0
-5
-10
-15
-20
50
60
70
80
90
100
(%)

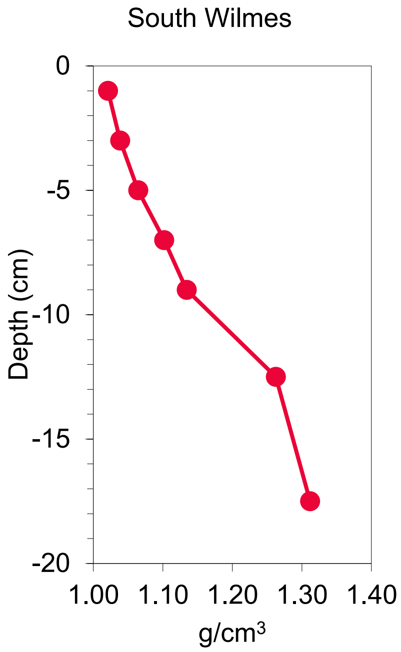

Armstrong
Colby
La
Markgafs
Wet Bulk Density
Depth (cm)
0
-5
-10
-15
-20
1.00
1.02
1.04
1.06
1.08
1.10
1.20
1.30
g/cm³



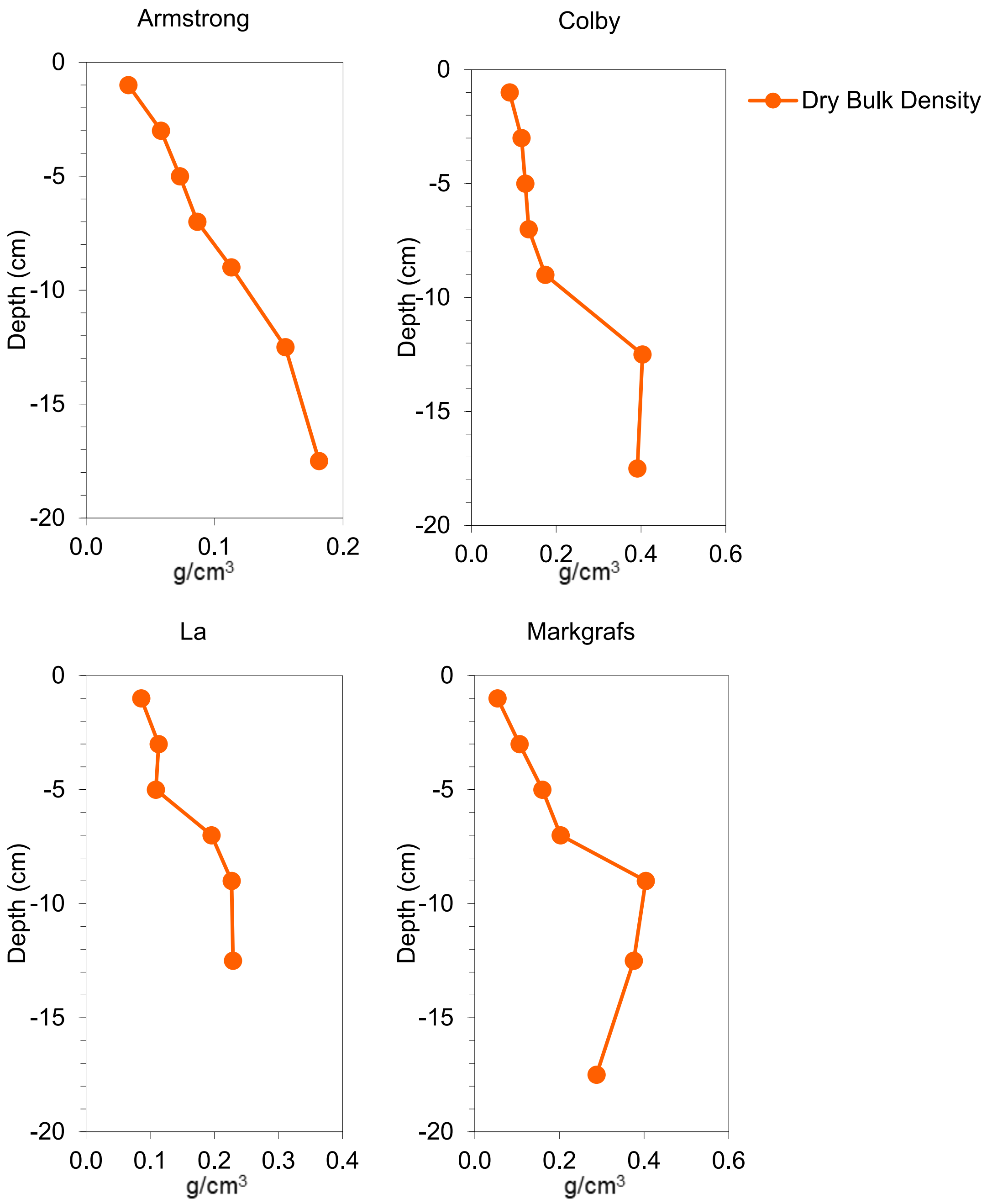
Ravine

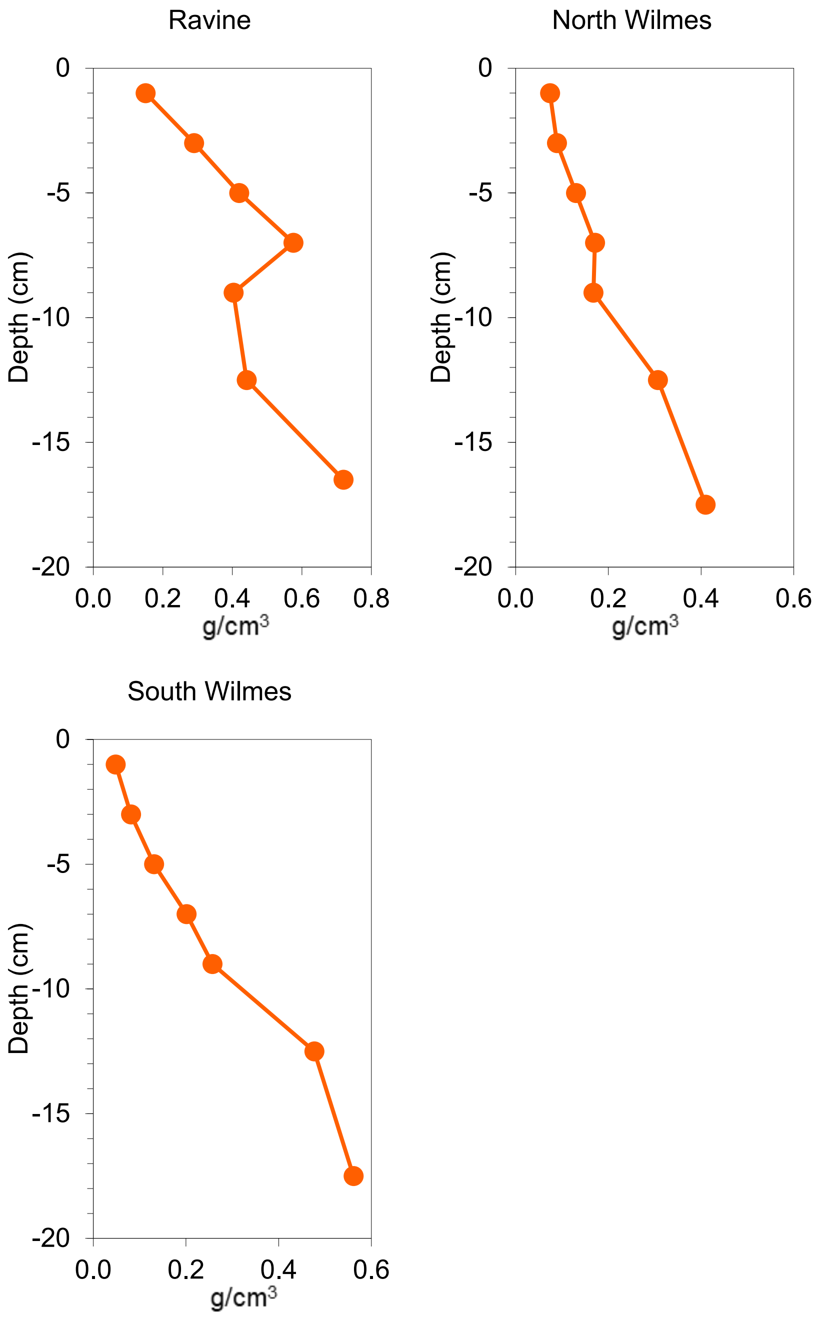


North Wilmes



South Wilmes


Armstrong
Colby
La
Markgrafs
Dry Bulk Density
Depth (cm)
0
-5
-10
-15
-20
g/cm³
0.0
0.1
0.2
0.3
0.4
0.6


Ravine
North Wilmes
South Wilmes
Depth (cm)
0
-5
-10
-15
-20
0.0
0.2
0.4
0.6
0.8
g/cm3

Appendix E

Average Loading Summary for Armstrong

Water Budgets | **Phosphorus Loading**

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		563	7.3	340	403	1.0	373
2						1.0	
3						1.0	
4						1.0	
5						1.0	
6						1.0	
	Summation	*563*	*7*	*340*			373.1

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
18	34.8	34.8	0.00	0.24	1.0	4.3
		Dry-year total P deposition =		0.222		
		Average-year total P deposition =		0.239		
		Wet-year total P deposition =		0.259		
		(Barr Engineering 2004)				

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
0.07			Oxic		1.0	0
0.07	50.1		Anoxic	1.7	1.0	14
Summation						14
	Net Discharge [ac-ft/yr] =		**340**	**Net Load [lb/yr] =**		**391**

Average Lake Response Modeling for Armstrong

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	6.80	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	177.3	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.04	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	422.5	[μg/l]
Model Predicted In-Lake [TP]			**70**	**[ug/l]**
Observed In-Lake [TP]			**70**	**[ug/l]**

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

Average Loading Summary for Armstrong

Water Budgets | **Phosphorus Loading**

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		563	7.3	340	313	1.0	290
2						1.0	
3						1.0	
4						1.0	
5						1.0	
6						1.0	
	Summation	*563*	*7*	*340*			290.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
18	34.8	34.8	0.00	0.24	1.0	4.3
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
0.07			Oxic		1.0	0
0.07	50.1		Anoxic	1.7	1.0	8
Summation						8
		Net Discharge [ac-ft/yr] =	**340**		**Net Load [lb/yr] =**	**302**

Average Lake Response Modeling for Armstrong

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	6.80	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	137.1	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.04	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	326.7	[µg/l]
Model Predicted In-Lake [TP]			**60**	**[ug/l]**

Average Loading Summary for Colby

Water Budgets				Phosphorus Loading		

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^{1} [--]	Load [lb/yr]
1		2,924	7.2	1,751	235	1.0	1,118
2							
3							
4							
5							
6							
	Summation	*2,924*	*7*	*1,751*			1118.4

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^{1} [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		Drainage Area [acre]	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	S Wilmese		4,016	2,517	73.0	1.0	500
2					-	1.0	
3					-	1.0	
	Summation			*2,517*	*73.0*		*500*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
69	34.8	34.8	0.00	0.24	1.0	16.4
	Dry-year total P deposition =			0.222		
	Average-year total P deposition =			0.239		
	Wet-year total P deposition =			0.259		
	(Barr Engineering 2004)					

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
					1.0	
0.28	65.0		Anoxic	10.7	1.0	427
Summation						427
		Net Discharge [ac-ft/yr] =	**4,268**		Net Load [lb/yr] =	**2,061**

Average Lake Response Modeling for Colby

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.30	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	935.1	[kg/yr]
		Q (lake outflow) =	5.3	[10^6 m^3/yr]
		V (modeled lake volume) =	0.5	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	177.5	[µg/l]
Model Predicted In-Lake [TP]			**156**	**[ug/l]**
Observed In-Lake [TP]			**156**	**[ug/l]**

Average Loading Summary for Colby

Water Budgets				Phosphorus Loading		

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		2,924	7.2	1,751	63	1.0	300
2							
3							
4							
5							
6							
	Summation	*2,924*	*7*	*1,751*			300.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		Drainage Area [acre]	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	S Wilmese		4,016	2,517	58.7	1.0	402
2					-	1.0	
3					-	1.0	
	Summation			*2,517*	*58.7*		*402*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
69	34.8	34.8	0.00	0.24	1.0	16.4
	Dry-year total P deposition =			0.222		
	Average-year total P deposition =			0.239		
	Wet-year total P deposition =			0.259		
	(Barr Engineering 2004)					

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
					1.0	
0.28	65.0		Anoxic	1.0	1.0	40
Summation						40
		Net Discharge [ac-ft/yr] =	**4,268**		Net Load [lb/yr] =	**758**

Average Lake Response Modeling for Colby

TOTAL IN-LAKE PHOSPHORUS CONCENTRATION

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

Modeled Parameter	Equation	Parameters	Value	[Units]
		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.30	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	344.0	[kg/yr]
		Q (lake outflow) =	5.3	[10^6 m^3/yr]
		V (modeled lake volume) =	0.5	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	65.3	[µg/l]
Model Predicted In-Lake [TP]			**60.0**	**[ug/l]**

Average Loading Summary for La

Water Budgets				Phosphorus Loading		

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		64	1.9	10	199	1.0	6
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*64*	*2*	*10*			5.5

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

	Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
	52	34.8	34.8	0.00	0.24	1.0	12.3
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					

Groundwater

	Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
	0	0.0		0.00	0	1.0	0

Internal

	Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
				Oxic		1.0	
	0.21	54.5		Anoxic	1.7	1.0	42
	Summation						42
			Net Discharge [ac-ft/yr] =	**10**		**Net Load [lb/yr] =**	**60**

Average Lake Response Modeling for La

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = P_i \bigg/ \left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	1.12	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	27.4	[kg/yr]
		Q (lake outflow) =	0.0	[10^6 m^3/yr]
		V (modeled lake volume) =	0.3	[10^6 m^3]
		T = V/Q =	20.0	[yr]
		P_i = W/Q =	2185.8	[µg/l]
Model Predicted In-Lake [TP]			**68**	**[ug/l]**
Observed In-Lake [TP]			**68**	**[ug/l]**

Average Loading Summary for La

Water Budgets	Phosphorus Loading

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		64	1.9	10	199	1.0	6
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*64*	*2*	*10*			5.5

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
52	34.8	34.8	0.00	0.24	1.0	12.3
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
			Oxic		1.0	
0.21	54.5		Anoxic	1.0	1.0	25
Summation						25
		Net Discharge [ac-ft/yr] =	**10**		**Net Load [lb/yr] =**	**43**

Average Lake Response Modeling for La

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				

$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$

as f(W,Q,V) from Canfield & Bachmann (1981)

Parameters	Value	[Units]
C_P =	1.12	[--]
C_{CB} =	0.2	[--]
b =	0.5	[--]
W (total P load = inflow + atm.) =	19.5	[kg/yr]
Q (lake outflow) =	0.0	[10^6 m^3/yr]
V (modeled lake volume) =	0.3	[10^6 m^3]
T = V/Q =	20.0	[yr]
P_i = W/Q =	1557.5	[µg/l]
Model Predicted In-Lake [TP]	**56**	**[ug/l]**

Average Loading Summary for Markgrafs

Water Budgets				Phosphorus Loading			

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1	0	425	10.2	362	181	1.0	178
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*425*	*10*	*362*			177.8

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
47	34.8	34.8	0.00	0.24	1.0	11.2
		Dry-year total P deposition =		0.222		
		Average-year total P deposition =		0.239		
		Wet-year total P deposition =		0.259		
		(Barr Engineering 2004)				

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
			Oxic		1.0	
0.19	65.3		Anoxic	5.1	1.0	141
Summation						141
		Net Discharge [ac-ft/yr] =	**362**		**Net Load [lb/yr] =**	**330**

Average Lake Response Modeling for Markgrafs

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = P_i \Big/ \left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)$		as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.97	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	149.6	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.3	[10^6 m^3]
		T = V/Q =	0.6	[yr]
		P_i = W/Q =	334.8	[µg/l]
Model Predicted In-Lake [TP]			**125.5**	**[ug/l]**
Observed In-Lake [TP]			**125.4**	**[ug/l]**

Average Loading Summary for Markgrafs

Water Budgets	Phosphorus Loading

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1	0	425	10.2	362	83	1.0	82
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*425*	*10*	*362*			82.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

	Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
	47	34.8	34.8	0.00	0.24	1.0	11.2
				Dry-year total P deposition =	0.222		
				Average-year total P deposition =	0.239		
				Wet-year total P deposition =	0.259		
				(Barr Engineering 2004)			

Groundwater

	Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
	0	0.0		0.00	0	1.0	0

Internal

	Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
				Oxic		1.0	
	0.19	65.3		Anoxic	1.0	1.0	27
	Summation						27
			Net Discharge [ac-ft/yr] =	**362**		**Net Load [lb/yr] =**	**121**

Average Lake Response Modeling for Markgrafs

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	0.97	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	54.7	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.3	[10^6 m^3]
		T = V/Q =	0.6	[yr]
		P_i = W/Q =	122.5	[µg/l]
Model Predicted In-Lake [TP]			**60**	**[ug/l]**

Average Loading Summary for Powers

Water Budgets	**Phosphorus Loading**

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		1,257	16.4	1,721	140	1.0	657
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*1,257*	*16*	*1,721*			656.8

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1						1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
62	34.8	34.8	0.00	0.24	1.0	14.9
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
			Oxic		1.0	
0.25	63.8		Anoxic	5.1	1.0	181
Summation						181
		Net Discharge [ac-ft/yr] =	**1,721**		**Net Load [lb/yr] =**	**853**

Average Lake Response Modeling for Powers

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	3.90	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	386.8	[kg/yr]
		Q (lake outflow) =	2.1	[10^6 m^3/yr]
		V (modeled lake volume) =	1.4	[10^6 m^3]
		T = V/Q =	0.6	[yr]
		P_i = W/Q =	182.1	[µg/l]
Model Predicted In-Lake [TP]			**28**	**[ug/l]**
Observed In-Lake [TP]			**28**	**[ug/l]**

*no targets bc not impaired

Average Loading Summary for Ravine

Water Budgets					Phosphorus Loading		

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		2,191	1.7	319	278.141	1.0	241
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*2,191*	*2*	*319*			241.1

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

	Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
	27	34.8	34.8	0.00	0.24	1.0	6.4
		Dry-year total P deposition =			0.222		
		Average-year total P deposition =			0.239		
		Wet-year total P deposition =			0.259		
		(Barr Engineering 2004)					

Groundwater

	Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
	0	0.0		0.00	0	1.0	0

Internal

	Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
				Oxic		1.0	0
	0.11	52.6		Anoxic	12.3	1.0	154
	Summation						154
		Net Discharge [ac-ft/yr] =		**319**	**Net Load [lb/yr] =**		**401**

Average Lake Response Modeling for Ravine

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	as f(W,Q,V) from Canfield & Bachmann (1981)			
$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$		C_P =	3.00	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	182.0	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.433732	[yr]
		P_i = W/Q =	463.0	[μg/l]
Model Predicted In-Lake [TP]			**75.4**	**[ug/l]**
Observed In-Lake [TP]			**75.5**	**[ug/l]**

Average Loading Summary for Ravine

Inflow from Drainage Areas

	Water Budgets				Phosphorus Loading		
	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		2,191	1.7	319	278.141	1.0	241
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*2,191*	*2*	*319*			241.1

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name			Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1					-	1.0	
2					-	1.0	
3					-	1.0	
	Summation			*0*	-		*0*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
27	34.8	34.8	0.00	0.24	1.0	6.4
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
			Oxic		1.0	0
0.11	52.6		Anoxic	12.3	1.0	13
Summation						13
		Net Discharge [ac-ft/yr] =	**319**		Net Load [lb/yr] =	**260**

Average Lake Response Modeling for Ravine

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	as f(W,Q,V) from Canfield & Bachmann (1981)			
		C_P =	3.00	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	117.9	[kg/yr]
		Q (lake outflow) =	0.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.433732	[yr]
		P_i = W/Q =	300.0	[µg/l]
Model Predicted In-Lake [TP]			**58**	**[ug/l]**

$$P = P_i \Big/ \left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)$$

Average Loading Summary for N. Wilmes

Water Budgets	Phosphorus Loading

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1		2,413	7.8	1,570	194	1.0	828
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*2,413*	*8*	*1,570*			828.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)[1] [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		Drainage Area [acre]	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	Armstrong		563	340	70.0	1.0	65
2					-	1.0	
3					-	1.0	
	Summation			*340*	*70.0*		*65*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
19	34.8	34.8	0.00	0.24	1.0	4.5
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
0.08			Oxic		1.0	
0.08	55.1		Anoxic	12.0	1.0	112
Summation						112
		Net Discharge [ac-ft/yr] =	**1,910**		**Net Load [lb/yr] =**	**1,009**

Average Lake Response Modeling for N. Wilmes

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	3.80	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	457.8	[kg/yr]
		Q (lake outflow) =	2.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	194.3	[μg/l]
Model Predicted In-Lake [TP]			**75**	**[ug/l]**
Observed In-Lake [TP]			**75**	**[ug/l]**

Average Loading Summary for N. Wilmes

Water Budgets	Phosphorus Loading

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		2,413	7.8	1,570	158	1.0	675
2						1.0	0
3						1.0	0
4						1.0	0
5						1.0	0
6						1.0	0
	Summation	*2,413*	*8*	*1,570*			675.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							0
2							0
3							0
4							0
5							0
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		Drainage Area [acre]	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	Armstrong		563	340	59.7	1.0	55
2					-	1.0	
3					-	1.0	
	Summation			*340*	*59.7*		*55*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
19	34.8	34.8	0.00	0.24	1.0	4.5
			Dry-year total P deposition =	0.222		
			Average-year total P deposition =	0.239		
			Wet-year total P deposition =	0.259		
			(Barr Engineering 2004)			

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
0	0.0		0.00	0	1.0	0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
0.08			Oxic		1.0	
0.08	55.1		Anoxic	1.0	1.0	9
Summation						9
		Net Discharge [ac-ft/yr] =	**1,910**		**Net Load [lb/yr] =**	**744**

Average Lake Response Modeling for N. Wilmes

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = P_i \Big/ \left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	3.80	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	337.5	[kg/yr]
		Q (lake outflow) =	2.4	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	143.2	[µg/l]
Model Predicted In-Lake [TP]			**60.0**	**[ug/l]**

Average Loading Summary for S. Wilmes

Water Budgets	Phosphorus Loading

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		615	4.8	245	162	1.0	108
2							
3							
4							
5							
6							
	Summation	*615*	*5*	*245*			107.7

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							
2							
3							
4							
5							
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		drainage area	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	Nwilmes		2,976	1,910	74.9	1.0	389
2	Markgrafs		425	362	125.5	1.0	124
3					-	1.0	
	Summation			*2,272*	*100.2*		*513*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
19	34.8	34.8	0.00	0.24	1.0	4.6

Dry-year total P deposition = 0.222

Average-year total P deposition = 0.239

Wet-year total P deposition = 0.259

(Barr Engineering 2004)

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
			0.00			0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
						0
0.08	53.2		Anoxic	12.9	1.0	125
Summation						125

Net Discharge [ac-ft/yr] = 2,517 **Net Load [lb/yr] = 750**

Average Lake Response Modeling for S. Wilmes

Modeled Parameter	Equation	Parameters	Value	[Units]
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$$P = \frac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\frac{W_P}{V}\right)^b \times T\right)}$$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	1.60	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	340.2	[kg/yr]
		Q (lake outflow) =	3.1	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	109.5	[µg/l]
Model Predicted In-Lake [TP]			**73**	**[ug/l]**
Observed In-Lake [TP]			**73**	**[ug/l]**

Average Loading Summary for S. Wilmes

Water Budgets | **Phosphorus Loading**

Inflow from Drainage Areas

	Name	Drainage Area [acre]	Runoff Depth [in/yr]	Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1		615	4.8	245	122	1.0	81
2							
3							
4							
5							
6							
	Summation	*615*	*5*	*245*			81.0

Point Source Dischargers

	Name			Discharge [ac-ft/yr]	Phosphorus Concentration [ug/L]	Loading Calibration Factor (CF)^1 [--]	Load [lb/yr]
1							
2							
3							
4							
5							
	Summation			*0*			*0.0*

Failing Septic Systems

	Name	Total Systems	Failing Systems	Discharge [ac-ft/yr]	Failure [%]		Load [lb/yr]
1							
2							
3							
4							
5							
	Summation	*0*	*0*	*0.0*			*0.0*

Inflow from Upstream Lakes

	Name		drainage area	Discharge [ac-ft/yr]	Estimated P Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
1	Nwilmes		2,976	1,910	60.0	1.0	373
2	Markgrafs		425	362	59.7	1.0	59
3					-	1.0	
	Summation			*2,272*	*59.8*		*432*

Atmosphere

Lake Area [acre]	Precipitation [in/yr]	Evaporation [in/yr]	Net Inflow [ac-ft/yr]	Aerial Loading Rate [lb/ac-yr]	Calibration Factor [--]	Load [lb/yr]
19	34.8	34.8	0.00	0.24	1.0	4.6
		Dry-year total P deposition =		0.222		
		Average-year total P deposition =		0.239		
		Wet-year total P deposition =		0.259		
		(Barr Engineering 2004)				

Groundwater

Lake Area [acre]	Groundwater Flux [m/yr]		Net Inflow [ac-ft/yr]	Phosphorus Concentration [ug/L]	Calibration Factor [--]	Load [lb/yr]
			0.00			0

Internal

Lake Area [km^2]	Anoxic Factor [days]			Release Rate [mg/m^2-day]	Calibration Factor [--]	Load [lb/yr]
						0
0.08	53.2		Anoxic	12.9	1.0	125
Summation						125
	Net Discharge [ac-ft/yr] =		**2,517**	**Net Load [lb/yr] =**		**642**

Average Lake Response Modeling for S. Wilmes

Modeled Parameter	**Equation**	**Parameters**	**Value**	**[Units]**
TOTAL IN-LAKE PHOSPHORUS CONCENTRATION				
	$P = \dfrac{P_i}{\left(1 + C_P \times C_{CB} \times \left(\dfrac{W_P}{V}\right)^b \times T\right)}$	as f(W,Q,V) from Canfield & Bachmann (1981)		
		C_P =	1.60	[--]
		C_{CB} =	0.2	[--]
		b =	0.5	[--]
		W (total P load = inflow + atm.) =	263.6	[kg/yr]
		Q (lake outflow) =	3.1	[10^6 m^3/yr]
		V (modeled lake volume) =	0.2	[10^6 m^3]
		T = V/Q =	0.1	[yr]
		P_i = W/Q =	84.9	[µg/l]
Model Predicted In-Lake [TP]			**59**	**[ug/l]**

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