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Wenck File #0094-29

March 2014

Duck and Red Rock Lake Watersheds Basin Inventory and Maintenance Assessment

Prepared for:

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Table of Contents

Table of Contents (Cont.)

Table of Contents (Cont.)

APPENDICES

TABLES

Table of Contents (Cont.)

FIGURES

Table of Contents (Cont.)

Acronyms

AF	Acre-feet
BMP	Best Management Practice
BWSR	Board of Water and Soil Resources
DNR	Department of Natural Resources
EPA	Environmental Protection Agency
GIS	Geographical Information System
HUC	Hydrologic Unit Code: 8-digit HUC fourth-level (cataloguing unit)
MDH	Minnesota Department of Health
MnDOT	Minnesota Department of Transportation
MPCA	Minnesota Pollution Control Agency
MS4	Municipal Separate Storm Sewer Systems
NPDES	National Pollutant Discharge Elimination System
NURP	Nationwide Urban Runoff Program
PAHs	Polycyclic Aromatic Hydrocarbons
PCCA	Purgatory Creek Conservation Area
SCS	Soil Conservation Service
SDS	State Disposal System
SWPPP	Stormwater Pollution Prevention Plan
TIN	Triangulated Irregular Networks
TP	Total phosphorus
TSS	Total Suspended Solids
WCA	Wetland Conservation Act

Executive Summary

The City of Eden Prairie, MN (population 60,797) is a suburb of Minneapolis with an area of approximately 36 square miles. The City's stormwater system consists of approximately 970 water bodies or basins. These include constructed ponds, wetlands, wetland mitigation areas, lakes, infiltration BMPs, drainage swales or ditches, and creek segments. Following NPDES requirements, the City inspects each publically-owned constructed pond and receiving basin a minimum of once in a 5-year period. The Minnesota Pollution Control Agency (MPCA), however, has asked the City to take an additional step to evaluate the treatment effectiveness of key water treatment basins (constructed ponds, infiltration BMPs, creeks and wetlands which receive stormwater). For this analysis, the City included basins that are either City-owned, included within a drainage easement, receive public drainage or are within City right-of-way.

BASIN INVENTORY & ASSESSMENT

In 2009, the Minnesota Pollution Control Agency (MPCA) asked the City to take an additional step to monitor stormwater basins that are either City-owned, under a drainage easement, receive public drainage or are within a City right-of-way. This phase of the project covers the Duck and Red Rock Lake watersheds.

In 2012, the basin inventory completed by the City identified 97 basins within the Duck Lake and Red Rock Lake project area. Of the 97 basins, 20 basins did not have an area greater than 0.25 acres and were not surveyed. An additional 3 basins were identified as private. The remaining 74 basins were determined to be public and were evaluated. The basins are considered public if they meet one or more of the following conditions; located on City property, within City right-of-way, under a drainage and utility easement, or private but receiving runoff from public right-of-way.

A total of 74 basins were assessed for functionality and sedimentation. Of the inventoried basins, there were 15 constructed ponds, 50 stormwater wetlands, 3 swales, 4 segments of Purgatory Creek, and 2 lakes (Duck and Red Rock). Stormwater wetlands are defined as wetlands that receive water from developed areas and were modified to add inlet and/or outlet structures.

SEDIMENTATION SURVEY

The sedimentation survey was conducted using a survey-grade sub-centimeter GPS unit to complete bathymetric surveys of the basins. A "Stormwater System Follow-up Checklist was developed to document information collected during the field survey. The following information was collected in the field:

- Bottom elevation of each basin
- Estimated accumulated sediment depth

- Approximate percent coverage of the permanent pool surface that appeared to be regularly covered by aquatic vegetation
- Water surface elevation
- Basin outlet/overflow data, including elevations and location
- Basin length and width (approximate)
- Photographs of key features of the basins

During the field review, Wenck also documented any “plain-sight” maintenance needs on the worksheets. This included items such as erosion, accumulation of debris on trash guards, damaged structures and others.

The City also provided storm sewer, grading and as-built plans when available for use during the field evaluation. The plans were taken into the field with the inspector to allow for easy comparison between proposed and constructed facilities.

Bathymetric surveys were conducted using cross-sections surveyed throughout each basin. At each survey point in the cross-section, the basin bottom elevation and the top of accumulated sediment were determined. Sediment depth was determined by advancing a rod into the basin muck until resistance is felt (the original basin bottom).

BASIN ANALYSIS

Data collected from the sedimentation survey was used to determine sedimentation amounts, pollutant removal effectiveness, and sediment removal. The load-based removal efficiency was calculated and compared to Nationwide Urban Runoff Program (NURP) design standards. Maintenance needs were prioritized by degree of sedimentation, proximity to public waters, location within the stormwater treatment system, potential water quality benefits, and budget available.

The project area was broken into several smaller subwatersheds that represent basins in series to better evaluate the critical basins and the overall treatment in that subwatershed prior to discharge to receiving waters. Nine basins were identified for potential expansion or clean-out to improve water quality performance.

WATER QUALITY AND LAKE-RESPONSE MODELS

The tasks and analysis discussed above provide the City with an assessment of individual basin performance throughout much of Duck and Red Rock Lake watersheds. It does not, however, indicate whether there is an adequate level of pollutant removal for Duck and Red Rock Lakes and what the overall benefit to the lake would be as a result of key projects. Therefore, a watershed-wide P8 model and a lake-response model were created for Duck Lake and Red Rock Lake.

RESULTS

The basin inventory and assessment identified 7 basins as high priority basins that should be routinely inspected. These basins were identified based on evidence of potential sedimentation and location in the treatment train. Six constructed ponds and four stormwater wetlands were identified as possible projects for cleanout or expansion through as-built comparisons and the sedimentation survey.

The BATHTUB lake response model indicates that in order to meet State standards (60 µg/L for phosphorus), Duck Lake requires 14.4 lbs/yr of phosphorus reduction (all coming from the watershed). To meet the standard, a reduction of 42% from all watersheds is required.

The BATHTUB lake response model indicates that Red Rock Lake is already meeting State standards (60 µg/L for phosphorus) so no reductions are required. The model is further supported by the water quality data collected in 2009 through 2012 that illustrates a decline in concentrations and an average value of 45 µg/L.

If all the proposed projects are completed, 17 lbs TP/year of the total phosphorus reduction is projected. The estimated cost of the proposed projects is $1,355,000, equating to $79,693 per pound phosphorus removal.

1.0 Introduction

1.1 BACKGROUND

The City of Eden Prairie, MN (population 60,797; Figure 1.1) is a suburb of Minneapolis with an area of approximately 36 square miles. The City's stormwater system consists of approximately 970 basins including constructed ponds, stormwater wetlands, natural wetlands, lakes, infiltration BMPs, drainage swales or ditches and creek segments. This system has been designed to be used for flood control and water quality treatment for many years. Some constructed ponds and stormwater wetlands are now greater than 20 years old and may have reached a point where dredging of accumulated sediment may be needed to retain their effectiveness.

The City operates the stormwater management system under the General NPDES Permit for Municipal Separate Storm Sewer Systems (MS4). Following NPDES requirements, the City must manage, operate, and maintain the stormwater management system in a manner to reduce the discharge of pollutants to the maximum extent practicable. To this end, the City inspects a minimum of 20% of their basins annually and recently completed an inventory to identify and help track all of the basins in the City.

In 2009, the Minnesota Pollution Control Agency (MPCA) asked the City to take an additional step to monitor the basins that are either City-owned, under a drainage easement, receive public drainage or are within a City right-of-way. This phase of the project covers the Eden and Neill Lake watersheds.

1.2 PURPOSE

The purpose of this study was to enhance the understanding of the City's maintenance responsibilities, assist City staff with scheduling and budgeting resources, and maintain compliance with the City's MS4 SWPPP. As described below, this assessment included three main components to achieve these objectives:

- <u>Inventory and Assess Stormwater Systems</u> – identify basins to be maintained by the City; visually inspect City-maintained basins for routine maintenance issues; perform bathymetric survey of City-maintained basins.
- <u>Evaluate Data</u> – evaluate sediment depths and volumes in City-maintained basins; identify key basins and their water quality effectiveness; evaluate the effects of these basins on receiving waters such as Staring Lake and Purgatory Creek.
- <u>Recommend Improvements</u> – identify improvements/maintenance action items; complete cost estimates for sediment removal; prioritize basin maintenance efforts.

1.3 PROJECT AREA

The project area includes the drainage area of Duck Lake and Red Rock Lake along with the area north of Duck Lake that drains to Purgatory Creek (Figures 1.2). Duck Lake (DNR Lake ID 27-0069) and Red Rock Lake (DNR Lake ID 27-0076) are off-line lakes that drain to Purgatory Creek, which is a tributary to the Minnesota River. Duck Lake has a surface area of 38 acres and maximum depth of 10 feet. Red Rock Lake has a surface area of 97 acres and a maximum depth of 15 feet.

Historically, Duck Lake was not connected to Purgatory Creek. Duck Lake was connected to Purgatory Creek through a series of pipes and wetlands to alleviate flooding problems. Similarly, Red Rock Lake was not connected to Purgatory Creek. Round and Mitchell Lakes drain to Red Rock Lake before Red Rock discharges to McCoy Lake and eventually to Staring Lake. Red Rock Lake is part of a chain of lakes which was connected through a series of pipes and basins in 1988 to alleviate flooding problems.

1.4 PROJECT HISTORY AND PLANS

The inventory and maintenance assessment for the City of Eden Prairie is a project with multiple phases that have and continue to span multiple years. Project information for each phase that has been completed, in progress or planned is included below.

<u>Phase I</u>

The inventory and maintenance assessment started with the Staring Lake watershed. The project extents included the contributing Purgatory Creek watershed between the northern city limit where Purgatory Creek enters Eden Prairie to Staring Lake, and the Staring Lake watershed. The Staring Lake watershed was selected as Phase I to support the efforts of the RPBCWD (Riley Purgatory Bluff Creek Watershed District) with an intensive lake management project for Staring Lake. The field assessment was conducted in 2010.

<u>Phase II</u>

The second phase of the inventory and maintenance assessment was the Eden and Neill Lake watersheds. The project extents included the Eden and Neill Lake watersheds. The Eden and Neill Lake watersheds were selected because the proposed light rail corroder is along the northern extents of the project area. The field assessment was conducted in 2011.

<u>Phase III</u>

The Duck and Red Rock Lake watershed project area is Phase III in the plan to survey and inspect basins throughout Eden Prairie. The project extent includes the Duck Lake and Red Rock Lake watersheds, and the upper Purgatory Creek watershed from the western city limit where Purgatory Creek enters Eden Prairie to the northern city limit where Purgatory Creek leaves Eden Prairie. The Phase III project area was selected because the assessment for the

Purgatory Creek direct watershed upstream of Staring Lake would be completed, Duck Lake drains to Purgatory Creek upstream of Staring Lake, and Red Rock Lake is the first lake in a chain of lakes upstream of Staring Lake. The field assessment was conducted in 2012.

Phase IV

The lower Riley Creek watershed is Phase IV of the inventory and maintenance assessment. The project extents include the Riley Creek watershed south of Riley Lake and extend from the western city limit to the western portion of Flying Cloud Airport. The field assessment was conducted in 2013.

Phase V

The Round Lake and Mitchell Lake watersheds are planned for Phase V of the inventory and maintenance assessment. Round Lake and Mitchell Lake watersheds are upstream of Staring Lake that have not been inventoried and assessed. This phase will complete the Purgatory Creek watershed upstream of Staring Lake. The field assessment is planned for 2014.

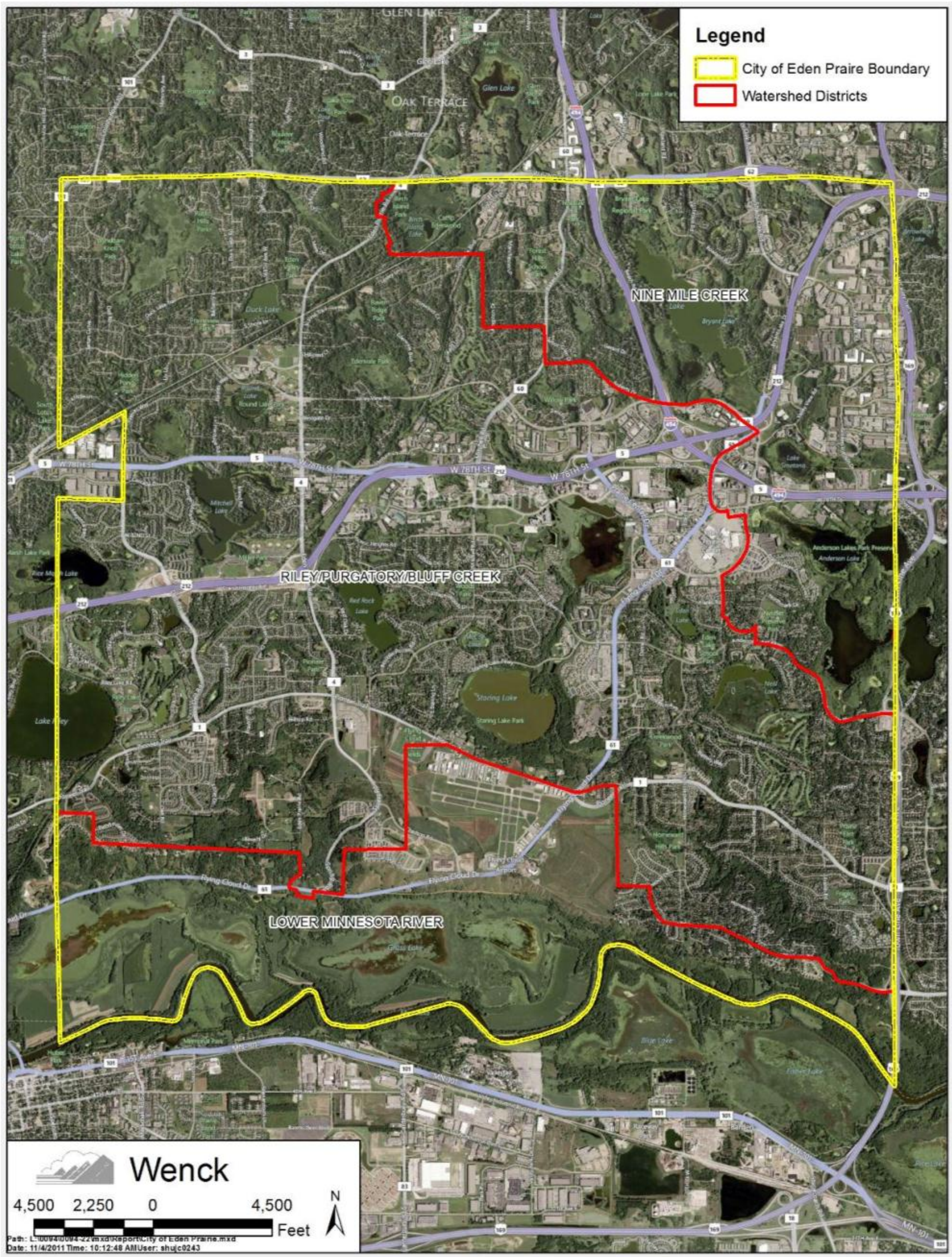

Figure 1.1. City of Eden Prairie.

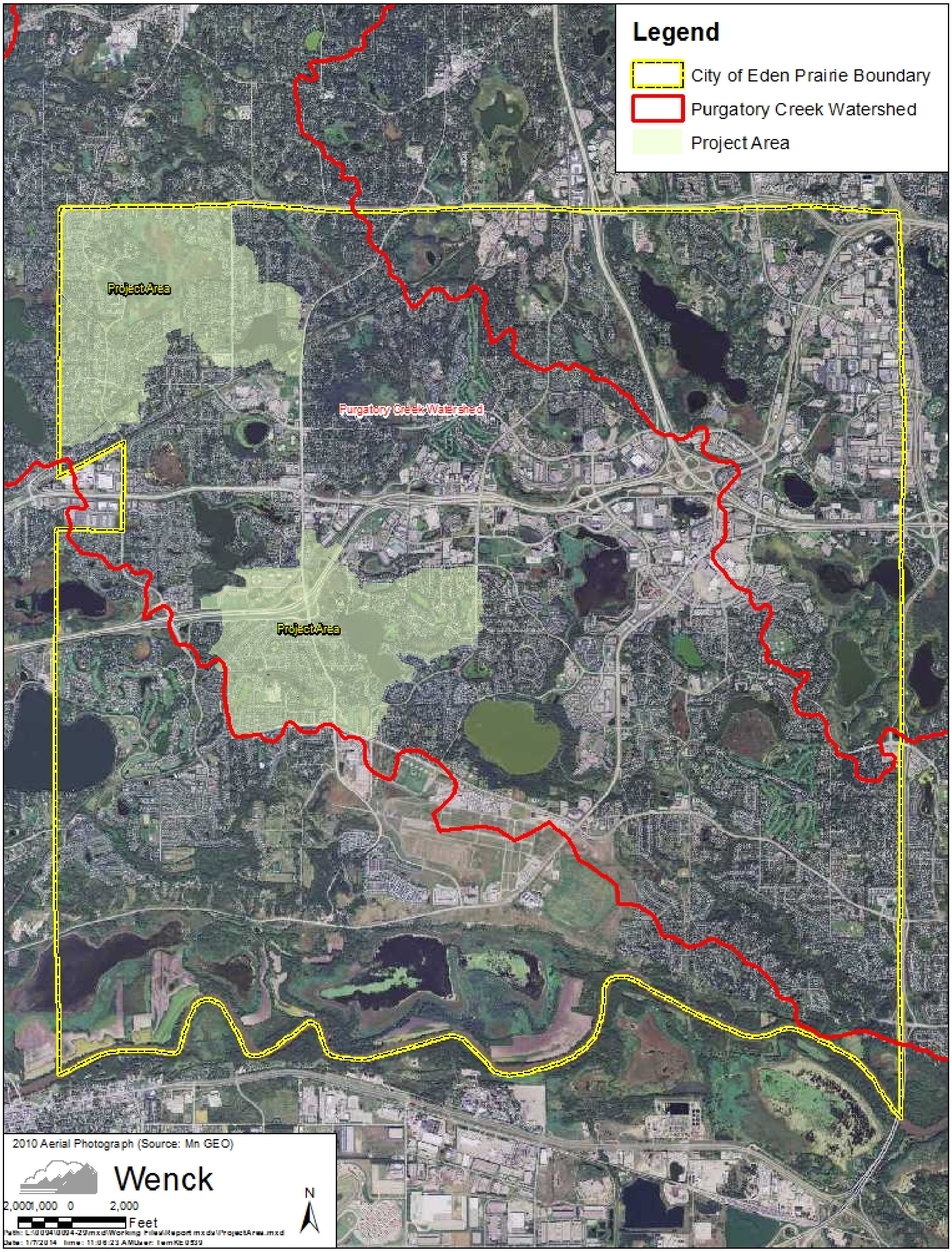

Figure 1.2. Project Area.

2.0 Stormwater System Assessment Methodology

2.1 BASIN INVENTORY AND ASSESSMENT

In 2012, the City completed a basin inventory in the Duck Lake watershed, Upper Purgatory Creek watershed, and Red Rock Lake watershed. The basin inventory identified 97 basins that were designated for stormwater management (Figure 2.1). Of the 97 basins, 20 basins did not have an area greater than 0.25 acres and were not surveyed. The basins were further researched to determine which could be categorized as public. The criteria to be considered a public basin included one or more of the following:

- Located on City property
- Within a City right-of-way
- Within a drainage and/or utility easement
- Private property but receiving runoff from a public right-of-way

Research efforts involved reviewing design and record drawings to locate easements, using geographic information system (GIS) based parcel information to determine ownership, and delineating subwatersheds using two foot contours. Ultimately, a total of 74 basins were given a public designation in the project area watershed.

The 74 basins were visually inspected, and site surveys were completed to help assess the maintenance needs and existing storage capacities. These data were needed to estimate sediment volumes, complete water quality modeling, provide cost estimates, and prioritize maintenance activities.

Prior to conducting basin surveys, Wenck and City of Eden Prairie staff reviewed available design and as-built plans of the basins. Information obtained from the design or as-built plans included basin outlet elevations; basin flood or high water level elevations; size, type, and material of outlet structure; and basin length and width. Using a planimeter to obtain distances and areas from the design or as-built plans, the City of Eden Prairie staff also calculated permanent pool and flood pool areas and volumes for each basin.

2.1.1 Visual Inspections

During each basin survey, Wenck also conducted a visual inspection based on the City's "Stormwater System Follow-Up Checklist." Wenck completed the checklist by documenting the overall condition of the basin, including the condition of structures, the presence of erosion, maintenance needs, the presence of trash or debris, and aquatic vegetation coverage. Information from the checklist was used in the analysis of each basin and was entered into the City's database.

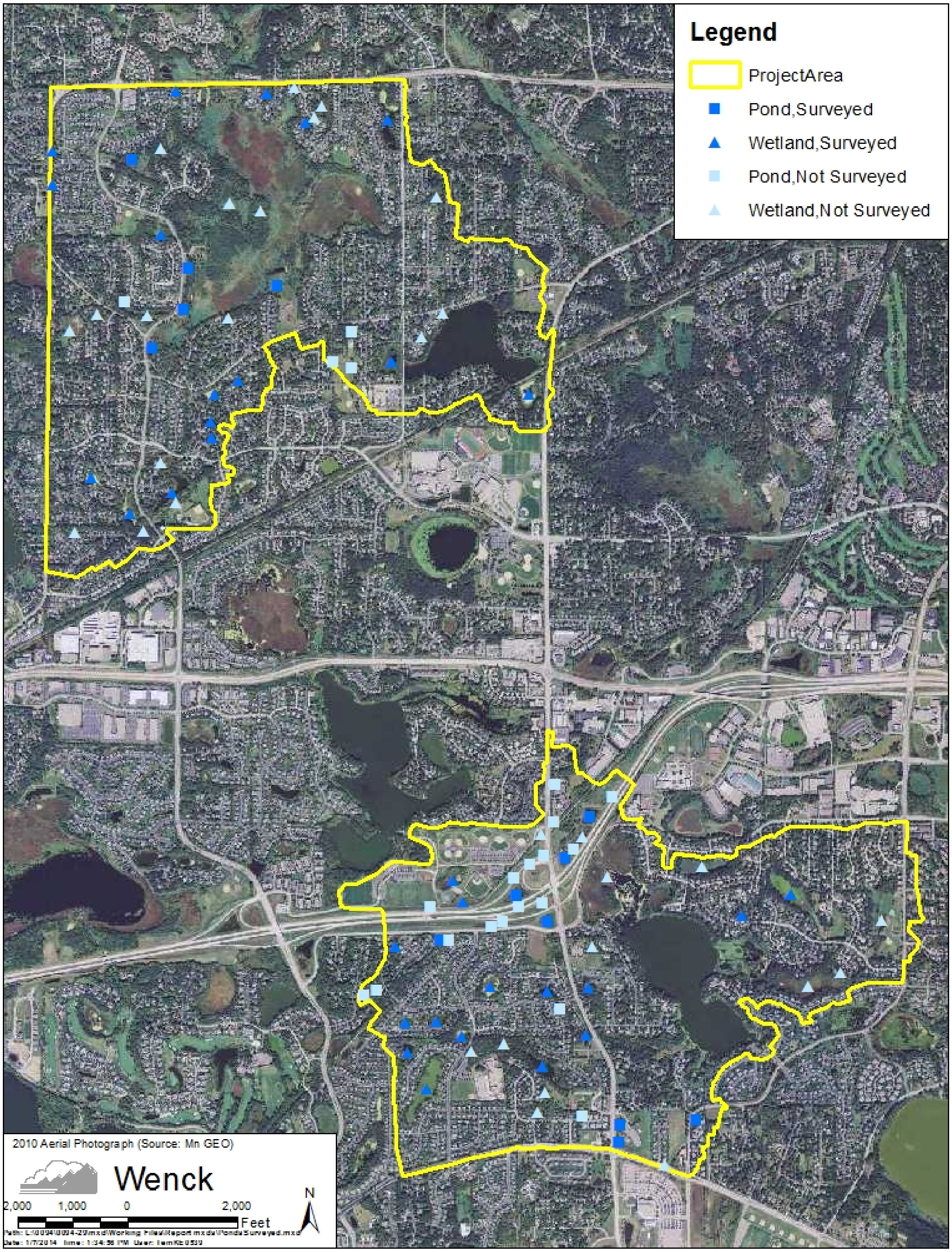

Figure 2.1. Basins in the Survey Area of the City of Eden Prairie Determined to Receive Public Drainage.

2.1.2 Sedimentation Surveys

Sedimentation surveys were conducted at each basin during 2012. Wenck used a Trimble R8 survey-grade GPS unit with sub-centimeter accuracy to collect elevation and location data at each basin. The survey included a bathymetric survey of the basin in which cross-sections were surveyed throughout each basin. Surveyed elevations include the basin bottom, the water surface elevation, and additional ground shots extending beyond the flood elevation.

At each survey point, Wenck collected the basin bottom elevation and the top of the accumulated sediment. Sediment depth was estimated by advancing a rod through the sediment until refusal. The inverts of outlets, inlets, or other structures, and water level elevations were also surveyed. Representative photos of each basin and structures within the basin were also taken.

2.1.2.1 Estimation of Sediment Quantities

Wenck used ArcMap 10.1 GIS software to process the GPS data collected during the sedimentation survey and estimate sediment deposition in each basin. The GIS software allowed Wenck to calculate the surface area of each basin, as well as the permanent pool and flood volumes. Basin volumes were calculated from elevation contours generated using ArcMap. The volume of sediment in each basin was determined by using the sediment depth measured in the field at survey points or by comparing the survey volumes to the as-built or design volumes.

Figure 2.2 shows the plan view of a typical stormwater basin. Each survey point collected was geographically referenced and has a corresponding elevation. Survey points represent water surface elevations, basin bottom transects, and overflow elevations. These data were combined with data from a digital elevation model to create Triangulated Irregular Networks (TINs). The differences between various TINs were used to generate estimates of the basins volumes.

The permanent pool, or dead storage volume, is the volume below the outlet elevation. The flood pool is the volume between the outlet and the overflow point. If no outlet is present, the permanent pool was calculated as the volume below the overflow point.

The extent of sediment deposition in the stormwater basins was estimated by comparing the existing permanent pool volume to the estimated "original" permanent pool volume for each basin. Determining the original permanent pool volume of a basin can be a challenge since accurate data on the "as-built" construction of the basin is not often readily available. As-built or construction documents and pre-construction plans were used, when available, to determine the original basin characteristics. In some cases, the original basin permanent pool volume resulted in negative values for changes in permanent pool volume, though some positive values were noted. Since it is unlikely that permanent pool volumes increased, it was determined that these ponds may have been overbuilt or not built to original basin specifications.

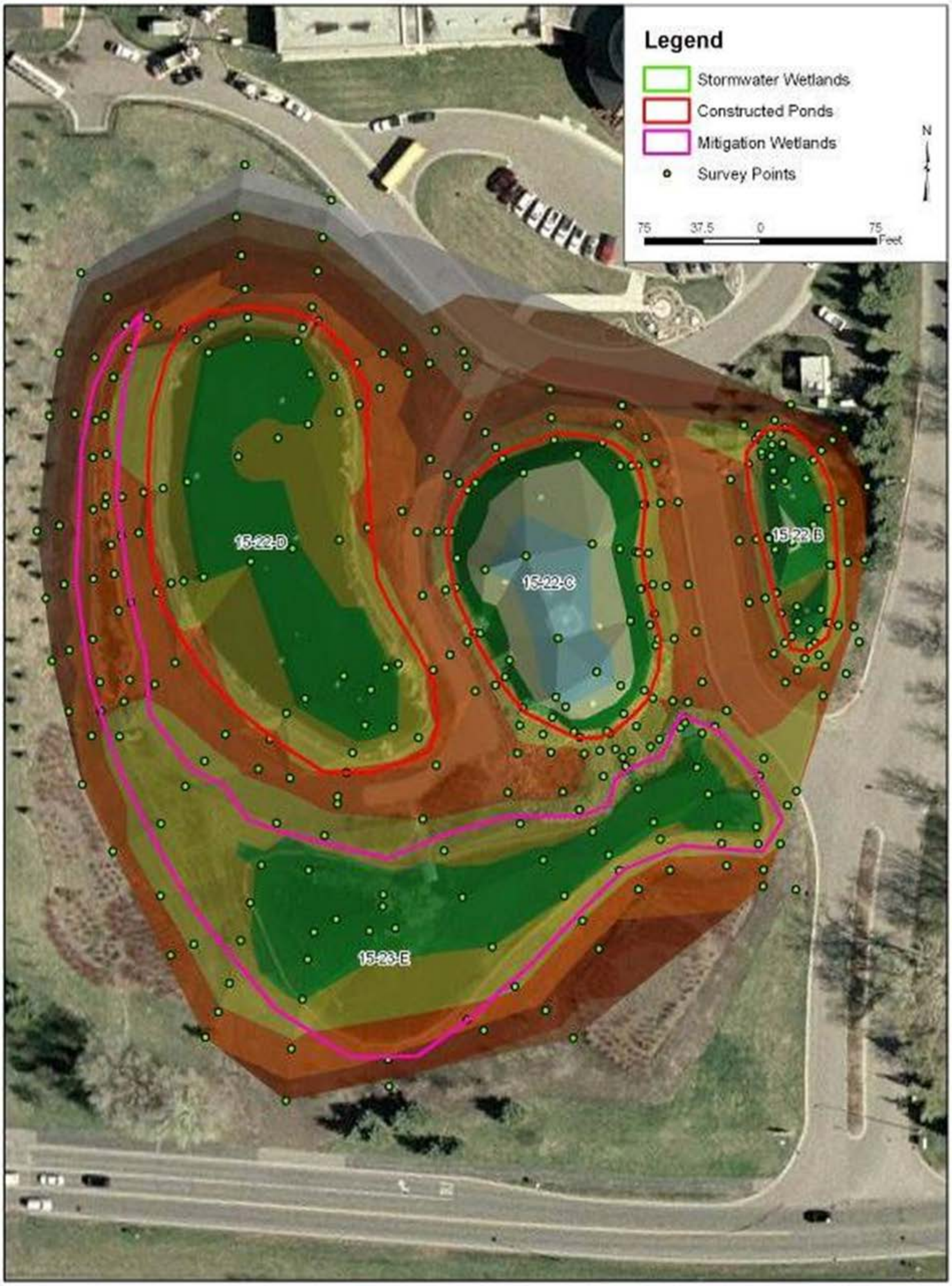

Figure 2.2. Plan View of a Typical Stormwater Basin.

2.1.2.2 NURP Evaluation

The Environmental Protection Agency's (EPA) Nationwide Urban Runoff Program (NURP) focuses on detention basin design criteria related to phosphorus removal from urban watersheds. Sources from urban areas such as fertilizers, leaves, grass, bird droppings, pet waste or erosion around the basins contribute to increased total phosphorus loadings. Because basin depth and permanent storage capacities have been linked to Total Suspended Solids (TSS) and Total Phosphorus (TP) removal efficiencies, NURP standards require stormwater detention basins to have a permanent storage volume equal to or greater than the runoff from a 2.5-inch, 24-hour storm event. The permanent pool storage volume needed to meet NURP standards was calculated for each basin using the estimated impervious surface area, pervious surface area based on soil types and vegetative cover, and the subwatershed area tributary to each basin. The purpose of this evaluation was to determine the optimal areas that could be improved to provide additional treatment within the Duck and Red Rock Lake watersheds.

2.1.3 Planning Level Sediment Removal Cost Estimates

Planning level sediment removal costs were developed for the removal of accumulated sediments or for expansion of basins (Table 2.1). The cost estimates are based on past experience with basin expansions and construction as well as discussions with local contractors. The cost estimates include:

- Construction costs (including mobilization, site preparation, sediment excavation and disposal, minor storm sewer or structural work, and erosion control)
- Level 2 sediment disposal costs according to the MPCA guidance
- 30% engineering costs
- 30% contingency cost

These costs do not include laboratory analysis, wetland mitigation, sediment characterization, major structural work or land/easement acquisition. All costs were rounded to reflect planning level estimates.

Table 2.1. Planning Level Costs for Basin Excavation.

Basin Excavation Volume (AF)	Approximate Unit Cost ($ per acre-foot)
0 to 0.5	139,000
0.5 to 1	107,000
1 to 2	85,000
2 to 5	65,000
>5	51,000

2.1.4 Sediment Characterization Costs

Basin sediments need to be characterized to determine disposal options. This analysis includes particle size analysis, laboratory analysis for potential contaminates, and determination of the number of samples to be collected. Excavated material that is mostly sand and/or gravel (>93%) is unlikely to be contaminated and chemical laboratory analysis would typically not be required.

If lab sediment analysis is required, sediment samples must be analyzed for a list of parameters established by the MPCA. Based on recent MPCA guidance, Managing Dredged Materials in the State of Minnesota (June 2009), sediment samples from urban stormwater basins must be analyzed for copper, arsenic, and Polycyclic Aromatic Hydrocarbons (PAHs). The historic land use within the drainage area of a stormwater basin must also be reviewed to help determine the likelihood of other pollutants being present in the sediment.

The recommended number of sediment samples to be collected is dependent upon the estimated volume of material to be excavated. Table 2.2 summarizes the current minimum recommended number of samples to be collected for urban stormwater basins, based on the MPCA's most recent guidance (MPCA, 2009).

Table 2.2. MPCA Recommended Number of Samples for Sediment Characterization.

Estimated Volume of Dredge Material (cubic yards)	Minimum Recommended Number of Samples for Analysis
0 to 100	0
100 to 500	1
500 to 3,000	2
3,000 - 30,000	3
30,000 - 100,000	5
100,000 - 500,000	6
500,000 - 1,000,000	8
>1,000,000	>8

Costs for sediment analysis including collection and lab processing can range from $2,000 to $4,000. These costs are included in the planning level cost assessment.

2.2 P8 MODEL

2.2.1 Model Construction

The P8 Model (Program for Predicting Polluting Particle Passage through Pits, Puddles and Ponds, IEP, Inc., 1990) is a computer model used for predicting the generation and transport of stormwater runoff pollutants in urban watersheds. The P8 model was used in this study to simulate the hydrology, total suspended solids, and phosphorus loads introduced from the watershed of each basin and the transport of phosphorus throughout the stormwater system. P8 is a useful diagnostic tool for evaluating and designing watershed improvements and best management practices (BMPs). The model requires user input on watershed characteristics, basin attributes, local precipitation and temperature, and other parameters relating to water quality and basin removal performances.

Examination of the watershed characteristics for each basin being modeled involved assessment of soil type, land use and residential density, and the impervious fraction of the land in the watershed. Arcview GIS software was used extensively in assessing watershed characteristics.

In P8, pervious and impervious areas are modeled separately. Runoff volumes from pervious areas are computed using the Soil Conservation Services (SCS) Curve Number method. Runoff from impervious areas begins once the cumulative storm rainfall exceeds the specified depression storage, with the runoff rate equal to the rainfall intensity.

Because P8 calculates runoff separately from pervious and impervious areas, it was necessary to determine the impervious fraction of each watershed. For the P8 models, the impervious areas were assumed to be all directly connected. An impervious area is considered directly connected if runoff flows directly from it into the drainage system via continuous paved areas. The directly-connected impervious fraction was calculated for each watershed based on the land use(s), with each land use having an assumed impervious percent. The assumed impervious percent's are listed in Table 2.3.

Watershed runoff volumes from pervious areas were computed for P8 by using the SCS Curve Number (CN) method. Within each watershed a pervious CN was calculated based on the soil type and land use. The pervious CN was area weighted in each subwatershed using the values in Table 2.3.

Table 2.3. Assumed Impervious Percent and Pervious Curve Numbers for Land Uses in Eden Prairie.

	Impervious Fraction	Pervious Curve Number			
Land Use	**percent**	**A**	**B**	**C**	**D**
Agricultural	0.05	49	69	79	84
Airport	0.30	68	79	86	89
Farmstead	0.10	49	69	79	84
Golf Course	0.10	39	61	74	80
Industrial and Utility	0.67	68	79	86	89
Institutional	0.32	39	61	74	80
Major Highway	0.50	49	69	79	84
Mixed Use Commercial	0.67	49	69	79	84
Mixed Use Industrial	0.50	68	79	86	89
Mixed Use Residential	0.60	39	61	74	80
Multifamily	0.60	39	61	74	80
Open Water	0.00	85	85	85	85
Office	0.32	39	61	74	80
Park, Recreational, or Preserve	0.10	39	61	74	80
Railway	0.20	68	79	86	89
Retail and Other Commercial	0.67	49	69	79	84
Single Family Attached	0.30	39	61	74	80
Single Family Detached	0.20	39	61	74	80
Undeveloped	0.05	39	61	74	80

The P8 model requires an hourly precipitation record (rain and snowfall) and daily temperature record. Precipitation and temperature data were obtained from the Minneapolis-St. Paul International Airport.

The NURP50 file was selected for the P8 models. The component concentrations in the NURP 50 file represent the 50th percentile (median) values compiled in the EPA's Nationwide Urban Runoff Program (NURP).

The treatment devices in P8 provide collection, storage, and/or treatment of watershed discharges. A variety of treatment devices can be modeled in P8, including detention basins (wet or dry), infiltration basins, swales, buffers, aquifers, and pipes. For this study, nearly all constructed ponds and wetlands were modeled as detention basins. The user-defined characteristics of these basins are described in the following sections.

Even though some watersheds were delineated for basins under 0.25 acres, they were not modeled in P8. Also, basins that had heavy cattails and no open water that were unable to be surveyed were assigned a depth of 0.5 ft at permanent pool elevation and the depth at flood control elevation was based on the difference between the overflow elevation and outlet elevation. If flood elevation was unable to be determined, the flood control elevation was assigned a depth of 0.5 ft. In P8, the removal efficiency for the basins that were unable to be surveyed was reduced by 70%.

2.3 BATHTUB MODEL

A BATHTUB lake response model was developed for Duck Lake and for Red Rock Lake to assess the potential impacts of various improvement projects on in-lake water quality. The purposes of the model are to develop a phosphorus budget for each lake, identify the major factors influencing current and future water quality, and provide an understanding of the level and magnitude of project implementation required to meet identified water quality goals.

A publicly available model, BATHTUB was developed by William W. Walker for the U.S. Army Corps of Engineers (Walker 1999). BATHTUB has been used successfully in many lake studies in Minnesota and throughout the United States. It is a steady-state model, annual or seasonal, that predicts a lake's summer (June-September) mean surface water quality. Its annual time-scale is appropriate because watershed phosphorus loads are determined on an annual or seasonal basis, and the summer season is critical for lake use and ecological health.

BATHTUB has built-in statistical calculations that account for data variability and provide a means for estimating confidence in model predictions. It accounts for water and phosphorus inputs from tributaries, watershed runoff, the atmosphere, sources internal to the lake, and (if appropriate) groundwater; and accounts for outputs through the lake outlet, groundwater (if appropriate), water loss via evaporation, and phosphorus sedimentation and retention in the lake sediments.

BATHTUB allows choice among several different mass-balance phosphorus models. For deep lakes in Minnesota, the option of the Canfield-Bachmann lake formulation (Canfield and

Bachmann 1981) has proven to be appropriate in most cases. For shallow Minnesota lakes, other options have often been more useful.

In addition to total phosphorus concentration, BATHTUB's in-lake water quality predictions include two additional response variables, chlorophyll-*a* concentration and Secchi depth. A response variable is a measured outcome from changes in nutrient loading. For example, increases in total phosphorus are typically followed by increases in chlorophyll-*a* because phosphorus limits the growth of algae. Increases in algae lead to a decrease in water clarity or Secchi depth which is another response to changes in phosphorus loading. Empirical relationships between in-lake total phosphorus, chlorophyll-*a*, and Secchi depth form the basis for predicting the two response variables.

2.4 SEDIMENT RELEASE RATE ASSESSMENT

Wenck collected four intact sediment cores (undisturbed) from the deepest part of Duck Lake and Red Rock Lake each. The samples were analyzed to estimate the anoxic and oxic release of phosphorus from the sediments.

These results were combined with dissolved oxygen and temperature profiles from Duck Lake and Red Rock Lake to develop a component of the annualized phosphorus loads from the sediments of Duck and Red Rock Lake (internal load).

3.0 Stormwater System Conditions

3.1 BASIN IDENTIFICATION

The City of Eden Prairie maintains a database of basins within the City. This database was used along with a review of aerial photographs to identify potential basins in the project area. There were 97 basins identified in the Duck and Red Rock Lake watersheds designated for stormwater management.

Wenck delineated the subwatersheds of the 97 basins to determine whether they receive public stormwater drainage from the City or were wholly private. Ultimately, a total of 74 basins (Figure 2.1) were given a public designation in the Duck and Red Rock Lake watersheds and had areas over 0.25 acres.

Of the 97 designated basins, 13 were MnDOT basins with 8 of those basins receiving City stormwater as well as highway runoff (Figure 3.1). Of the 8 basins that receive public drainage, 4 were smaller than 0.25 acres. Of the remaining 5 basins, 1 was smaller than 0.25 acres, 3 were private and 1 was identified as a swale. In the end, 4 MnDOT basins were surveyed.

A total of 74 basins were assessed for functionality and sedimentation. Of the inventoried basins:

- 15 constructed ponds
- 50 stormwater wetlands
- 3 swales or ditches
- 4 creek segments
- 2 lakes (Duck Lake and Red Rock Lake).

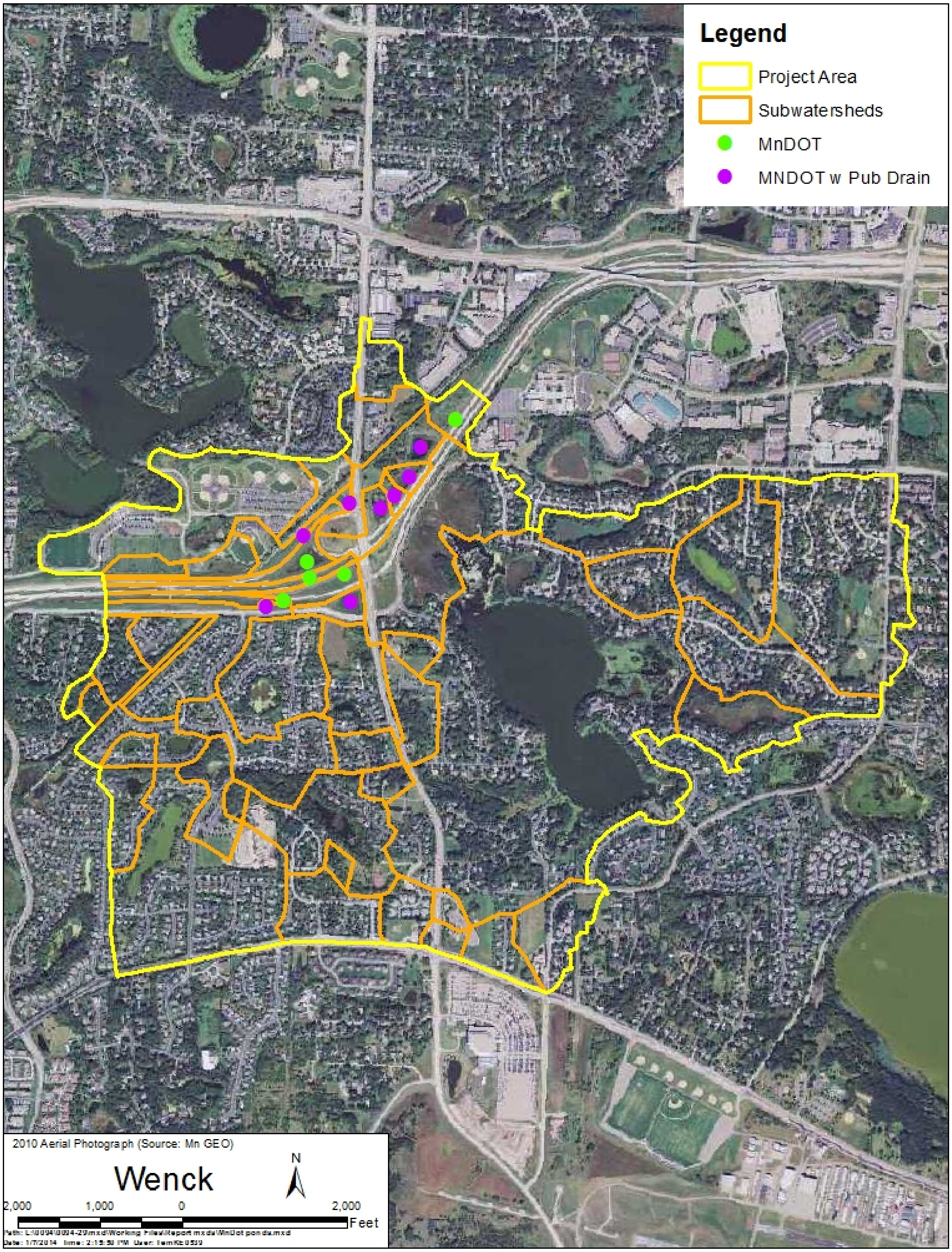

Figure 3.1. MnDOT Constructed Ponds and Wetlands in the Study Area.

3.1.1 Constructed Ponds

A total of 26 constructed ponds were identified in the project area. Of these, 15 receive City drainage and have a permanent pool over 0.25 acres. Constructed ponds are those basins designed and built specifically for the purpose of stormwater control including either flooding or water quality. Constructed ponds do not include wetlands modified to treat stormwater.

3.1.2 Stormwater Wetlands

The project area contained a total of 56 stormwater wetlands. Of these, 50 receive City drainage and have a permanent pool over 0.25 acres. A stormwater wetland is defined as any natural wetland that receives stormwater from impervious or developed areas. Stormwater inflow may be from an open channel (overland flow) or pipe.

The purpose of the wetland survey was to identify the wetlands used for stormwater management and evaluate their current condition and performance. Because this analysis was focused on sedimentation, only the open water areas of the wetlands were surveyed. Additionally, all of the inlets and outlets were inspected for maintenance needs. For wetland areas that did not have significant open water, the perimeter of the wetland was surveyed. Many of these do not have as-builts or grading plans available for comparison.

3.1.3 Creek Segments

Four of the basins in the City database were segments of Purgatory Creek. For these segments, the inlets and outlets were surveyed and inspected. No water surveys or cross-sections were completed.

3.1.4 Swales

Nine of the identified basins in the City database were classified as swales though only 3 had areas greater than 0.25 acres. Swales are defined as vegetated depressions or ditches used for the conveyance and treatment of stormwater.

3.1.5 Lakes

Two of the identified basins in the City database are listed as lakes, specifically Duck Lake and Red Rock Lake.

3.2 STORMWATER BASIN VISUAL INSPECTION

Visual inspections were conducted at each of the basins in the survey to identify any structural maintenance needs at the basins. Visual inspections included any signs of erosion, sedimentation, failing infrastructure or clogged inlets and outlets. Basins listed in poor or fair condition are provided in Table 3.1. All results where issues were identified are presented in Appendix A. A rating of good meant that the basin inlets and outlets were in operating condition and there was little erosion. A rating of fair indicated that there was some obstruction of inlets and outlets, and/or some bank erosion. A rating of poor meant that the inlets or outlets were clogged or not functioning and/or bank erosion was severe.

Table 3.1. Selected Visual Inspection Results for the Duck Lake and Red Rock Lake Watershed Basin Survey.

Basin ID	Priority	Overall Condition	Erosion Concern	Sediment Concern	Debris Concerns	Notes/Other Issues
05-33-A	High	Fair	No	No	No	Inlet 1130 has a large willow growing inside.
06-23-A	High	Poor	No	No	Yes	Trashguard is damaged and may need to be replaced. One inlet is partially crushed. However both are open and flowing.
06-43-A	High	Poor	Yes	Yes	No	None
07-12-C	High	Poor	No	No	No	Piping for inlet has been exposed by erosion. Exposed pipe is approximately 6 to 8 feet long.
07-23-A	High	Poor	No	Yes	Yes	Outlet 0500 was submerged.
16-34-A	High	Fair	No	Yes	Yes	None
20-13-D	High	Poor	Yes	No	No	Last section of the outlet at 1:00 has disconnected from the rest of the pipe.

3.3 STORMWATER BASIN SEDIMENTATION

Constructed ponds and stormwater wetlands were evaluated for sediment deposition by comparing the existing permanent pool volume to the estimated original permanent pool volume for each constructed pond and stormwater wetland. Estimating the original permanent pool volume was accomplished by reviewing as-builts where available. Basin sedimentation was also evaluated using field collected sediment depth data for all of the constructed ponds and wetlands. To assess sediment depths, a rod was pushed into basin sediments to refusal. Surface contours were then developed for the refusal depths and the sediment surface to determine sediment volumes.

There are a few considerations that must be taken into account when interpreting the results of the survey including:

1. Estimating the original permanent pool volume is difficult and highly dependent on the accuracy of the as-built information or design plans. Many of the constructed ponds and wetlands do not have design plans or as-built information available. The absence of accurate design plans or as-built information for estimating the original permanent pool volumes can result in significant error in the sedimentation analysis. Consequently, results should be used cautiously in light of the uncertainty.

2. The depth to refusal may or may not represent sediment that has accumulated in the basin. Some or all of the sediment may be original basin or wetland sediment. However, there is no accurate way to distinguish between the original sediment and accumulated sediment.

3. Construction information is not readily available for all basins, so some of the basins identified as stormwater wetlands may be constructed ponds.

3.3.1 Constructed Ponds and Stormwater Wetlands with As-Built Information

Of the 97 basins identified in the project area, there were 2 basins with at least partial design or as-built information. The 2 basins are designated as constructed ponds. Table 3.2 presents the basins and lists the basins in downstream order. To evaluate the usefulness of comparing as-built dead pool storage to field surveyed dead pool storage, the basin surface areas were first compared.

For 1 of the basins, the field surveyed permanent pool volume was significantly less than the as-built permanent pool volume. The difference between the surveyed permanent pool volume and the as-built permanent pool volume ranges from 11% to -52% of the as-built permanent pool volume. Data for constructed ponds was more reliable than data for stormwater wetlands likely due to changes in wetland vegetation over time.

Those basins with field surveyed dead pool areas less than the design or as-built dead pool areas may offer an opportunity to increase basin storage and improve water quality treatment.

Table 3.2. Constructed Pond and Wetland Characteristics for Basins with As-Built or Design Information.

Basin ID	As-Built Permanent Pool Area (acres)	Surveyed Permanent Pool Area (acres)	As-Built Permanent Pool Volume (AF)	Surveyed Permanent Pool Volume (AF)	Surveyed minus As Built Permanent Pool[1] (AF)	Accumulated Sediment Volume (AF)	Sediment Percent of Permanent Pool
Constructed Ponds							
21-31-A	0.31	0.29	0.62	0.69	-0.07	0.14	17%
21-32-C	0.27	0.27	1.43	0.68	0.75	0.23	25%

Negative values indicate that the surveyed volume was larger than the as-built volume.

3.4 CRITICAL STORMWATER BASINS

Basin performance was evaluated for the basins in series using P8 and by evaluating NURP requirements cumulatively for each basin. Basin performance was evaluated by comparing surveyed permanent pool volumes to the required permanent storage volume to meet NURP standards. The number is presented as a ratio where values less than one do not meet NURP standards and values greater than one exceed NURP standards. For our purposes, NURP standards are defined as having a permanent pool volume equal to the 2.5 inch, 24 hour rainfall event runoff volume (Table 3.3).

The term "NURP pond" refers to retention basins (also called "wet ponds") that capture sediment from stormwater runoff as it is detained, and that are designed to perform to the level of the more effective basins observed in the NURP studies. Some practitioners may assume that a "NURP pond" design conforms to some particular standard issued by EPA, but in fact EPA has issued no regulations or other requirements regarding the design of stormwater basins. However, some states and municipalities have issued stormwater design manuals, and these publications may include a reference to a "NURP pond."

Table 3.3. Typical Minnesota Basin Design Standards.

Parameter	Standard Design
Permanent Pool Depth	4 to 10 feet
Permanent Pool Surface Area	Greater of 2% of watershed's impervious area and 1% of the watershed
Permanent Pool Length to Width Ratio	3:1 or greater with an irregularly shaped shoreline
Side Slopes	10:1 for 10-foot bench centered on the normal water elevation and between 3:1 and 20:1 elsewhere
Side Slope Stabilization	Native seed with MnDOT 310, BWSR W2 or equivalent between NWL and HWL, provide 10' buffer where possible with MnDOT 330 (short) or MnDOT 340 (tall).
Floatable Removal	Skimming device discharging at no greater than 0.5 fps during the 1-year event or a submerged outlet with a minimum 0.5 feet from the normal water level to the crown of the outlet pipe.
Sediment Accumulation Area	Provide maintenance pads to remove sediment deltas at inlets.
Permanent Pool Volume	A 4-foot mean depth and equal to 2.5-inch rain over the watershed.

Source: Protecting Water Quality in Urban Areas (MPCA 2000)

All of the tables are organized so that the constructed ponds and wetlands move from the top of the watershed to the bottom of the watershed as you move down the table.

3.4.1 Duck Lake Area

The Duck Lake area includes the basins that are west of Eden Prairie Road (Table 3.4 and Figure 3.2). All the basins in the area drain to Duck Lake (05-34-A) which then drains east to Purgatory Creek. Four of the basins (05-33-C, 05-33-D, 05-33-B, 05-34-C) are less than 0.25 acres in size and were not surveyed. Basin 05-34-B was unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

The basins in this area meet NURP standards and have relatively high removal percentages based on the P8 model. Consequently, no projects are needed in this area. For long term protection of water quality, projects in this area could include retrofitting the direct drainage watershed to Duck Lake with infiltration practices such as rain gardens. Although 05-34-C was not evaluated due to its small size, it could be considered for expansion. However, it would first need to be evaluated.

Table 3.4. Constructed Pond and Wetland Characteristics for the Duck Lake Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to Duck Lake, 05-34-A								
05-33-A	18.82	3.35	5.52	2	98	84	64	SW
Discharges to Duck Lake, 05-34-A								
05-34-B[3]	--	--	--	5	95	93	61	SW
08-12-A	34.90	20.92	2.58	0	100	51	65	SW

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] SW=Stormwater Wetland.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

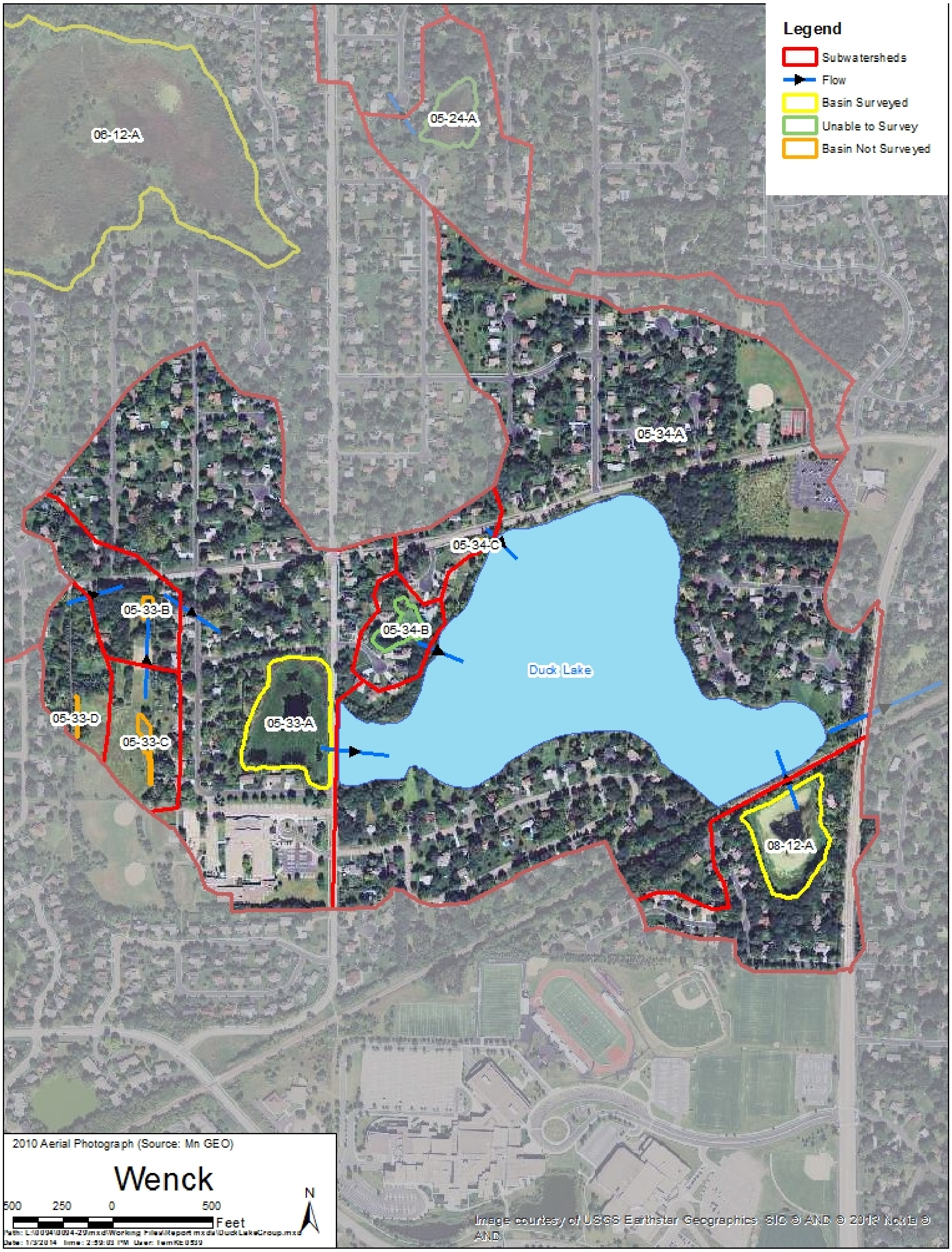

Figure 3.2. Constructed Ponds, Wetlands and Flow Patterns in the Duck Lake Subwatershed.

3.4.2 North Rustic Hills Park Area

The North Rustic Hills Park Area includes basins south of Hwy 62 and to the north of Purgatory Creek (Table 3.5 and Figure 3.3). All of the basins drain to Purgatory Creek (06-12-A). Two of the basins (06-11-E, 06-11-A) are less than 0.25 acres in size and were not surveyed. Two basins (06-11-B, 05-24-A) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed. Due to the wetland designations, project options including expansion or dredging are limited in this area.

Group 1 basins are designated wetlands that drain through 05-22-A before discharging to Purgatory Creek. 05-22-A exceeds NURP standards. Although this basin has a large sediment volume, this is likely peat deposits in the wetland and not new sediment.

Group 2 basins in the North Rustic Hills basins are all designated as wetlands and are generally undersized for water quality protection according to the P8 model percent removal. One wetland at the bottom of the chain can be evaluated for expansion (06-11-C) since it is undersized and looks more like a constructed pond than a wetland.

Table 3.5. Constructed Pond and Wetland Characteristics for the North Rustic Hills Park Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges in sequence to Purgatory Creek, 06-12-A (Group 1)								
05-24-A[3]	--	--	--	10	0	109	0	SW
05-22-A	8.03	2.18	3.13	2	96	87	54	SW
Discharges in sequence to Purgatory Creek, 06-12-A (Group 2)								
06-11-B	0.15	0.24	--	9	88	107	52	SW
06-11-C	0.22	0.24	0.17	15	72	125	32	SW
Discharges to Purgatory Creek, 06-12-A (Group 2)								
06-11-D	Swale			20	76	139	41	SE

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] SE=Swale; SW=Stormwater Wetland.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

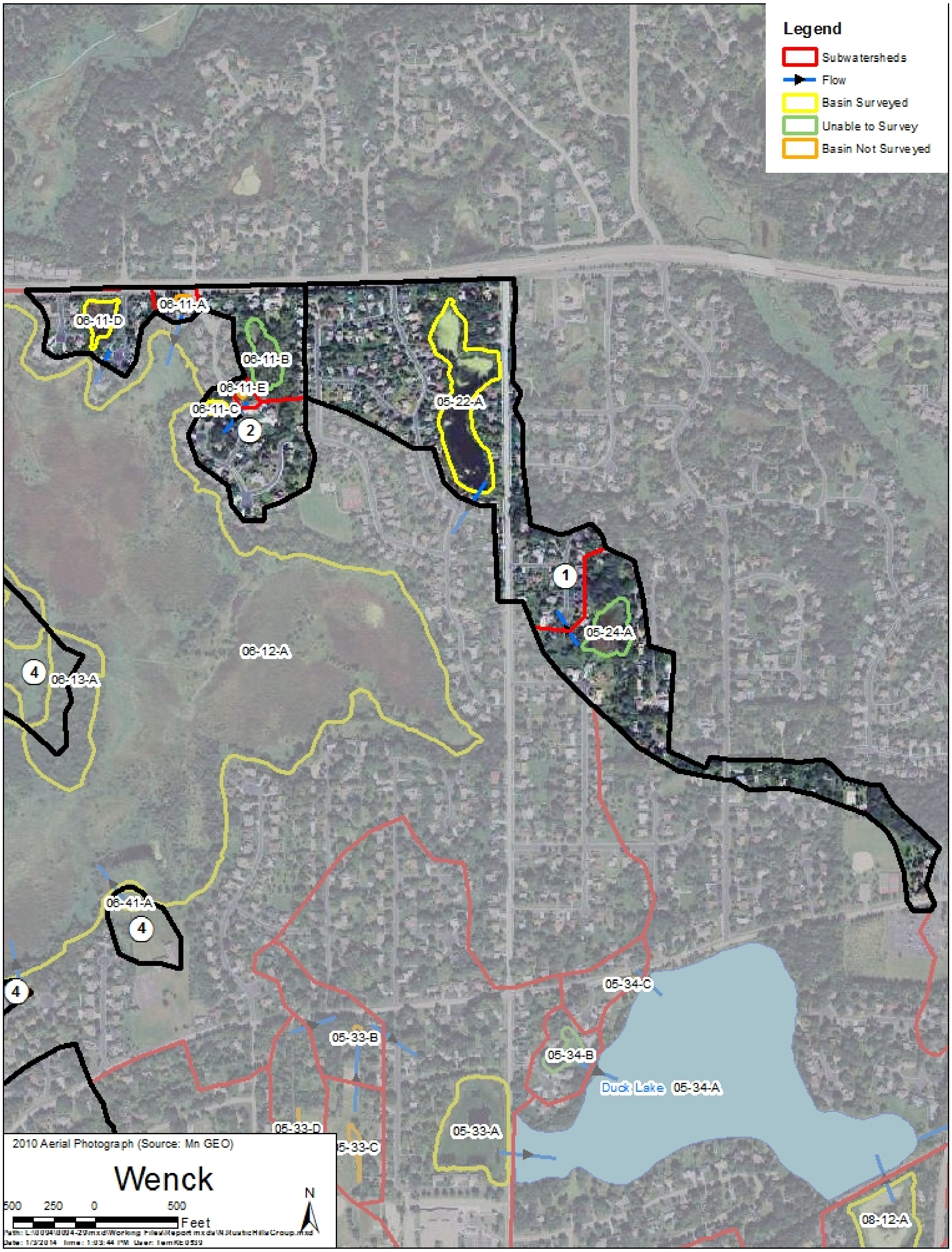

Figure 3.3. Constructed Ponds, Wetlands and Flow Patterns in the North Rustic Hills Park Area Subwatershed.

3.4.3 Wyndham Knoll Park Area

The Wyndham Knoll Park Area includes basins south of Hwy 62 and east of Highway 101 (Table 3.6 and Figure 3.4). All of the basins drain to Purgatory Creek (06-12-A). Basin 06-43-B is less than 0.25 acres in size and was not surveyed. Four of the basins (06-13-A, 06-21-C, 06-21-D) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

One basin (06-21-C) in this group is a key constructed pond in the Wyndham Knoll Park area that needs to be resurveyed. It is planned to survey this basin in winter of 2014.

Constructed pond 06-42-B drains 16 acres of the City before discharging to Purgatory Creek and is well below NURP standards. This basin should be considered for expansion. However, expansion of this basin may be difficult due to site constraints from the adjacent wetlands.

If it is determined that 06-21-C is undersized, expansion or an addition of a filter bench should be considered due to the large area the basin treats and the location in the treatment train. Basin 06-42-B is also a constructed pond owned by the city and has a large drainage area. This basin should also be considered for expansion or an addition of a filter bench.

Table 3.6. Constructed Pond and Wetland Characteristics for the Wyndham Knoll Park Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to 06-21-C (Group 3)								
06-22-A	Swale			18	79	133	45	SE
06-23-A	Swale			13	85	119	51	SE
Discharges to 06-21-D (Group 3)								
06-21-A	0.56	0.80	--	8	91	103	56	SW
06-21-C	--	--	--	46	44	198	14	CP
Discharges to Purgatory Creek, 06-12-A (Group 4)								
06-13-A[3]	--	--	--	1	98	83	63	SW
06-21-D[3]	--	--	--	9	84	105	47	SW
06-24-A	0.09	0.04	--	18	78	132	42	SW
06-42-A	0.82	1.11	--	6	93	96	59	CP
06-42-B	0.09	0.06	--	21	75	143	39	CP
06-41-A	0.43	0.97	--	11	88	111	54	CP

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] CP=Constructed Pond; SW=Stormwater Wetland; SE=Swale.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

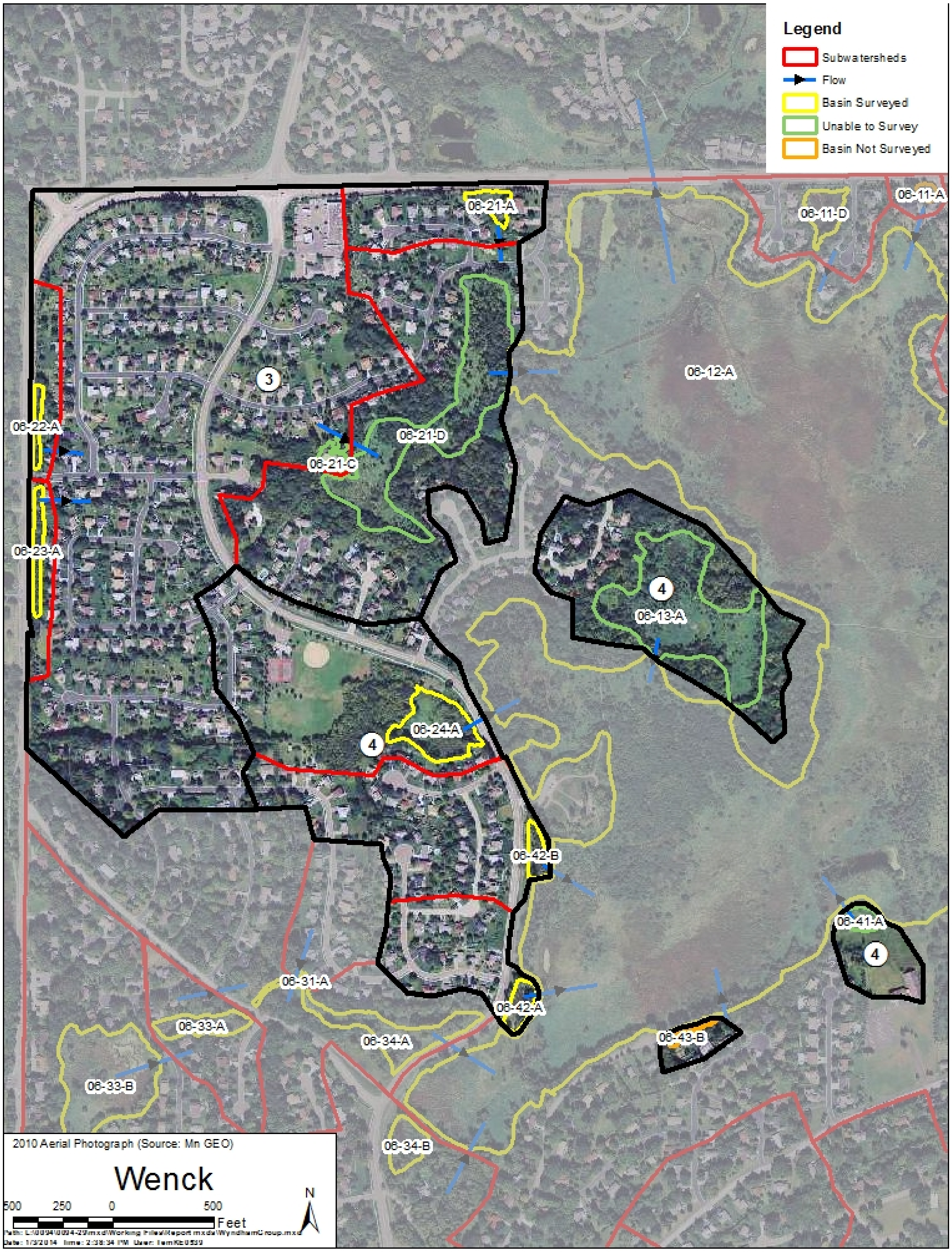

Figure 3.4. Constructed Ponds, Wetlands and Flow Patterns in the Wyndham Knoll Park Area Subwatershed.

3.4.4 Hidden Ponds Park Area

The Hidden Ponds Park drainage area is east of Highway 101 and north of railroad tracks (Table 3.7 and Figure 3.5). The entire area drains to Purgatory Creek. The area was broken into two groupings based on the drainage basins and potential key basins. All the drainage from the Hidden Ponds Park area drains through 06-34-B before discharging to Purgatory Creek. Four of the basins (07-24-A, 07-24-C, 07-24-E, and 07-32-A) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

Almost all of the basins in the Hidden Ponds Park area are designated wetlands which may limit expansion or dredging options. Basin 06-34-B is the only constructed pond in the area and is located at the end of the treatment train which would make it an ideal basin to add additional treatment through expansion or construction of a filter bench. However, the watershed is well ponded and does not require much additional treatment.

Table 3.7. Constructed Pond and Wetland Characteristics for the Hidden Ponds Park Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to 07-24-F (Group 5)								
07-23-A	2.51	0.42	1.63	9	89	106	54	SW
07-24-E	0.38	0.54	--	8	90	104	55	SW
07-32-A[3]	--	--	--	13	84	117	49	SW
Discharges to 07-24-B (Group 5)								
07-24-C[3]	--	--	--	11	86	111	50	SW
07-24-F	3.61	0.65	1.59	6	82	96	34	SW
Discharges in sequence to 07-12-A (Group 5)								
07-24-B	10.56	3.45	4.40	2	85	86	24	SW
07-24-A[3]	--	--	--	2	68	86	9	SW
07-12-C	2.00	3.13	0.55	3	67	87	10	SW
07-12-B	0.59	3.02	0.27	3	46	87	5	SW
Discharges in sequence to Purgatory Creek, 06-12-A (Group 6)								
06-43-A	0.34	0.19	0.15	20	76	139	41	SW
07-12-A	2.81	2.34	1.00	3	70	88	14	SW
06-34-B	1.28	1.52	--	7	65	100	17	CP

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] CP=Constructed Pond; SW=Stormwater Wetland.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

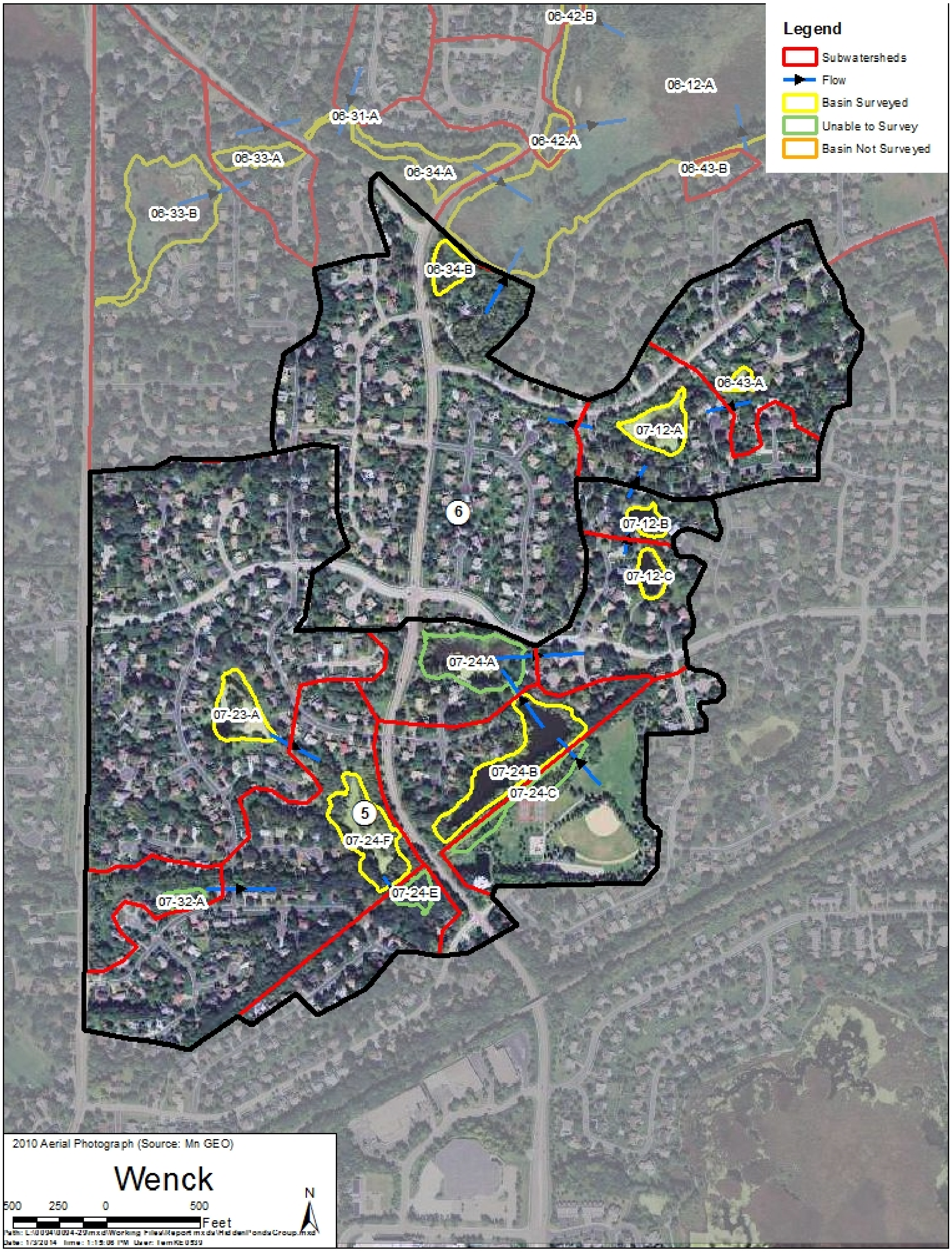

Figure 3.5. Constructed Ponds, Wetlands and Flow Patterns in the Hidden Ponds Park Area Subwatershed.

3.4.5 Miller Park and Highway 212 Area

The Miller Park and Highway 212 area is north of Highway 212 and ultimately drains to Red Rock Lake 16-33-A (Table 3.8 and Figure 3.6). Most of the basins in the area are designated MnDOT basins so any projects proposed for this area would need to be approved by and coordinated with MnDOT. Seven of the basins (17-14-B, 17-14-C, 17-14-D, 17-34-F, 17-42-A, 17-42-D, and 17-43-B) were less than 0.25 acres in size or were private basins, and were not surveyed. Four of the basins (17-41-A, 17-41-B, 17-41-D, and 17-44-B) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

Almost all of the area drains into a few MnDOT basins prior to discharging to Red Rock Lake. These basins include 17-41-C and 17-41-D which captures most of Miller Park prior to discharging to Red Rock Lake. Basin 17-14-A captures most of the area to the north, but is a little undersized and could be expanded. The City would need to work with MnDOT on these projects, but they provide the best opportunity for water quality improvements.

Table 3.8. Constructed Pond and Wetland Characteristics for the Miller Park and Highway 212 Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to 17-41-C (Group 7)								
17-34-A	0.63	0.67	--	4	95	91	60	SW
Discharges in Sequence to 17-41-D (Groups 8 and 10)								
17-43-B[4]	Swale			37	60	188	25	SE
17-43-D[3,4]	2.51	2.37	--	13	73	120	39	CP
17-41-C[4]	13.12	3.42	2.05	16	37	126	8	CP
Discharges to 17-41-D (Group 7)								
17-31-A	0.04	0.01	0.08	22	70	145	33	SW
Discharges in Sequence to 17-41-A (Group 10)								
17-14-A[4]	0.74	0.63	0.99	15	82	126	48	CP
17-41-B[3,4]	--	--	--	18	54	134	19	SW
Discharges to 17-41-A (Group 10)								
17-41-D[3,4]	--	--	--	15	15	125	5	CP
17-44-B[3]	--	--	--	8	90	102	55	CP
Discharges to Red Rock Lake, 16-33-A (Group 10)								
17-41-A[3,4]	--	--	--	5	80	94	34	SW

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] CP=Constructed Pond; SW=Stormwater Wetland; SE=Swale.
[3] Unable to survey basin; surveyed inlets/outlets.
[4] MnDOT basin.
-- Information not available.

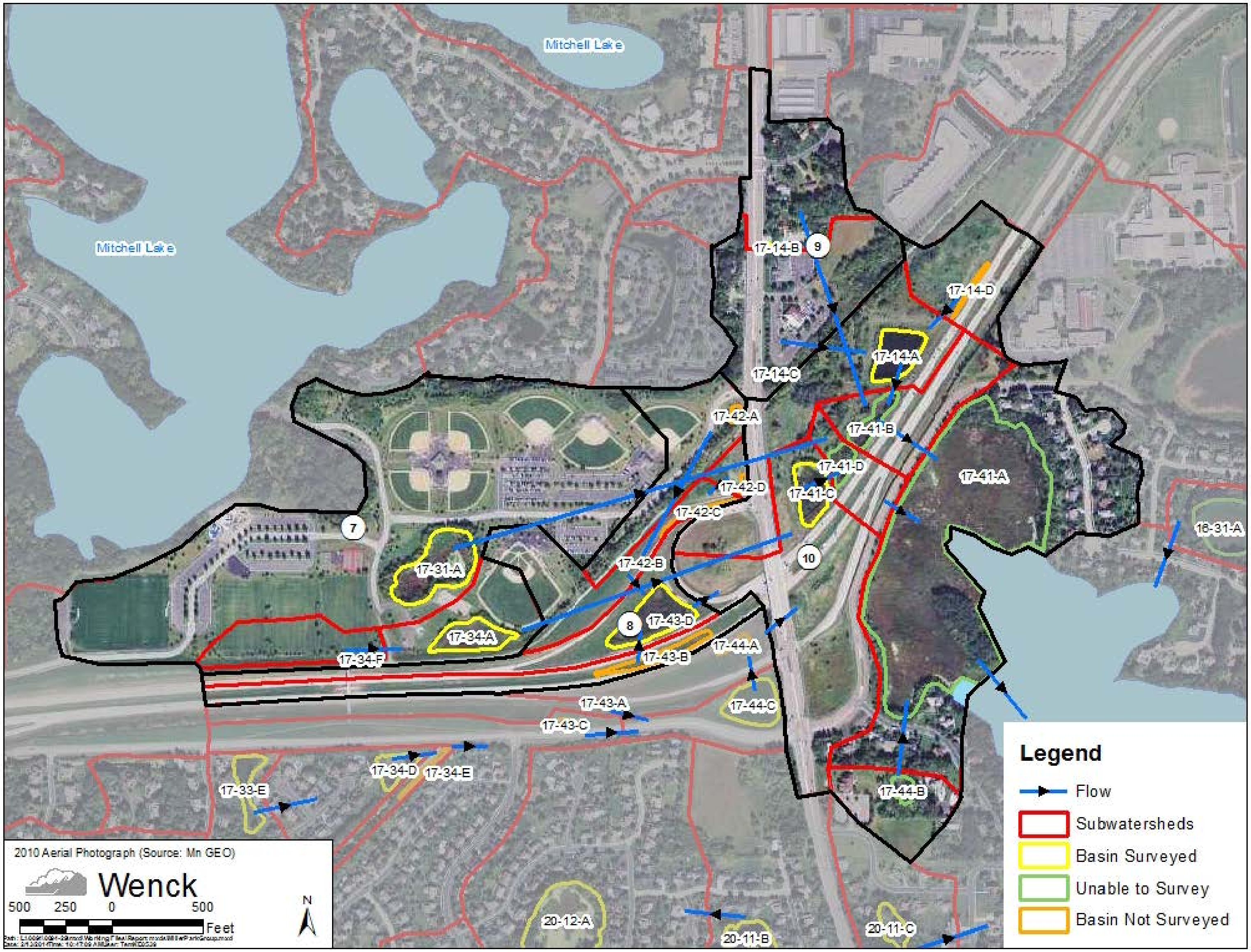

Figure 3.6. Constructed Ponds, Wetlands and Flow Patterns in the Miller Park and Highway 212 Area Subwatershed.

3.4.6 Scenic Heights Road Area

The Scenic Heights Road area receives drainage from west of Eden Prairie Road and south of Highway 212 (Table 3.9 and Figure 3.7). All the drainage from this area is directed to MnDOT basin 17-44-C which eventually drains to Red Rock Lake. Four of the basins (17-34-E, 17-43-A, 17-43-C, 17-44-A) were less than 0.25 acres in size or were private basins, and were not surveyed. Two of the basins (20-22-A, 20-22-B) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

The basins in this area are mostly wetlands and MnDOT basins which may limit the available projects. Basin 17-44-C is oversized and protects the entire watershed. This basin accepts a lot of the drainage from this area but is a designated MnDOT basin so any projects would need to be approved by and coordinated with MnDOT. This basin is a potential candidate for an iron enhanced sand filter to improve the basin's performance for removing dissolved phosphorus. Otherwise, this watershed does not require any improvements.

Table 3.9. Constructed Pond and Wetland Characteristics for the Scenic Heights Road Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges in sequence to 17-44-C								
20-22-A[3]	--	--	--	7	90	102	56	SW
20-22-B[3]	--	--	--	8	83	104	41	SW
17-33-E	1.41	1.44	0.12	5	92	93	51	SW
17-34-D	1.30	1.55	--	4	85	92	35	CP
Discharges to 17-44-C								
17-34-E	Swale			15	79	124	43	SE
Discharges to 17-41-C								
17-44-C[4]	0.83	1.55	0.25	11	82	114	42	CP

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] CP=Constructed Pond; SW=Stormwater Wetland; SE=Swale.
[3] Unable to survey basin; surveyed inlets/outlets.
[4] MnDOT basin.
-- Information not available.

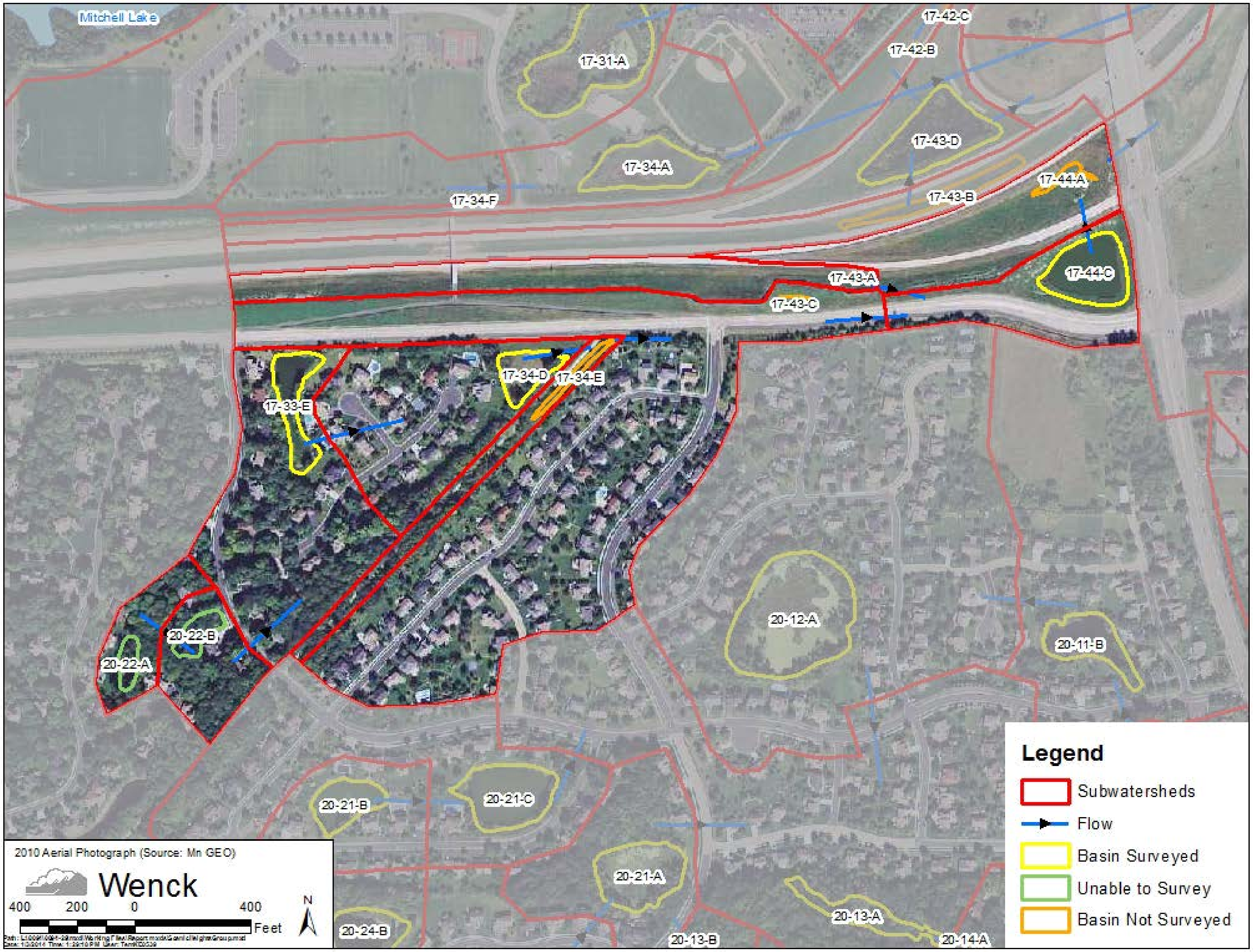

Figure 3.7. Constructed Ponds, Wetlands and Flow Patterns in the Scenic Heights Road Area Subwatershed.

3.4.7 Pioneer Park Area

The Pioneer Park area watershed drains the area north of Pioneer Trail and west of Eden Prairie Road (Table 3.10 and Figure 3.8). Most of the evaluated basins in this area are designated wetlands that drain to 20-14-A before discharging to Red Rock Lake. Two of the basins (20-11-D, 20-13-B) were less than 0.25 acres in size and were not surveyed. Three of the basins (20-13-A, 20-13-C, 20-13-D) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed. Most basins in this area meet NURP standards.

Basin 20-41-A is undersized and could be expanded using some adjacent park land to improve its water quality performance. Basin 20-14-A is large enough that it has capacity to effectively treat stormwater from the contributing watershed (including 20-41-A), however, there is a short circuit between the two basins since there is a shared two directional flow inlet/outlet pipe. Basin 20-14-A is a designated wetland and projects may have some permitting requirements.

Table 3.10. Constructed Pond and Wetland Characteristics for the Pioneer Park Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to 20-21-A (Group 11)								
20-13-B[3]	--	--	--	11	87	113	54	PW
Discharges in sequence to 20-13-A (Group 11)								
20-24-B	1.36	1.11	0.44	5	93	95	59	SW
20-24-A	12.92	1.54	6.16	4	94	92	57	SW
20-21-A	0.00	1.35	--	6	61	99	14	SW
Discharges in sequence to 20-13-A (Group 12)								
20-21-B	1.48	3.06	0.58	2	97	87	63	SW
20-21-C	2.51	2.26	0.94	3	94	89	54	SW
Discharges to 20-11-B (Group 12)								
20-11-A	0.74	1.50	--	6	93	96	61	SW
Discharges in sequence to 20-13-A (Group 12)								
20-11-B	0.21	0.41	0.33	19	71	137	34	SW
20-12-A	10.10	1.99	4.24	4	92	91	51	SW
Discharges in sequence to 20-14-A (Group 13)								
20-13-C[3]	--	--	--	20	76	138	41	SW
20-13-D[3]	--	--	--	14	42	123	16	SW
Discharges to 20-14-A (Group 13)								
20-41-A	0.06	0.07	0.02	33	62	176	28	CP
Discharges to Red Rock Lake, 16-33-A (Group 13)								
20-14-A	12.13	1.83	4.46	5	82	94	30	SW

Note: Sediment volumes only calculated for basins over the open water area.
1 The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
2 CP=Constructed Pond; SW=Stormwater Wetland; PP=Private Pond; PW=Private Wetlands.
3 Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

Figure 3.8. Constructed Ponds, Wetlands and Flow Patterns in the Pioneer Creek Area Subwatershed.

3.4.8 Pheasant Woods Park Area

Pheasant Woods Park area drains the area south of Scenic Heights Road and east of Red Rock Lake (Table 3.11 and Figure 3.9). All the basins in the area are designated wetlands that drain to Red Rock Lake. Four of the basins (16-31-A, 16-44-A, 21-11-C, 21-12-A) were unable to be surveyed because it was too wooded and the cattails were too dense. When possible, inlet and outlet invert elevations were surveyed.

The Pheasant Woods Park area is undertreated as most of the basins are wetlands that have little to no permanent pool. There are limited opportunities for adding stormwater treatment to this watershed. The wetland designation of these basins would limit the project possibilities to improve water quality.

Table 3.11. Constructed Pond and Wetland Characteristics for the Pheasant Woods Park Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges to 21-11-C								
16-42-A	113.56	33.85	4.08	1	99	62	65	SW
Discharges in sequence to Red Rock Lake, 16-33-A								
16-44-A[3]	--	--	--	9	89	106	55	SW
21-11-C[3]	--	--	--	12	47	110	11	SW
21-12-A[3]	--	--	--	5	73	92	27	SW
Discharges to Red Rock Lake, 16-33-A								
16-31-A[3]	--	--	--	4	94	93	61	SW
16-34-A	0.53	0.35	0.18	13	83	119	49	SW

[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] SW=Stormwater Wetland.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

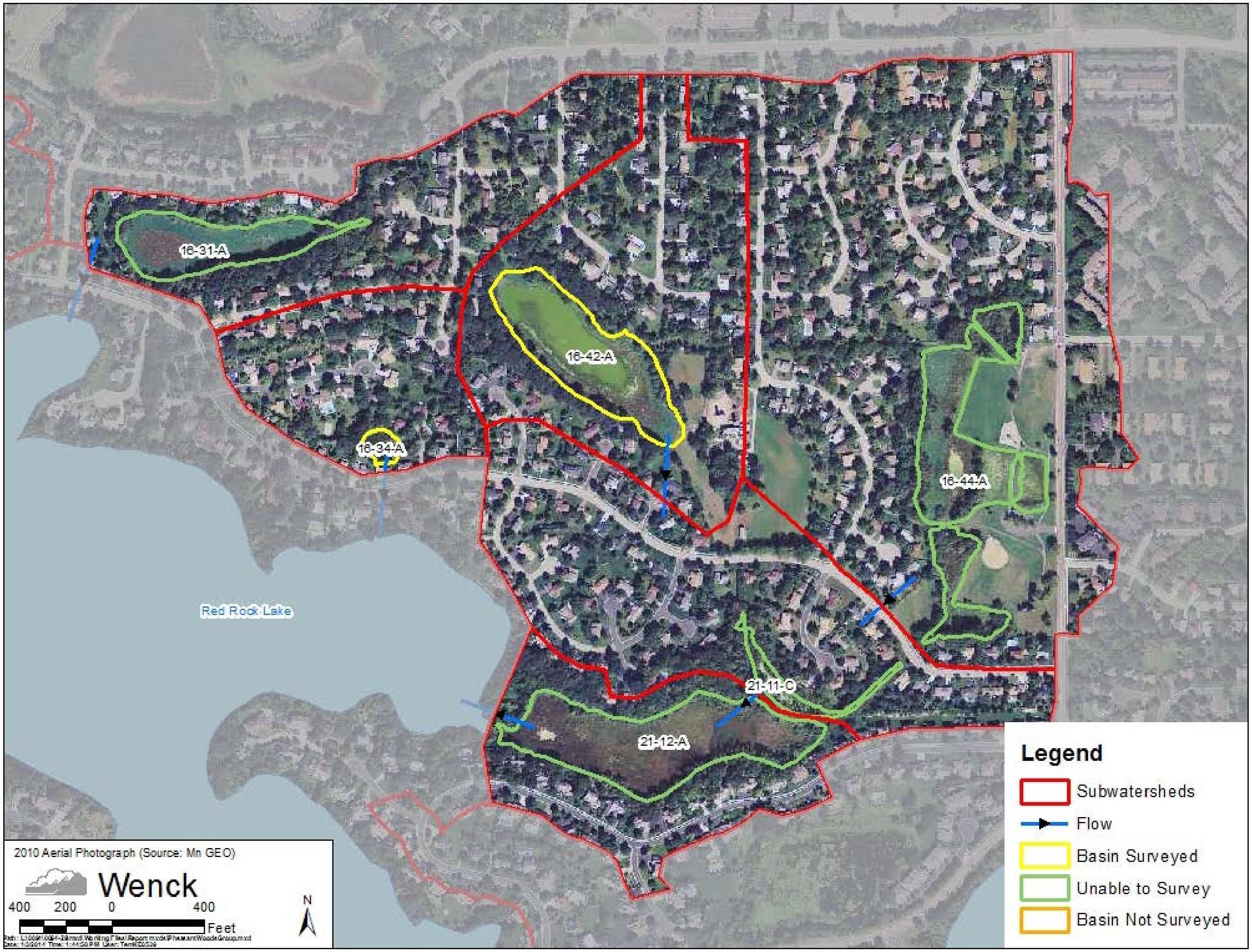

Figure 3.9. Constructed Ponds, Wetlands and Flow Patterns in the Pheasant Woods Park Area Subwatershed.

3.4.9 Red Rock Lake Area

The Red Rock Lake Area basins drain to Red Rock Lake and are north and east of Pioneer Trail and Eden Prairie Road (Table 3.12 and Figure 3-10).

Basin 21-31-A is a constructed pond that could be considered for expansion or dredging because it is undersized to treat the contributing watershed and has minor sediment accumulation.

Basin 21-32-A is also undersized and upstream of basin 21-31-A. This basin could be considered for expansion but may be limited due to site constraints.

Table 3.12. Constructed Pond and Wetland Characteristics for the Red Rock Lake Area Subwatershed.

Basin ID	Surveyed Permanent Pool Volume (AF)	NURP Ratio[1]	Sediment Volume (AF)	P8 Predicted TSS (mg/L)	P8 TSS Removal (%)	P8 Predicted TP (µg/L)	P8 TP Removal (%)	Basin Type[2]
Discharges in sequence to Red Rock Lake, 16-33-A								
21-32-B	0.07	0.22	--	16	82	128	48	CP
21-32-C	0.68	1.02	0.23	7	86	99	45	CP
Discharges in sequence to Red Rock Lake, 16-33-A								
21-32-A	0.02	0.02	--	34	59	178	24	SW
21-31-A	0.69	0.35	0.14	16	77	126	43	CP
Discharges to Red Rock Lake, 16-33-A								
20-11-C	0.88	0.71	0.04	8	90	102	56	SW

Note: Sediment volumes only calculated for basins over the open water area.
[1] The NURP ratio is based on the cumulative area and dead storage to account for basins in sequence. Values over 1 exceed NURP standards and values under 1 do not meet NURP standards.
[2] CP=Constructed Pond; SW=Stormwater Wetland.
[3] Unable to survey basin; surveyed inlets/outlets.
-- Information not available.

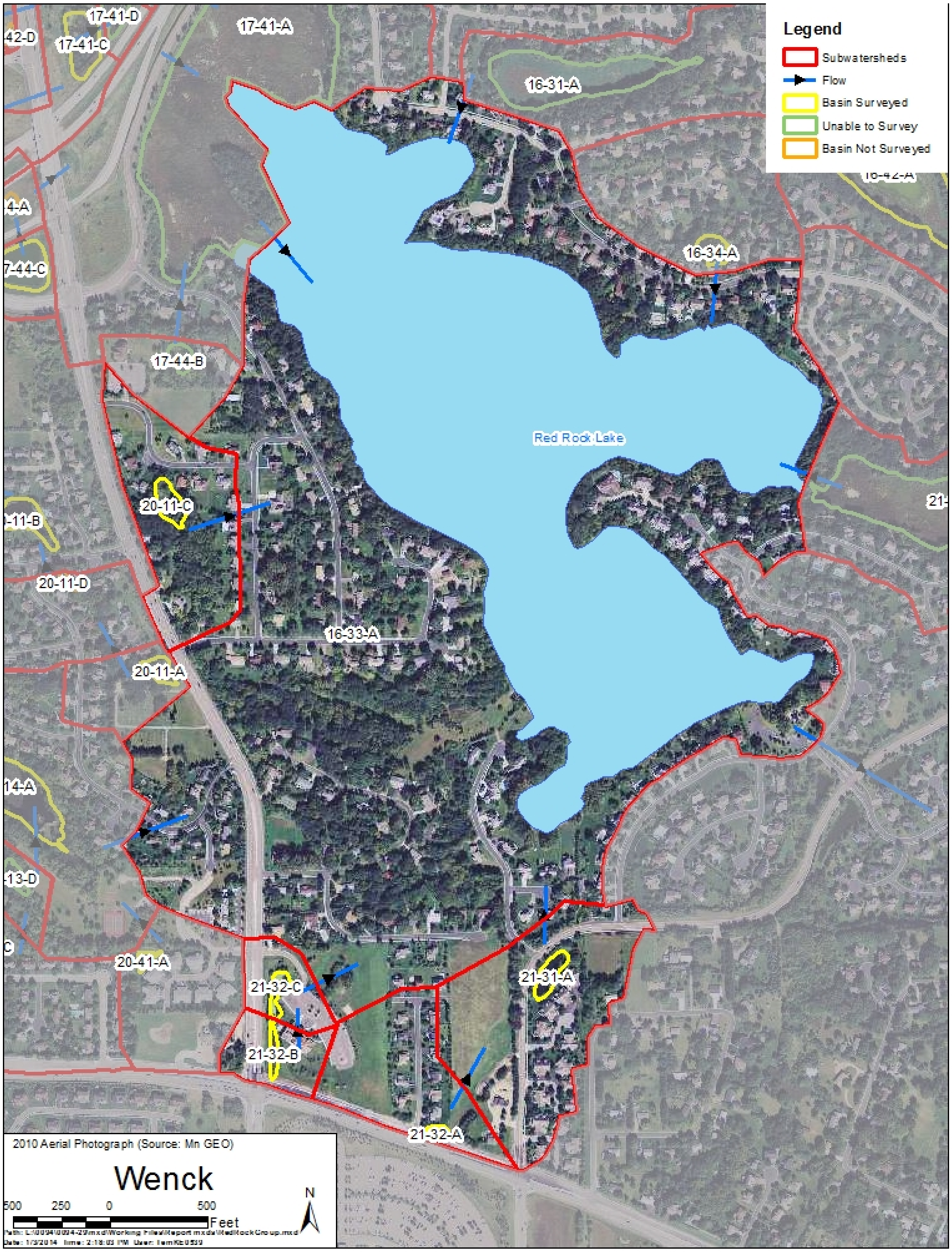

Figure 3.10. Constructed Ponds, Wetlands and Flow Patterns in the South Red Rock Lake Area Subwatershed.

4.0 Lake Nutrient Budget

4.1 INTRODUCTION

A nutrient budget is critical in understanding the potential impacts of stormwater on the receiving water. To that end, a nutrient budget and lake response model were developed for Duck Lake and Red Rock Lake to better understand the role of stormwater on the quality of the lake.

4.2 DUCK LAKE AND WATERSHED CHARACTERIZATION

Duck Lake (DNR Lake ID 27-0069) is an off-line lake on Purgatory Creek, which is a tributary of the Minnesota River. Located in Hennepin County, Duck Lake is just south of Duck Lake Trail and west of Eden Prairie Road. Duck Lake has a carry-on boat public access and is surrounded mainly by single family homes, residential streets, and a railroad along the south edge. During high flows, Duck Lake flows into Purgatory Creek east of Eden Prairie Road and eventually into Staring Lake.

4.2.1 Watershed Land Use and Hydrology

Duck Lake has a watershed that drains approximately 230 acres, which includes Duck Lake. Land use in the Duck Lake watershed is predominantly residential (65%). The second largest land use in the watershed is parks and open space (24%), if you include open water. The remaining 11% is a mix of institutional and undeveloped properties (Table 4.1; Figure 4.1). The watershed does not contain any major highways.

Table 4.1. Land Use Within the Duck Lake Watershed.

Land Use	Acres	Percent
Single Family Detached	149	65%
Open Water	49	21%
Undeveloped	14	6%
Institutional	11	5%
Parks, Recreational, or Preserve	7	3%

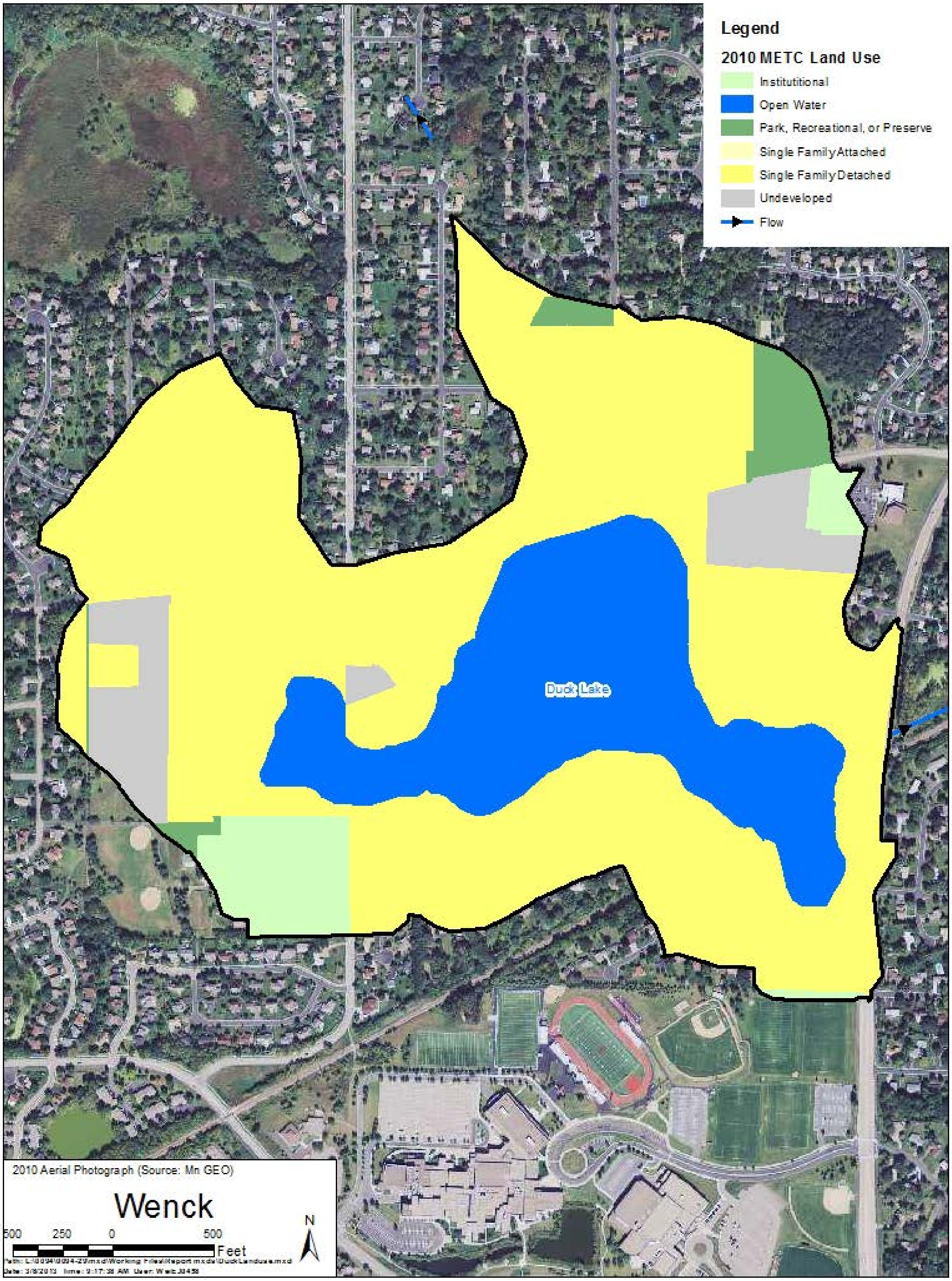

Figure 4.1. Land Use Within the Duck Lake Watershed.

4.2.2 Lake Morphometry

Duck Lake is a small, urban shallow lake with a surface area of 38 acres and a maximum depth of 10 feet (Table 4.2). The Minnesota Pollution Control Agency defines a shallow lake as any lake less than 15 feet in depth or with more than 80% capable of supporting submerged aquatic vegetation. The shallow nature of Duck Lake suggests that the lake should support submerged aquatic vegetation through most if not all of the lake. The area expected to support plant growth (less than 15 feet) is also defined as the littoral zone, the area where light penetration is deep enough to support submerged vegetation. Duck Lake has a large residence time with lake water being replaced by runoff approximately every 1.8 years.

Table 4.2. Duck Lake Characteristics.

Parameter	Duck Lake
Surface Area (acres)	38
Average Depth (feet)	4
Maximum Depth (feet)	10
Volume (acre-feet)	160
Residence Time (years)	1.8
Littoral Area (acres)	47
Littoral Area (%)	100
Watershed (acres)	230

4.2.3 Groundwater

Groundwater was not explicitly incorporated into the water budget of Duck Lake. Based on desktop review of available hydrogeological information, Duck Lake is at an average elevation of approximately 914 feet Above Mean Sea Level (AMSL), roughly 220 feet above the lakes within the adjacent Minnesota River valley. Its morphology suggests a kettle lake in the sandy outwash in the area. According to the Hennepin County Geologic atlas it is at the approximate level of the perched aquifer in the area. Based on its proximity to the Minnesota River valley bluffs, and higher water levels to the north, it appears to be a flow-through lake where shallow groundwater enters along the northern perimeter and discharges from the southern perimeter. There are no perched aquifer wells in the vicinity, based on the Minnesota Department of Health (MDH) well database, so further refinement of the lake’s relationship to the local water table is not possible at this time.

4.2.4 Water Quality

Lake water quality is typically measured by assessing the amount of algal growth and water clarity during the summer growing season. When excessive algae grow in a lake, water clarity is reduced and noxious smells can emit. These are symptoms of lake eutrophication. When lakes become hypereutrophic (excess nutrients leading to heavy algae growth), the entire food web is affected. Changes are found in the algal community and water quality, including depletion of dissolved oxygen and decreased water clarity. A healthy lake has a balanced growth of algae supporting the base of the food chain without degrading water quality or harming biological organisms.

Phosphorus

Algal growth (measured as total chlorophyll-*a*) is typically limited by the amount of phosphorus in the water column. Therefore, total phosphorus is considered the causative factor for algal growth. Water clarity is affected by the amount of algae as well as suspended and dissolved particles in the water column.

The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data from Duck Lake in 2011 and 2012. Blue Water Sciences collected data in 2008, 2009, and 2012. The 2012 May-September summer average of 98 µg/L reported by Blue Water Sciences is excluded in the figure below since individual sample information was unavailable. Summer average total phosphorus concentrations ranged from 38 to 138 µg/L, exceeding the state shallow lake standards for the North Central Hardwood Forest Eco region (<60 µg/L) in three of the four monitored years (Figure 4.2). These concentrations can support large algal populations and maintain Duck Lake in a turbid water state.

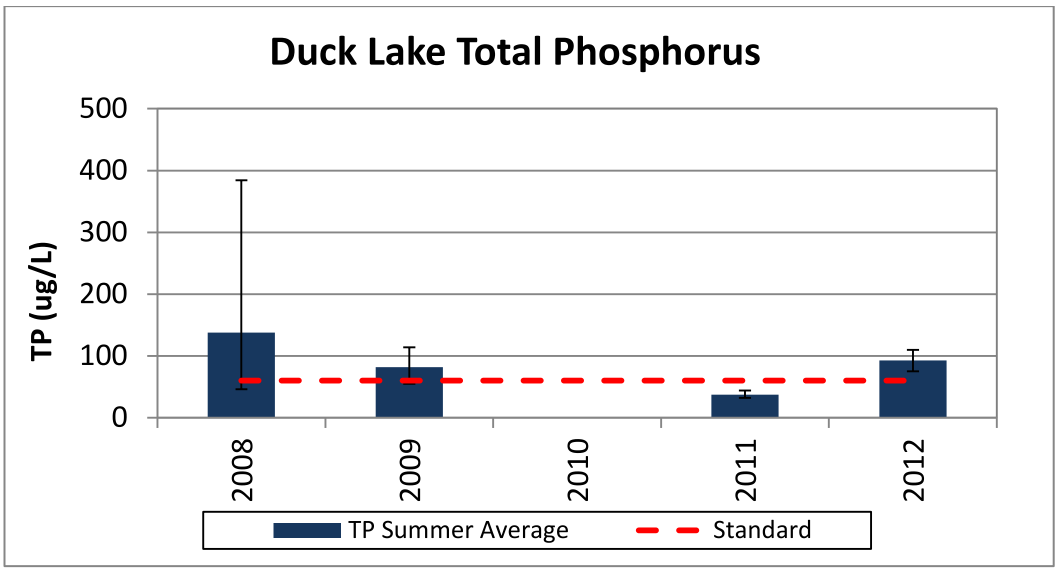

Figure 4.2. Summer (June 1 – September 30) Average Total Phosphorus for Duck Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with more than 4 summer samples are shown on the graph.

Chlorophyll-a

Chlorophyll-*a* is a measure of the amount of algal biomass in a basin at any given time. The greater the algal biomass and corresponding chlorophyll-*a* values, the more green and productive a lake appears with worst case scenarios including algal scum and foul odors. These conditions are considered nuisance algal blooms, and are both aesthetically unpleasing and potentially bad for fish and other biological organisms. Nuisance algal blooms cause poor smells and aesthetics, and can lead to more severe problems such as summer fish kills. Ultimately, a shallow lake should have a modest amount of algal productivity with light penetrating approximately 15 feet into the water column.

The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data from Duck Lake in 2011 and 2012. Blue Water Sciences collected data in 2008, 2009, and 2012. The 2012 May-September summer average of 42.2 µg/L reported by Blue Water Sciences is excluded in the figure below since individual sample information was unavailable. Summer Average chlorophyll-*a* concentrations in Duck Lake are high ranging from 4 to 54 µg/L (Figure 4.3) with two of the four monitored years exceeding the state water quality standard for shallow lakes in the North Central Hardwood Forest Eco region (<20 µg/L as a summer average).

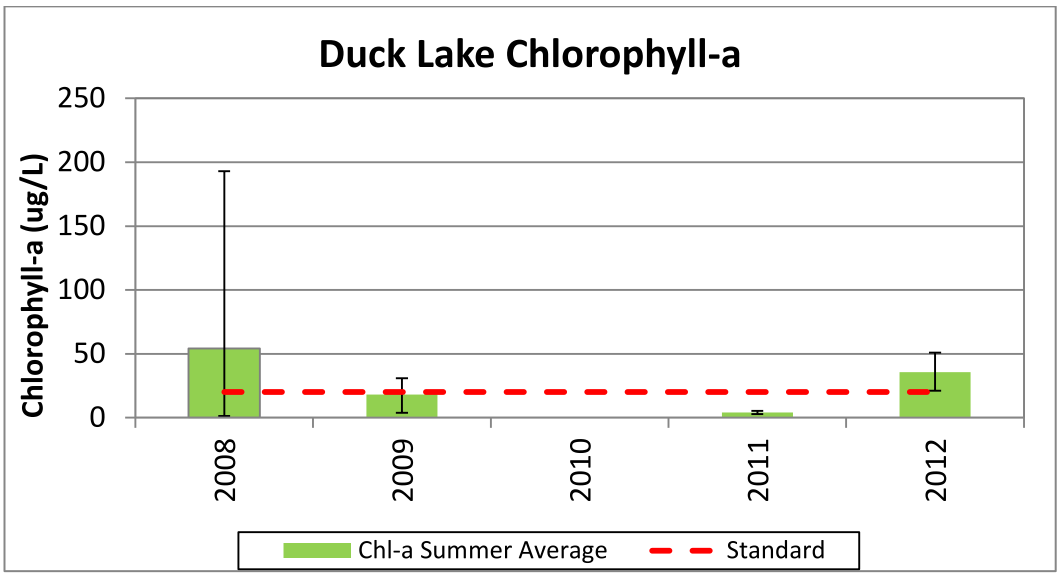

Figure 4.3. Summer (June 1 – September 30) Average Chlorophyll-*a* for Staring Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with more than 4 summer samples are shown on the graph.

Water Clarity

Water clarity in lakes is typically measured using a Secchi disk. A Secchi disk is a black and white disk that is lowered into the water column until it can no longer be seen. The depth at which the disk disappears is known as the Secchi depth and is considered the depth where 90% of the light is extinguished.

Water clarity in shallow lakes is controlled by several factors including the amount of algae in the water column as well as other suspended particles such as suspended sediment as a result of wind resuspension and bioturbation (such as carp). Since Duck Lake is a shallow lake, wind mixing can reach the sediments and stir up particles into the water column.

The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data from Duck Lake in 2011 and 2012. Blue Water Sciences collected data in 2008, 2009, and 2012. Water clarity varies in Duck Lake with summer average Secchi depths ranging from 0.83 meters to 2.15 meters (Figure 4.4). The large algal biomass (see chlorophyll-*a* data) is likely contributing to the clarity in Duck Lake.

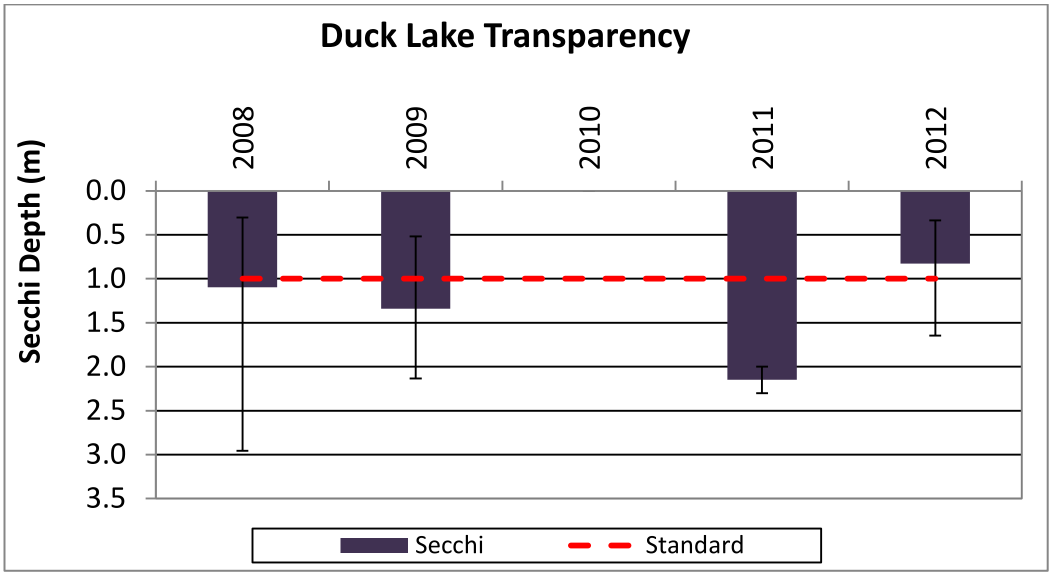

Figure 4.4. Summer (June 1 – September 30) Average Secchi Depth for Duck Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with more than 4 summer samples are shown on the graph.

4.2.5 Fisheries

The Minnesota DNR conducted a fish survey on Duck Lake in 1996. Based on the results of that survey, Duck Lake, which experiences periodic winterkills, is dominated by rough fish (black bullheads) and a few pan fish (black crappie and bluegill) (UAA Report, Barr 2005). Although blue gills are abundant, they are relatively small in size suggesting that the population may be stunted from a lack of top predators. Stunted bluegill populations can negatively affect water quality by reducing the number of cladocerans (zooplankton) that can effectively graze algae and help increase clarity in the water column.

The MN DNR occasionally stocks Duck Lake as part of the 1996 Duck Lake Management Plan.

4.2.6 Aquatic Vegetation

A submerged aquatic vegetation survey was completed on Duck Lake in May and August of 2012 by Blue Water Science. During the May visit, the lake was dominated by Curly-leaf pondweed (showing up at 58 of the 66 sites sampled) and Coontail being at 52 of the 66 sites. There were a total of 6 species of submerged aquatic vegetation present during the May visit which is considered to be low plant diversity. Aquatic plant coverage was about 36 of the 47 acres of Duck Lake.

During the August visit, Coontail was the dominant plant and was found at 59 of the 66 sampled sites. The next most abundant plant was Water Stargrass which was found at 10 of the sample sites. No Eurasian Watermilfoil was observed during the May or August visit.

Duck Lake has a submerged aquatic vegetation community to a water depth of about 9 feet. Submerged aquatic vegetation are critical in shallow lakes because they stabilize lake sediments preventing wind resuspension of sediments and also provide refugia for cladocerans to avoid fish predation.

4.3 PHOSPHORUS SOURCES

One of the primary drivers for lake productivity or algal growth is phosphorus. To better understand what is driving water quality in Duck Lake, a detailed phosphorus budget needs to be developed to identify both the sources and magnitude of the phosphorus sources. Phosphorus sources to lakes include stormwater runoff, internal sediment release of phosphorus, and direct atmospheric deposition of phosphorus to the lakes surface. In this section, a brief description of the potential source of phosphorus to Duck Lake is provided.

4.3.1 Atmospheric Deposition

Precipitation picks up dust particles that contain phosphorus that can ultimately end up in Duck Lake as a result of direct input on the basin surface or as a part of stormwater runoff from impervious surfaces in the watershed. Although they must be accounted for in development of a nutrient budget, atmospheric inputs are difficult if not impossible to control and are usually small compared to other sources (internal and external).

Atmospheric inputs of phosphorus from wet and dry deposition are estimated using rates set forth in the MPCA report "Detailed Assessment of Phosphorus Sources to Minnesota Watersheds" (Barr Engineering, 2004), and are based on annual precipitation. The values used for dry (< 25 inches), average, and wet precipitation years (>38 inches) for atmospheric deposition are 24.9, 26.8, and 29.0 kg/km^2-year, respectively. These values are equivalent to 0.22, 0.24, and 0.26 pounds/acre-year for dry, average, and wet years in English units, respectively.

4.3.2 Stormwater

Phosphorus transported by stormwater represents one of the largest external contributors of phosphorus to surface waters in Minnesota. Impervious surfaces and storm sewer systems in the watershed improve the efficiency of runoff moving to streams, wetlands and lakes, resulting in increased transport of phosphorus into local basins. Phosphorus in stormwater is a result of leaves and grass clippings, fertilizers, sediments, pet waste, excessive lawn watering, automobiles and illicit sanitary sewer connections. Managing stormwater is a high-priority concern in urban watersheds.

Excess fertilizer applied to lawns is readily transported to local streams, wetlands and lakes during runoff events and is immediately available for algal growth. However, State law prohibits the use of lawn fertilizer containing phosphorus except when new lawns are being established by seeding or laying sod or when soil testing shows a need for additional phosphorus.

Stormwater runoff discharges into Duck Lake either without treatment (51%) or with treatment (49%).

4.3.3 Internal Loading

Over time, basins tend to accumulate phosphorus in their bottom sediments. One of the primary bonds for phosphorus is with iron. When oxygen is depleted near the sediment surface (water concentration less than 2.0 mg/L), phosphorus-iron ($FePO_4$) bonds and other chemical bonds are broken, releasing dissolved phosphorus for transport into the water column. This phosphorus is in a dissolved form that is readily available to algae and plants.

Internal phosphorus loading from sources already in basins has been demonstrated to be an important aspect of the phosphorus budgets of basins. However, measuring or estimating internal loads can be difficult, especially in shallow lakes that may mix many times throughout the year. To estimate internal loading, an anoxic factor (Nürnberg 2004), which estimates the period where anoxic conditions exist over the sediments, is estimated from the dissolved oxygen profile data. The anoxic factor is expressed in days but is normalized over the area of the lake. The anoxic factor is then used along with a sediment release rate to estimate the total phosphorus load from the sediments.

Because shallow lakes mix often, and dissolved oxygen data is typically collected every other week or monthly, a shallow lake equation that uses morphometry and lake water quality was applied to estimate internal load.

Phosphorus release rates were estimated by collecting cores from Duck Lake and incubating them in the lab under anoxic conditions (UW-Stout 2013; Appendix B). Table 4.3 summarizes the internal loading for Duck Lake.

Table 4.3. Internal Phosphorus Load Summary for Duck Lake.

Year	Release Rate ($mg/m^2/day$)	AF	Gross Load ($mg/m^2/summer$)	Kilograms	Pounds
Average	3.3	42.1	157	24	53
Oxic	0.54	NA	85	6	14

4.4 SOURCE SUMMARY AND CURRENT PHOSPHORUS BUDGET

The following is a description of the primary sources of phosphorus to Duck Lake based on the phosphorus source inputs and lake response (BATHTUB) modeling.

4.4.1 BATHTUB Model Fit

Lake response modeling was conducted for two years (2011 and 2012), where good data were available for Duck Lake. During these two years, Duck Lake demonstrated vastly different water quality conditions even though environmental conditions were similar. Additional data should be collected to calibrate the model to a greater extent (Figure 4.5).

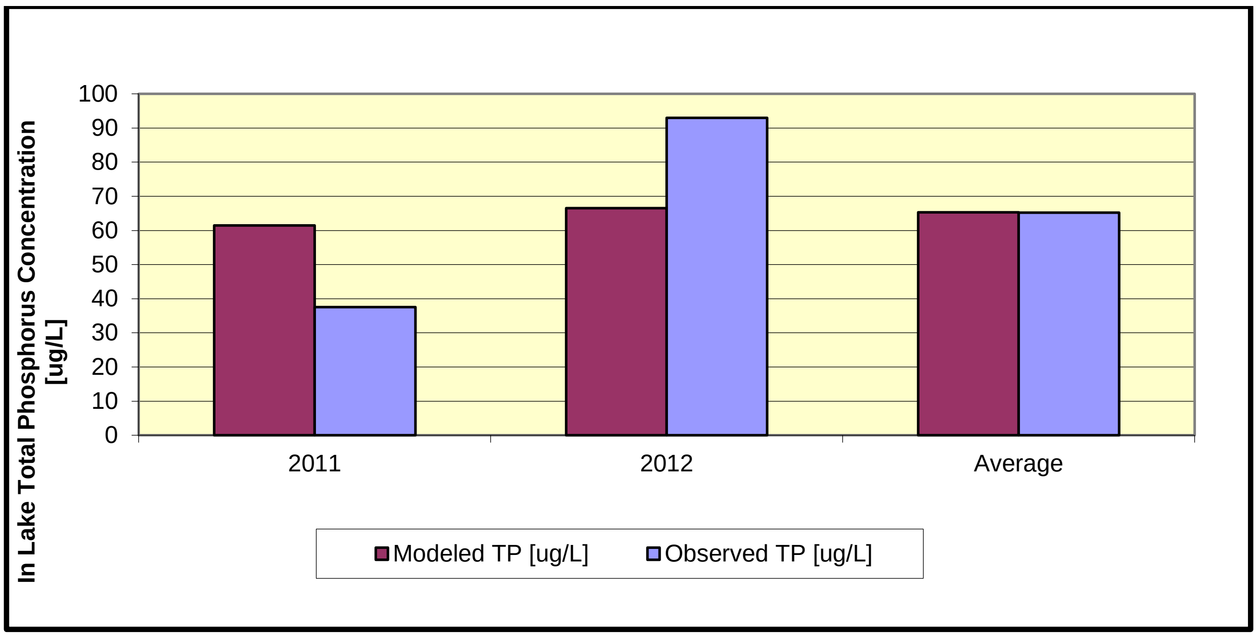

Figure 4.5. Modeled and Monitored In-Lake Total Phosphorus Concentrations.

4.4.2 Lake Phosphorus Budget

An average of the two modeled years was used to develop an average total phosphorus budget for Duck Lake (Figure 4.6). Internal loading represents 66% of the total phosphorus inputs to Duck Lake with stormwater comprising 25% of the total phosphorus load. Internal load is the dominant source of phosphorus to Duck Lake; however stormwater still plays a significant role in the phosphorus budget.

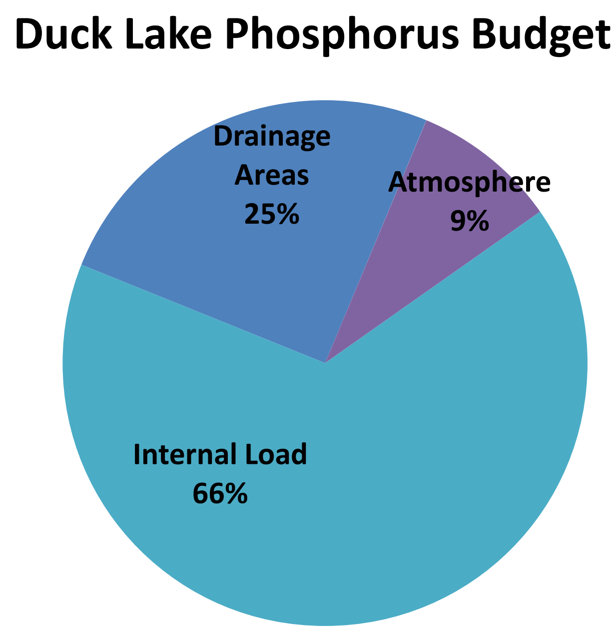

Figure 4.6. Phosphorus Sources for Duck Lake.

4.4.3 Phosphorus Load Reductions

To determine the required phosphorus loads to meet State water quality standards for shallow lakes in the North Central Hardwood Forest Ecoregion (NCHF; Table 4.3), the baseline phosphorus budget was used to determine the response of Duck Lake to total phosphorus reductions.

Table 4.4. Numeric Water Quality Goals for Duck Lake.

Intended Use	Average June-September Values		
	Total Phosphorus (µg/L)	**Chlorophyll-*a* (µg/L)**	**Secchi Depth (m)**
Indirect Contact Recreation	≤60	≤20	≥1

To meet this quality goal, modeling suggests a total reduction of 14.4 pounds of phosphorus loading to Duck Lake needs to occur. Table 4.4 breaks the watershed loading reduction into smaller subwatershed reduction requirements. The watershed loads were reduced until the baseline lake response model predicted a summer average of 60 µg/L total phosphorus. Currently, reductions for Duck Lake focus on the watershed even though the internal load accounted for over half of the phosphorus budget. This was because the average anoxic factor for Duck Lake is low. Since Duck Lake has a dense population of Curly-leaf Pondweed and rough fish, restoration efforts should focus there prior to large expenditures in the watershed. Monitoring data suggests that the current loading to Duck Lake is sustainable, rather internal lake processes are affecting water quality. Rain gardens and other small water quality practices could be considered in the direct drainage area to Duck Lake to maintain water quality once the lake goals are met.

Table 4.5. Current and predicted phosphorus loading to meet the state water quality standards in Duck Lake.

	Current TP Load (pounds)	TP Load at the Standard (pounds)	Required Reduction (pounds)	Percent Reduction
Duck Lake (no treatment)	22.7	13.2	9.5	42%
Duck Lake (treatment)	11.7	6.8	4.9	42%
Internal Load	66.7	66.7	0	0%
Atmospheric	9.1	9.1	0	0%
TOTAL	110.2	95.8	14.4	13%

4.5 RED ROCK LAKE AND WATERSHED CHARACTERIZATION

Red Rock Lake (DNR Lake ID 27-0076) is an off-line lake to Purgatory Creek, a tributary of the Minnesota River. Located in Hennepin County, Red Rock Lake is just south of Round Lake, Mitchell Lake and Highway 212, and east of Eden Prairie Road. Red Rock Lake has public access and is surrounded by parks and single family homes. Round Lake, Mitchell Lake and Red Rock Lake were connected by a series of pipes in 1988 to stabilize lake levels. During high flows, the lakes flow into McCoy Lake and eventually Staring Lake.

4.5.1 Watershed Land Use and Hydrology

Red Rock Lake has a watershed that drains approximately 2625 acres, which does include Red Rock Lake itself. Land use in the Red Rock Lake watershed is predominantly residential (55%) and open space (29%). The remaining land uses are institutional, industrial and commercial (10%), and major highways 212 and 5 (6%) (Table 4.6; Figure 4.7). The watershed also includes Round Lake and Mitchell Lake to the north.

Table 4.6. Land Use Within the Red Rock Lake Watershed.

Land use	Acres	%
Single Family Detached	1261	48%
Park, Recreational, or Preserve	400	15%
Open Water	260	10%
Single Family Attached	167	6%
Major Highway	148	6%
Institutional	130	5%
Industrial and Utility	103	4%
Undeveloped	101	4%
Multifamily	32	1%
Retail and Other Commercial	9.5	<1%
Office	5.9	<1%
Agricultural	5.2	<1%
Mixed Use Commercial	1.9	<1%

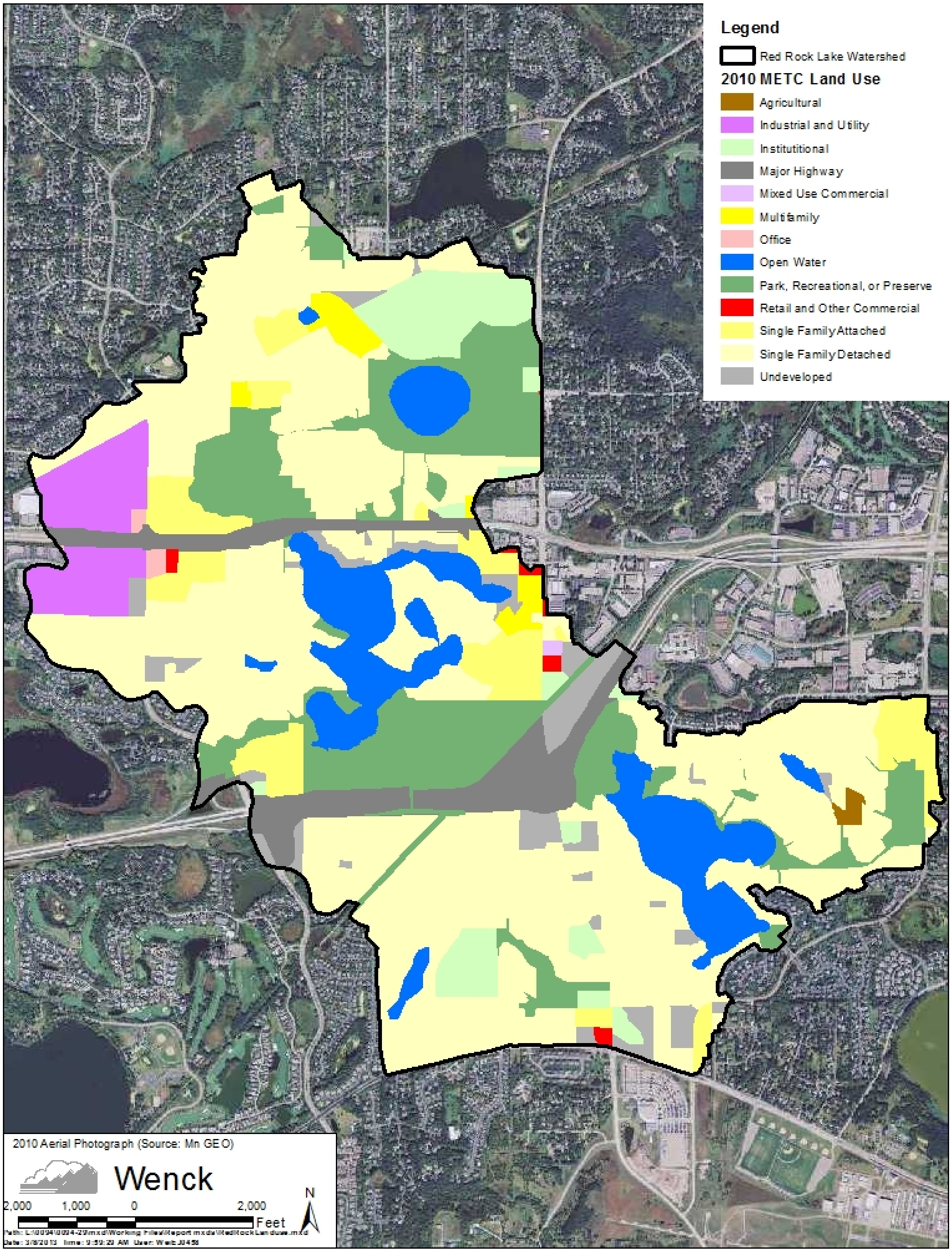

Figure 4.7. Land Use Within the Red Rock Lake Watershed.

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4.5.2 Lake Morphometry

Red Rock Lake is a small, urban shallow lake with a surface area of 108 acres and a maximum depth of 16 feet (Table 4.7). The Minnesota Pollution Control Agency defines a shallow lake as any lake less than 15 feet in depth or with more than 80% capable of supporting submerged aquatic vegetation. The shallow nature of Red Rock Lake suggests that the lake should support submerged aquatic vegetation through most if not all of the lake. The area expected to support plant growth (less than 15 feet) is also defined as the littoral zone, the area where light penetration is deep enough to support submerged vegetation. Red Rock Lake has a short residence time with lake water being replaced by runoff approximately every 120 days. This suggests that the lake will be more sensitive to stormwater runoff then neighboring Duck Lake, which has a residence time of 657 days.

Table 4.7. Red Rock Lake Characteristics.

Parameter	Red Rock Lake
Surface Area (acres)	97
Average Depth (feet)	4
Maximum Depth (feet)	16
Volume (acre-feet)	375
Residence Time (years)	0.33
Littoral Area (acres)	97
Littoral Area (%)	100
Watershed (acres)	2625

4.5.3 Groundwater

Groundwater was not explicitly incorporated into the water budget of Red Rock Lake. Based on desktop review of available hydrogeological information, Red Rock Lake is at an average elevation of approximately 840 feet AMSL, roughly 150 feet above the lakes within the adjacent Minnesota River valley. According to the Hennepin County Geologic Atlas, it is at the approximate level of the perched aquifer in the area. Based on its proximity to the Minnesota River valley bluffs, and the surrounding water levels, it appears to be a flow-through lake where shallow groundwater enters along the northern perimeter and discharges from the southern perimeter. There are no perched aquifer wells in the vicinity, based on the Minnesota Department of Health (MDH) well database, so further refinement of the lake's relationship to the local water table is not possible at this time.

4.5.4 Water Quality

Lake water quality is typically measured by assessing the amount of algal growth and water clarity during the summer growing season. When excessive algae grow in a lake, water clarity is reduced and noxious smells can emit. These are symptoms of lake eutrophication. When lakes become hypereutrophic (excess nutrients leading to heavy algae growth), the entire food web is affected. Changes are found in the algal community and water quality, including depletion of dissolved oxygen and decreased water clarity. A healthy lake has a balanced growth of algae supporting the base of the food chain without degrading water quality or harming biological organisms.

Phosphorus

Algal growth (measured as total chlorophyll-*a*) is typically limited by the amount of phosphorus in the water column. Therefore, total phosphorus is considered the causative factor for algal growth. Water clarity is affected by the amount of algae as well as suspended and dissolved particles in the water column.

The Metropolitan Council Environmental Services collected water quality data from Red Rock Lake in 2000, 2003, 2004, and 2006. The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data in 2011 and 2012. Blue Water Sciences collected data in 2008, 2009, 2010, and 2012. Summer average total phosphorus concentrations ranged from 30.8 to 98.9 µg/L, exceeding the state shallow lake standards for the North Central Hardwood Forest Eco region (<60 µg/L) in 5 of the 9 monitored years (Figure 4.8). These concentrations can support large algal populations and maintain Red Rock Lake in a turbid water state. Phosphorus concentrations have dropped below the standard for the last three years sampled (2010, 2011 and 2012).

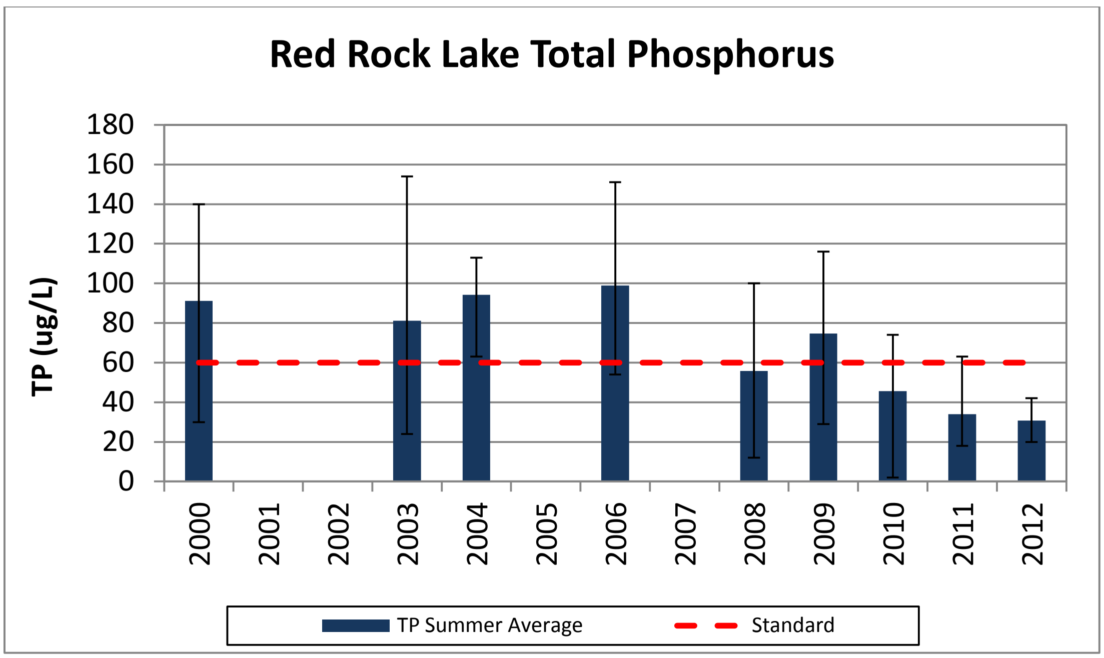

Figure 4.8. Summer (June 1 – September 30) Average Total Phosphorus for Red Rock Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with 4 or more summer samples are shown on the graph.

Chlorophyll-a

Chlorophyll-*a* is a measure of the amount of algal biomass in a basin at any given time. The greater the algal biomass and corresponding chlorophyll-*a* values, the more green and productive a lake appears with worst case scenarios including algal scum and foul odors. These conditions are considered nuisance algal blooms, and are both aesthetically unpleasing and potentially bad for fish and other biological organisms. Nuisance algal blooms cause poor smells and aesthetics, and can lead to more severe problems such as summer fish kills. Ultimately, a shallow lake should have a modest amount of algal productivity with light penetrating approximately 15 feet into the water column.

The Metropolitan Council Environmental Services collected water quality data from Red Rock Lake in 2003, 2004, and 2006. The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data in 2011 and 2012. Blue Water Sciences collected data in 2008, 2009, 2010, and 2012. Summer Average chlorophyll-*a* concentrations in Red Rock Lake are extremely high ranging from 4.3 to 79 µg/L (Figure 4.9) with 6 of the 8 monitored years exceeding the state water quality standard for shallow lakes in the North Central Hardwood Forest Eco region (<20 µg/L) as a summer average. The last two sampled years (2011 and 2012) were below state standards.

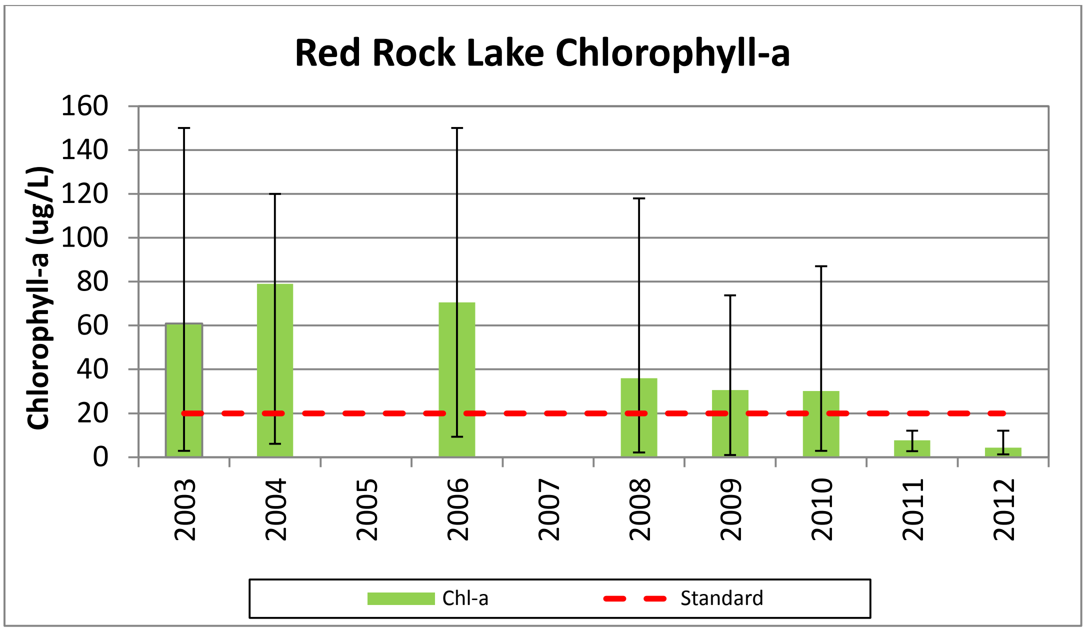

Figure 4.9. Summer (June 1 – September 30) Average Chlorophyll-*a* for Red Rock Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with 4 or more summer samples are shown on the graph.

Water Clarity

Water clarity in lakes is typically measured using a Secchi disk. A Secchi disk is a black and white disk that is lowered into the water column until it can no longer be seen. The depth at which the disk disappears is known as the Secchi depth and is considered the depth where 90% of the light is extinguished.

Water clarity in shallow lakes is controlled by several factors including the amount of algae in the water column as well as other suspended particles such as suspended sediment as a result of wind resuspension and bioturbation (such as carp). Since Red Rock Lake is a shallow lake, wind mixing can reach the sediments and stir up particles into the water column.

The Metropolitan Council Environmental Services collected water quality data from Red Rock Lake in 2003, 2004, 2006, and 2011. The Riley-Purgatory-Bluff Creek Watershed District (RPBCWD) collected water quality data in 2011 and 2012. The citizen Lake Monitoring Program collected water quality data in 2006, 2011, and 2012. Blue Water Sciences collected data in 2008, 2009, 2010, and 2012. Water clarity is acceptable in Red Rock Lake with summer average Secchi depths ranging from 1.1 to 2.5 meters (Figure 4.10). The large algal biomass (see chlorophyll-*a* data) could be contributing to the clarity in Red Rock Lake.

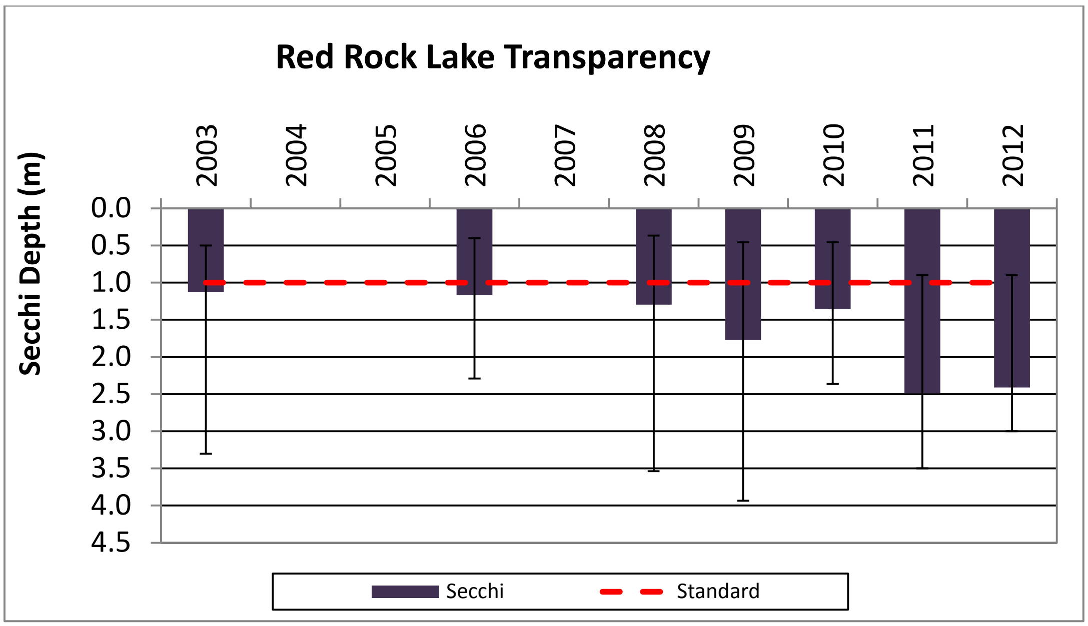

Figure 4.10. Summer (June 1 – September 30) Average Secchi Depth for Red Rock Lake. The red line indicates the State of Minnesota's standard for shallow lakes in the North Central Hardwood Forest Eco region. Error bars represent the minimum and maximum values. Only data with 4 or more summer samples are shown on the graph.

Fisheries

The Minnesota DNR conducted a fish survey on Red Rock Lake in 2011. Based on the results of that survey, Red Rock Lake is dominated by panfish (bluegills and pumpkinseeds), northern pike and yellow perch. Although bluegills and pumpkinseeds are abundant, they are relatively small in size suggesting that the population may be stunted from a lack of top predators. Stunted bluegill populations can negatively affect water quality by reducing the number of cladocerans (zooplankton) that can effectively graze algae and help increase clarity in the water column. Rough fish are present in low numbers in Red Rock Lake and no common carp were sampled in the 2011 survey.

4.5.5 Aquatic Vegetation

A submerged aquatic vegetation survey was completed on Red Rock Lake in May and August of 2012 by Blue Water Science. During the May visit, submerged aquatic vegetation was moderately diverse with 10 different species. The most common plant (Curly-leaf pondweed) showing up at 106 of the 160 sites sampled. Aquatic plant coverage was about 36 of the 97 acres of Red Rock Lake.

During the August visit, 11 submerged aquatic vegetation species were found covering 61 of the 97 acres. Coontail was the dominant plant species. Eurasian watermilfoil was not found during either survey.

Red Rock Lake has a moderate submerged aquatic vegetation community. Submerged aquatic vegetation is critical in shallow lakes because they stabilize lake sediments preventing wind resuspension of sediments. Submerged aquatic vegetation also provides refugia for cladocerans to avoid fish predation.

4.6 PHOSPHORUS SOURCES

4.6.1 Atmospheric Deposition

See section 4.3.1 for more information on atmospheric deposition of phosphorus.

4.6.2 Stormwater

The Red Rock Lake direct watershed represents approximately 43% of the Red Rock Lake watershed. Stormwater runoff from the direct watershed discharges into Red Rock Lake either without treatment (16%) or with treatment (84%).

See section 4.3.2 for additional information on stormwater phosphorus sources.

4.6.3 Internal Loading

Phosphorus release rates were estimated by collecting cores from Red Rock Lake and incubating them in the lab under anoxic conditions (**UW-Stout 2012; Appendix B**). Table 4.8 summarizes the internal loading for Red Rock Lake.

Table 4.8. Internal Phosphorus Load Summary for Red Rock Lake.

Year	Release Rate ($mg/m^2/day$)	AF	Gross Load ($mg/m^2/summer$)	Kilograms	Pounds
Average Anoxic	2.4	57.24	94.58	19	41
Oxic	0.82	NA	67.67	16	35

4.7 SOURCE SUMMARY AND CURRENT PHOSPHORUS BUDGET

Following is a description of the primary sources of phosphorus to Red Rock Lake based on the phosphorus source inputs and lake response (BATHTUB) modeling. Lake response modeling was conducted for 4 years (2009-2012). Additional data should be collected to calibrate the model to any great extent.

4.7.1 Lake Phosphorus Budget

An average of the 4 modeled years was used to develop an average total phosphorus budget for Red Rock Lake (Figure 4.11). Internal loading represents 20% of the total phosphorus inputs to Red Rock Lake with stormwater comprising 59% of the total phosphorus load and 15% coming from upstream lakes Round and Mitchell. Stormwater is the dominant source of phosphorus to Red Rock Lake; however, internal load and upstream lakes play a significant role in the phosphorus budget.

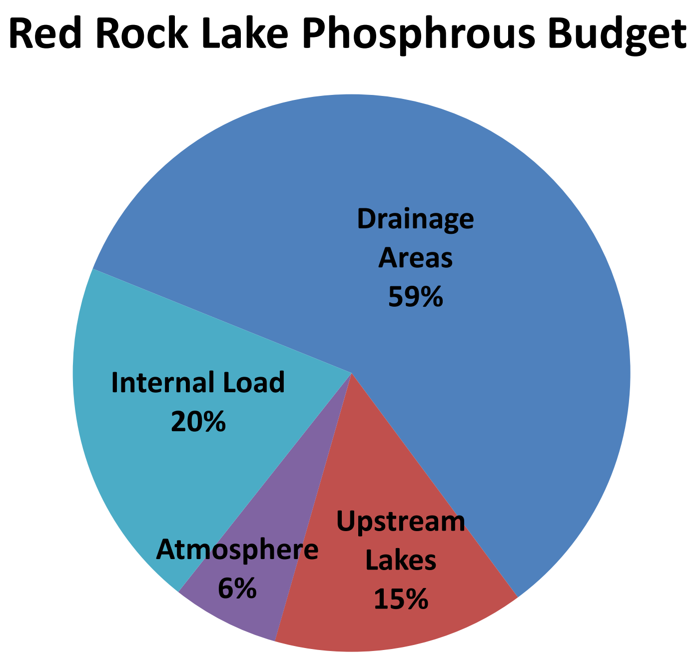

Figure 4.11. Phosphorus Sources for Red Rock Lake.

4.7.2 Phosphorus Load Reductions

Water quality in Red Rock Lake in the last four years has improved below the standard. No projects have been completed in the Red Rock Lake or the upstream lakes that would explain this decrease. However, a fish kill reportedly did occur recently in the lake. Since the water quality in Red Rock Lake meets the State water quality standards for shallow lakes in the North Central Hardwood Forest Ecoregion (NCHF; Table 4.9) for phosphorus, chlorophyll-a and transparency, no reductions are necessary based on current data.

Table 4.9. Numeric Water Quality Goals for Red Rock Lake.

Intended Use	Average June-September Values		
	Total Phosphorus (µg/L)	**Chorophyll-*a* (µg/L)**	**Secchi Depth (m)**
Indirect Contact Recreation	≤60	≤20	≥1

Continued monitoring of Red Rock Lake water quality is suggested to determine if the Lake stays below state standards.

Upcoming phases of the inventory and maintenance assessment will include the Round Lake and Mitchell Lake watersheds which will identify projects to improve water quality in the watersheds contributing to those lakes. Round Lake and Mitchell Lake ultimately drain to Red Rock Lake so projects identified during those phases will also improve water quality in the downstream waters such as Red Rock Lake.

5.0 Conclusions and Recommendations

5.1 INTRODUCTION

As part of their MS4 requirements, the City must inspect all outfalls, constructed ponds and stormwater wetlands each permit cycle. The City's current stormwater inventory includes more than 970 constructed ponds, wetlands, mitigation wetlands, infiltration BMPs, ditches, swales and creek segments that receive or route stormwater. For the purposes of this initial evaluation the City was divided up into a number of subwatersheds centering on lakes or creeks. Stormwater ponding areas (constructed ponds, infiltration BMPs and stormwater wetlands) that are either within a drainage easement, on public land or receive public drainage were evaluated.

The purpose of this study was to enhance the understanding of the City's maintenance responsibilities, assist City staff with scheduling and budgeting resources, and maintain compliance with the City's MS4 SWPPP. To that end, the City will use this information to guide annual implementation and maintenance activities.

The results of the survey were used to identify needed maintenance issues, key basins in treatment trains, and basins that either need excavation due to sediment deposition or that can be expanded to improve the efficiency of the system.

5.2 INVENTORY CONTINUATION AND SCHEDULE

The intent of the survey was to identify key constructed ponds or stormwater wetlands that need maintenance or could be expanded; however the survey can also be used to identify key basins in a treatment train, basins that are experiencing sedimentation, and basins that are oversized or non-critical in protecting receiving water quality. Following are the goals of this assessment:

- Prioritize and schedule basins for future inspections and schedules.

- Routinely inspect all basins as required in the City's MS4 Permit for any visual signs of maintenance needs using the City's visual inspection protocol (City of Eden Prairie Stormwater Inventory, Maintenance, and Inspection Plan dated 3/18/11). These basins were identified based on evidence of potential sedimentation and location in the treatment train.

- Evaluate high-priority basins every inventory cycle for sediment accumulation estimates.

- Determine if the cycle could be adjusted based on the results.

- Other basins should be evaluated a minimum of once during every other inventory cycle, which is estimated as 12 years per cycle.

None of the basins in the project area demonstrated enough sediment accumulation to warrant a more frequent schedule based on the age of the basins versus the amount of sediment accumulated.

5.3 SEDIMENT REMOVAL MAINTENANCE

Basins were identified for maintenance based on their position in the watershed and treatment train, their permanent pool volume as compared to NURP requirements, and signs of sedimentation. Basins with as-built information were also considered for expansion when the as-built permanent pool was larger than the surveyed permanent pool.

Planning level cost estimates were developed for each potential project. The cost estimates include sediment characterization, mobilization, site preparation, dredging, sediment disposal, minor storm sewer work, site restoration, erosion control, permitting, and maintenance. Costs exclude wetland restoration/mitigation (about $10/square foot), major storm sewer work, and land/easement acquisition. Additional problems that might occur during projects that would add to the cost are dewatering and access issues such as steep banks and tree removal.

It is important to note that costs can vary greatly if sediments are determined to be contaminated under MPCA guidelines. The estimated excavation cost in Table 5.2 assumes moderate (Level 2) levels of contamination. Sediment characterization is discussed in more detail in Section 5.4.2.

Projects were prioritized based on their position in the watershed and the treatment train in that watershed, the overall effectiveness of the cleanout or expansion, the type of basin and potential impact to the lake. Typically, stormwater wetlands were considered as low priority if no as-built information was available since it is difficult to differentiate between sediments that already existed in the wetland versus new sediment from stormwater. However, a few wetlands were in critical locations and considered medium priority even though the costs would likely be higher than the costs presented in this report due to potential requirements for wetland mitigation.

Table 5.2 presents identified projects for constructed ponds and wetlands. Only a few of the basins demonstrated signs of sedimentation, so most of these would be considered expansions. If historic conditions can be established, excavation of storm sediment is exempted from needing additional permits.

Figures 5.1 through 5.7 show the locations of the projects identified in Table 5.2. Cleanout volumes are associated with projects that were identified to expand the basin to meet NURP standards.

The total cost to complete all of these projects is approximately $1,355,000 assuming a moderate level of contamination. If all the projects were completed, there would be an estimated total reduction of 17 lbs TP/yr ($79,693/lb). It is important to note that cost estimates are based on current rates which could increase in the future.

Identifying projects for key basins in the watershed instead of focusing on small improvements to basins identified in Table 5.2 could provide a larger reduction in watershed loading at a smaller cost. These projects could include:

- Adding infiltration practices such as rain gardens and swales to the watershed that drains directly to Duck Lake
- Adding infiltration practices such as rain gardens and swales to the watershed that drains directly to Red Rock Lake
- Dredging and adding iron enhanced sand filters to basins 06-34-B, 16-31-A, 21-32-C.
- Redirect drainage from basin 17-31-A to basin 17-41-C which has capacity to treat additional runoff.

Table 5.1. Identified Wetland and Constructed Pond Projects Including Planning Level Costs.

Drainage Group	Basin ID	Surface Area of As-Built Permanent Pool (acres)	Surface Area of Surveyed Permanent Pool (acres)	Permanent Pool Volume Difference[2] (AF)	Survey Estimated Sediment Volume (AF)	NURP Estimated Volume Expansion[3] (AF)	Estimated Excavation Costs[4]	Priority	TSS Reduction (lbs/yr)	TP Reduction (lbs/yr)
Constructed Ponds										
Wyndham Knoll Park	06-21-C[5,6]	--	--	--	--	3.65	$250,000	High	3142.7	8.3
	06-42-B	--	0.21	--	--	1.41	$125,000	High	331.2	1.0
Hidden Ponds Park	06-34-B[5]	--	0.50	--	--	3.50	$240,000	Medium	306.3	1.0
Miller Park	17-14-A[1]	--	0.79	--	0.99	0.43	$60,000	Medium	137.3	0.4
Pioneer Park	20-41-A	--	0.06	--	--	0.84	$95,000	High	388.4	1.2
Red Rock lake	21-31-A	0.31	0.29	0.07	0.14	1.33	$120,000	High	282.8	0.9
Wetlands										
North Rustic Hills Park	06-11-C	--	0.13	--	0.17	0.69	$75,000	Medium	148.0	0.5
Pheasant Woods Park	16-34-A	--	0.31	--	0.18	1.01	$90,000	Medium	131.5	0.4
Red Rock Lake	21-32-A[5]	--	0.04	--	--	0.15	$20,000	Medium	161.5	0.5

[1] Basins are MNDOT owned; need to work with MNDOT to proceed with proposed projects.
[2] (Surveyed Permanent Pool volume) - (As-Built permanent pool volume)
[3] Estimated Volume expansion to meet NURP standards.
[4] Includes excavating the estimated volume to meet a NURP ratio of 1.
[5] Includes excavating the estimated volume to meet site constraints.
[6] Basin to be resurveyed; NURP volume expansion is based on an estimate of existing permanent pool volume and expansion to meet NURP ratio of 1.
-- Information not available.

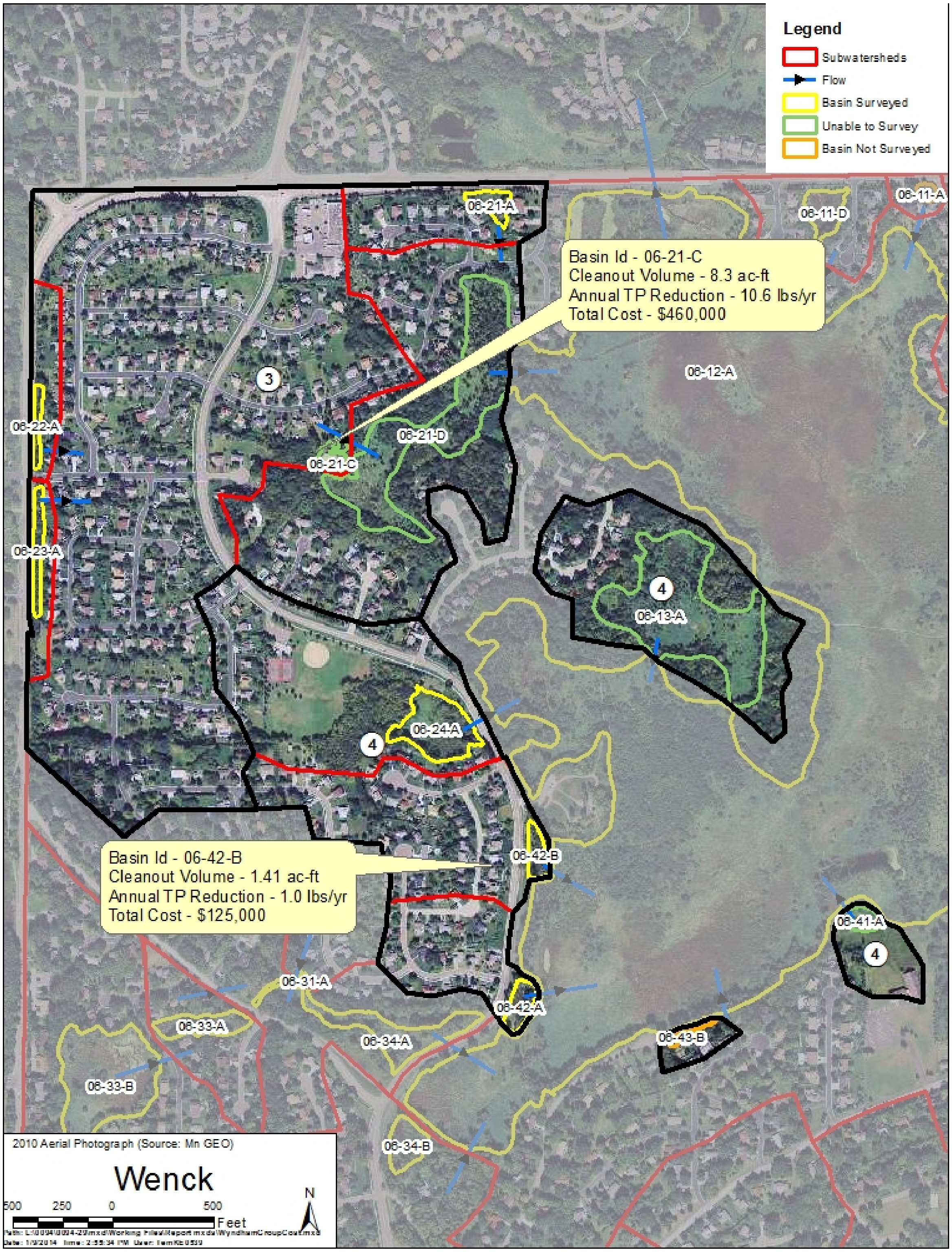

Figure 5.1. Project Locations Identified in the Wyndham Knoll Park Area.

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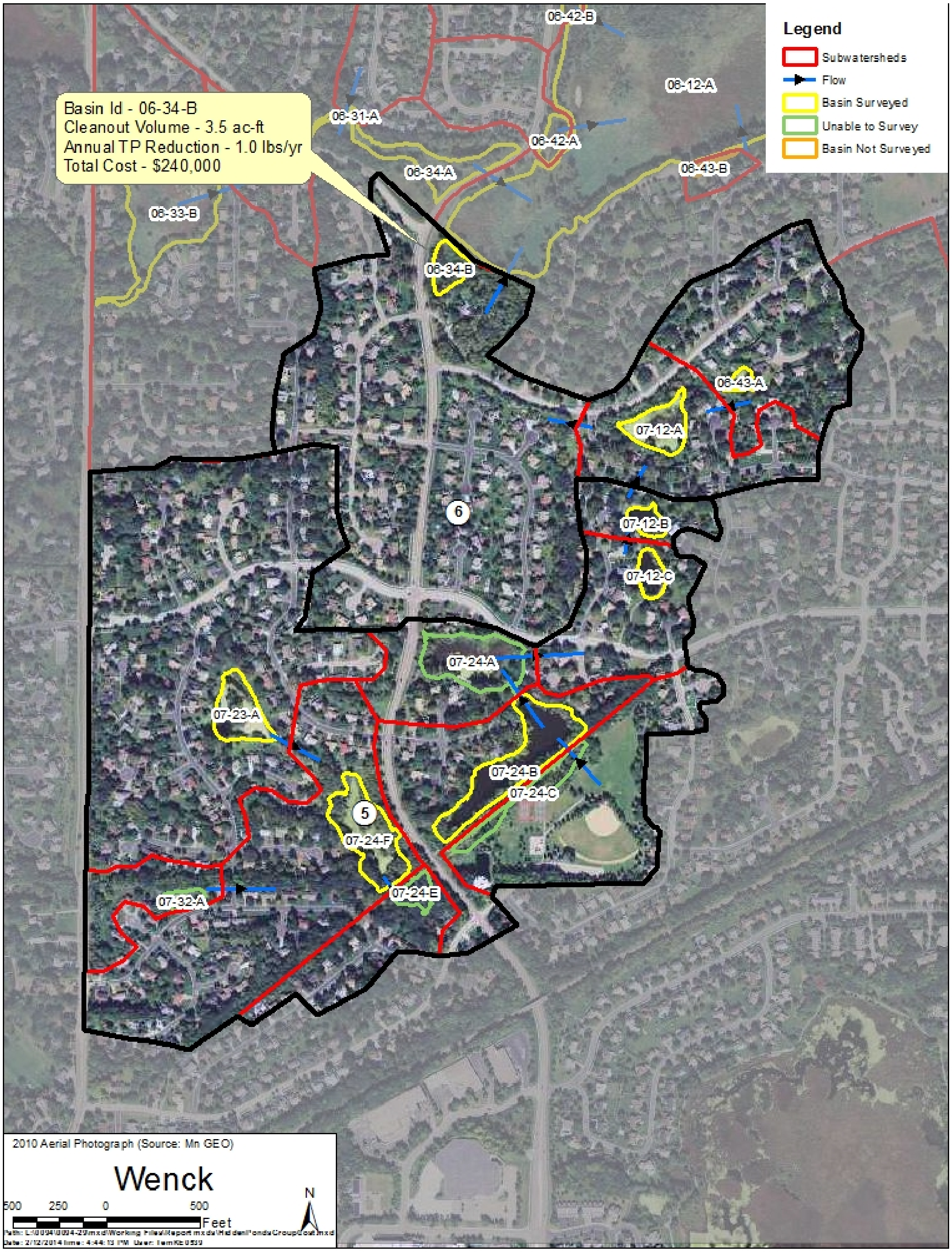

Figure 5.2. Project Location Identified in the Hidden Ponds Park Area.

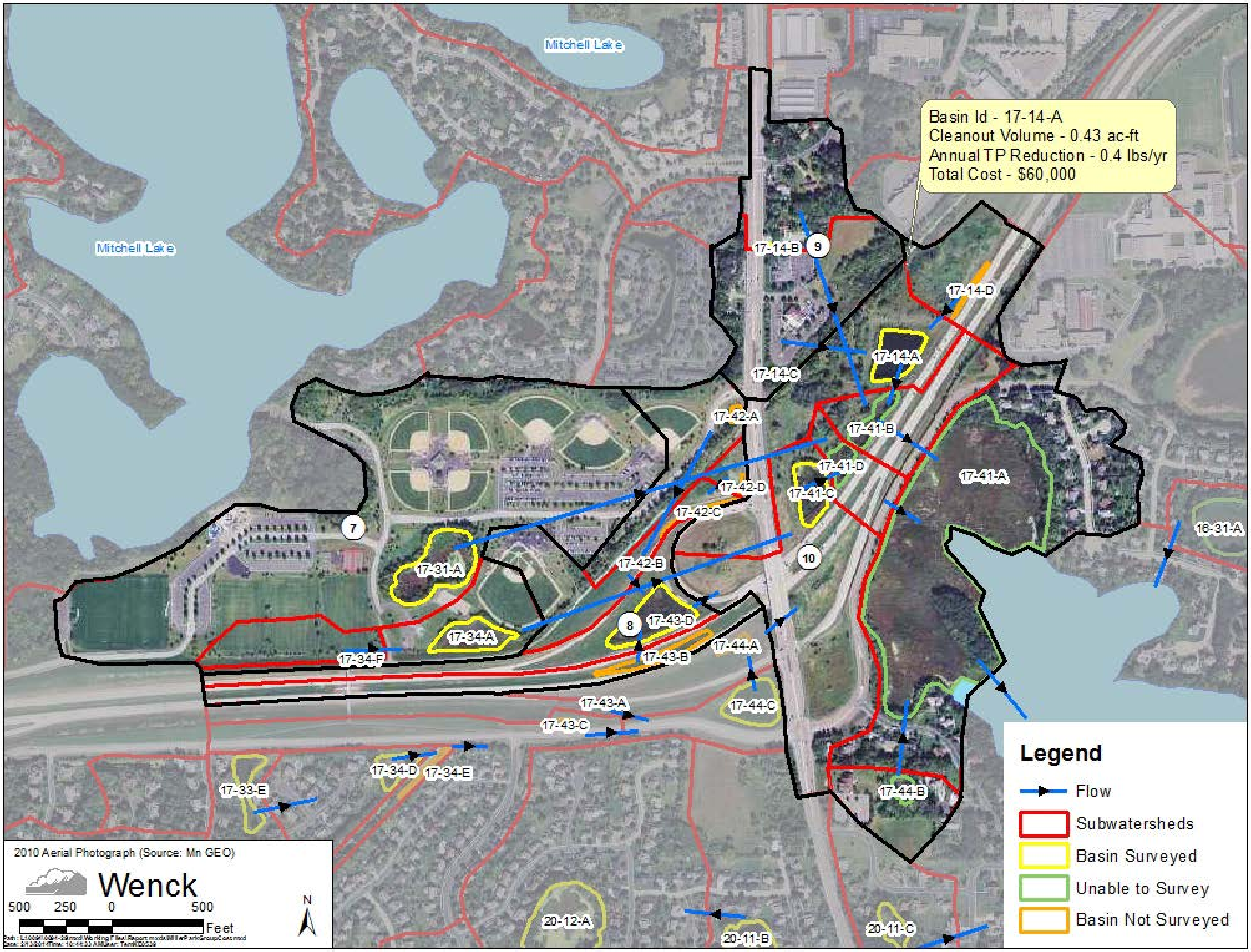

Figure 5.3. Project Locations Identified in the Miller Park Area.

Figure 5.4. Project Locations Identified in the Pioneer Park Area.

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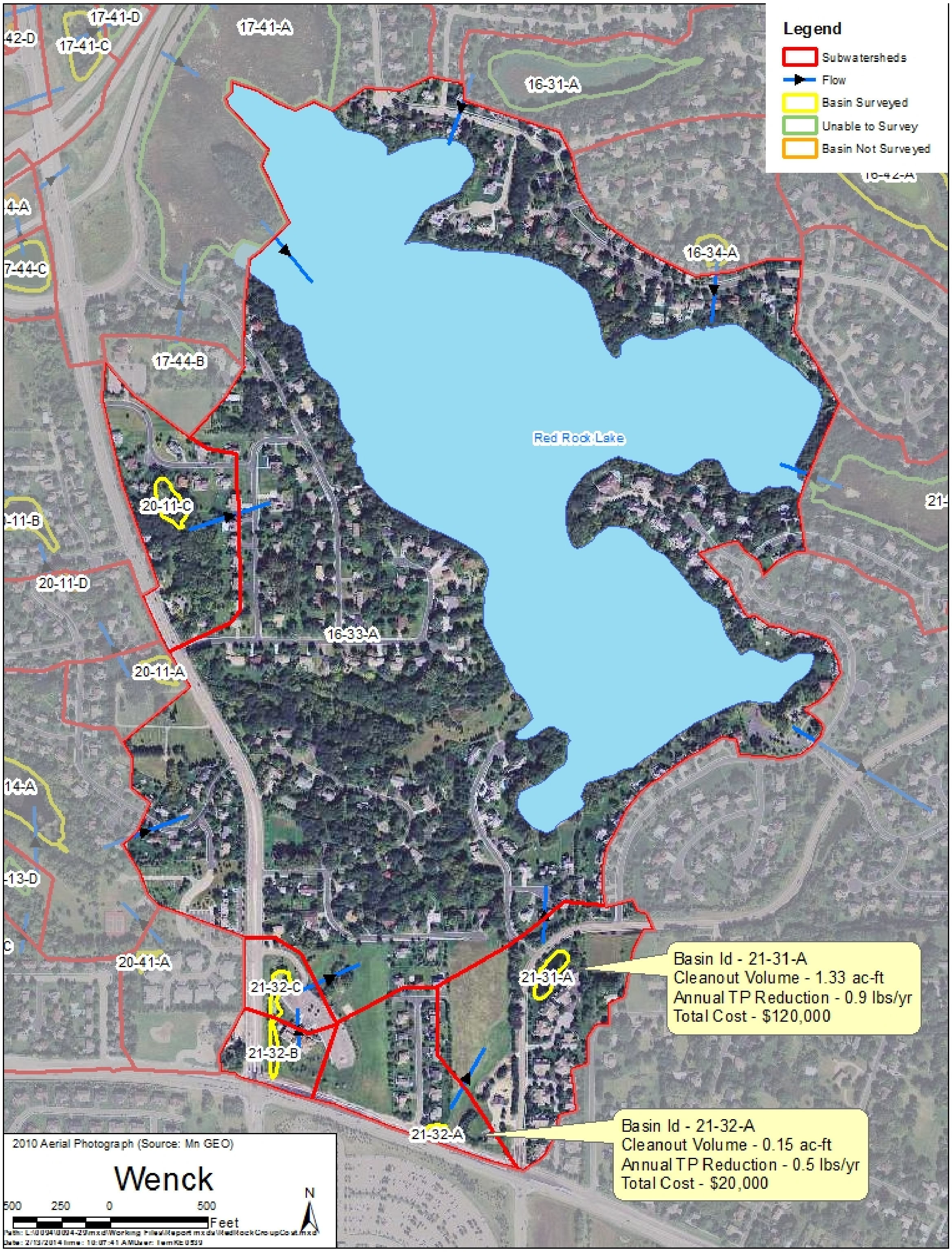

Figure 5.5. Project Locations Identified in the Red Rock Lake Area.

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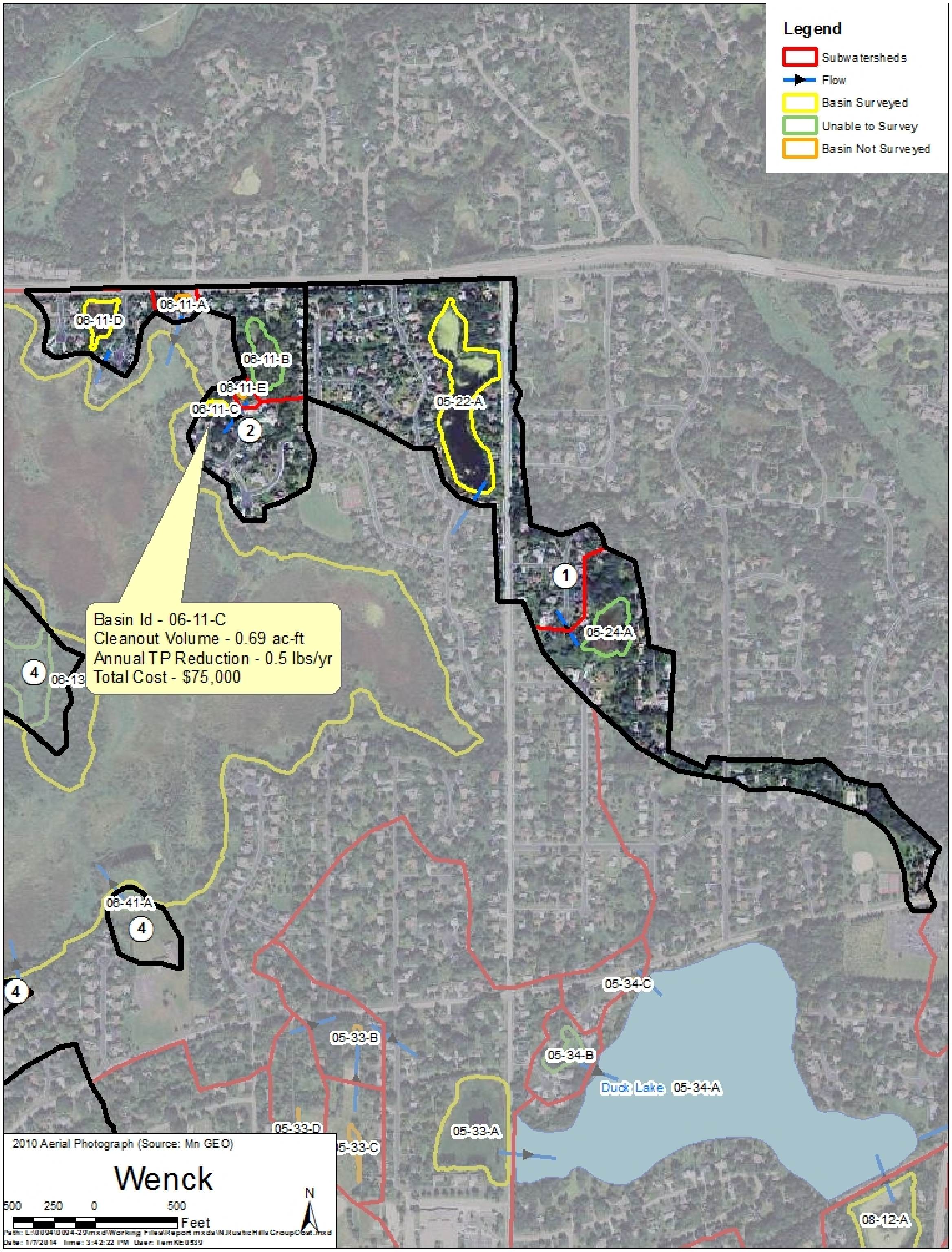

Figure 5.6. Project Locations Identified in the North Rustic Hills Park Area.

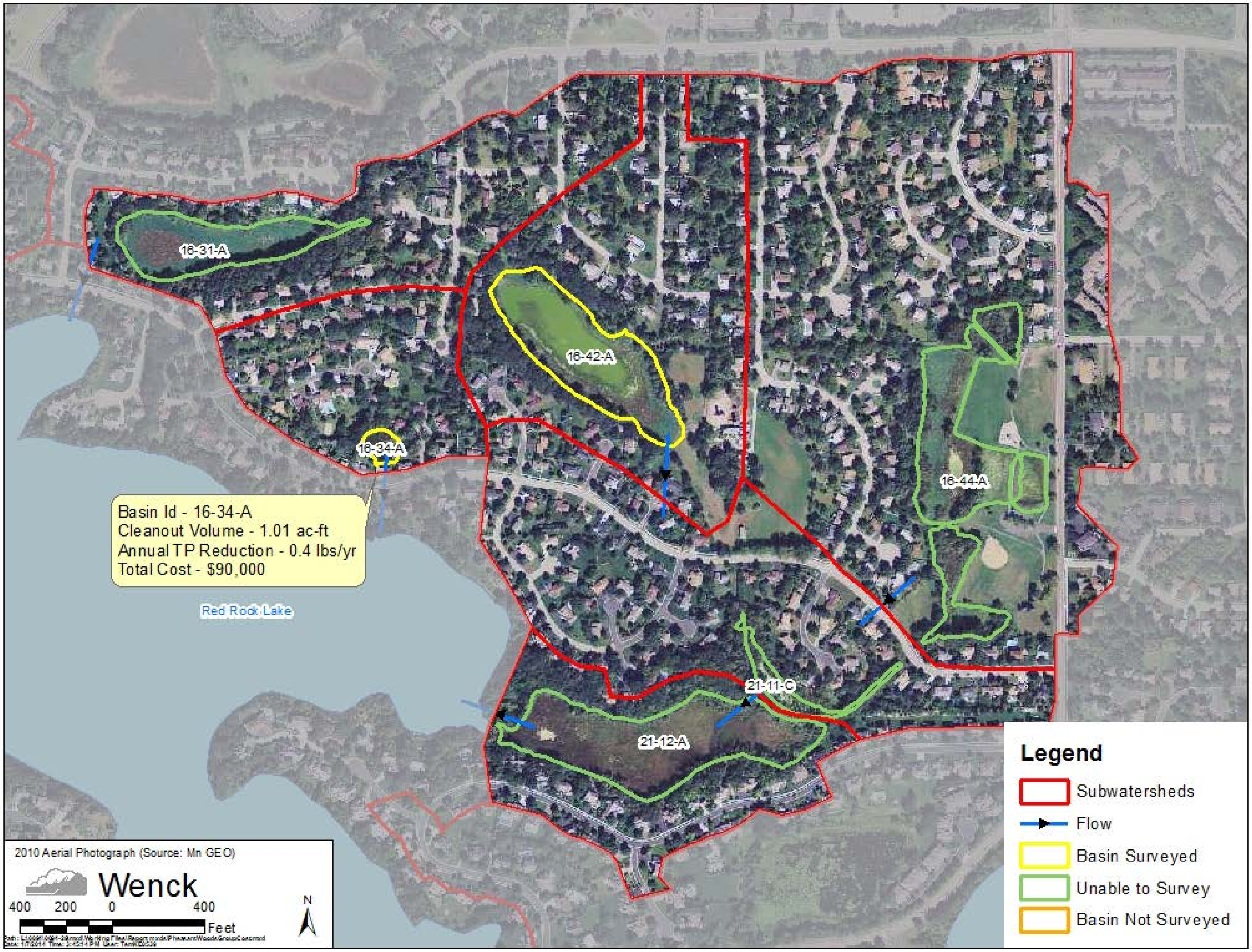

Figure 5.7. Project Locations Identified in the Pheasant Woods Park Area.

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5.4 PERMITTING REQUIREMENTS

Several permitting requirements should be considered prior to initiating any constructed pond and wetland excavation.

5.4.1 Wetlands

The Minnesota Wetland Conservation Act (WCA) requires replacement for excavation in Type 3, 4, or 5 wetlands, but provides an exemption for maintenance of wetland stormwater treatment basins if it is demonstrated that the wetlands/ponds were established prior to 1991. There is also a “No-Loss” exemption for excavation of deposited sediment for wetlands utilized for stormwater management (8420.0415 Item E). Required information includes engineering plans for the basin, materials that demonstrate the basin was designed and constructed as a stormwater treatment basin, outlet information, permits obtained for pond construction, or sediment measurements. Under the exemptions, the wetland stormwater treatment basin can be excavated to regain their original design or to remove deposited sediment. However, excavation which increases the basin's surface area or depth requires wetland replacement. Wetland replacement may also be required if the excavation will significantly disturb the wetland system, however it is the City’s policy to avoid disturbing natural wetlands if at all possible.

5.4.2 MPCA Dredged Materials Management

The MPCA issues permits for the management of dredged materials under the National Discharge Elimination System (NPDES) and/or the State Disposal System (SDS). In June 2009, the MPCA released *Managing Dredged Materials in the State of Minnesota,* where specific guidance was provided for projects involving sediment removal from municipal or urban stormwater systems.

The MPCA does not require a permit or reporting of results for small maintenance projects where project maintenance activity is less than 3,000 cubic yards and chemical sample data indicate that the dredge material meets management level 1. Dredged material is divided into 3 management levels based on the amount of contamination and therefore has different restrictions on disposal of the material. Level 1 dredged material, which has the lowest levels of contamination, is suitable for use or reuse on properties with a residential or recreational use category. Materials categorized as Level 2 are suitable for use or reuse on properties with an industrial use category and level 3 dredged material is considered to be significantly contaminated and must be managed specifically for the contaminants present (MPCA, December 2011).

A sediment characterization needs to be completed to evaluate the dredged materials level risk and to determine disposal options for the dredged sediment. The removal of individual sediment deltas by basin inlets or outfalls does not require the evaluation of the dredged materials level risk. Sampling is recommended by the MPCA if maintenance is performed at multiple inlet locations and if the material consolidated at one location is greater than 500 cubic yards.

Sediment from maintenance of individual stormwater inlets and outfalls may be combined for composite sampling as one project.

5.5 LAKE RESTORATION

5.5.1 Ecological Restoration

Shallow lakes are ecologically different from deep lakes. In shallow lakes, there is a greater area of sediment-water interface, 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 reflect a lake being in two alternative stable states: a clear water state and a turbid water state. 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 was developed in Europe is also applicable here in the United States:

- Forward “switch” detection and removal
- External and internal nutrient control
- Bio manipulation (reverse “switch”)
- Plant re-establishment
- Stabilizing and managing the 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). For Duck Lake, a whole lake drawdown is not feasible due to the current outlet structure and its large watershed. Rather, plants will need to be reestablished through other lake restoration techniques such as alum treatment and roughfish removal and control. Purgatory Creek Park is being considered for drawdown.

Although the ecological restoration of Duck Lake is not a focus of this study, it is important to recognize that lake water quality will not be improved by only reducing nutrient loading to Duck Lake. The purpose of this study is to provide insight into nutrient management options to set the stage for a successful ecological restoration of the lake. In addition, the study addresses the high cost and feasibility associated with the required load reduction.

5.5.2 Duck Lake

Based on the lake response modeling, required watershed load reductions to meet state water standards in Duck Lake were developed for the modeled years average (Table 5.4). A 42% reduction in the phosphorus loading to Duck Lake or a total phosphorus load reduction of 14.4 pounds is required. The reductions listed in Table 5.3 assumes equal reductions in each of the watersheds, although it might be more realistic to assign the watershed reductions to Duck Direct and 05-33-A since they have the highest loading rates.

Table 5.2. Watershed Loading and Estimated Reduction Requirements for the 10-year Average.

Main Watershed	Flow	Total Suspended Solids		Total Phosphorus		TP Reduction	
	AF	mg/L	lbs /yr	µg/L	lbs /yr	lbs /yr	%
Duck Direct	37.7	70.4	7,214	203	20.8	8.74	42%
08-12-A	6.2	0.3	5.4	51.3	0.9	0.38	42%
05-34-C	1.8	86.8	432	236	1.2	0.50	42%
05-34-B	1.9	4.6	23.6	93.0	0.5	0.21	42%
05-33-A	32.8	1.8	157.2	84.1	7.5	3.15	42%

No internal load reduction is suggested for Duck Lake to meet State water quality standards for shallow lakes in the North Central Hardwood Forest Ecoregion. The internal load is already relatively low for a shallow lake and would not offer the dollars per pound of reduction that can be achieved by reducing watershed loading.

It is important to note that Duck Lake is dominated by Curly-leaf pondweed and roughfish which may be causing or contributing to the current water quality conditions. Water quality in 2011 was much better than 2012 which is hard to explain just from changes in nutrient loading. This may be a result of a change in the fish community leading to changes in lake water quality. Prior to any large expenditure in the Duck Lake watershed, in-lake management efforts should be explored.

5.5.3 Red Rock Lake

Based on the lake response modeling, no reductions are required to meet state water standards in Red Rock Lake. However, one year did violate the state water quality standards suggesting that other shifts have occurred in the lake other than nutrient reductions to cause the improvement in water quality. One possible explanation is a recent fish kill that may have reduced the rough fish population. Because of these conditions, some watershed projects were recommended to protect water quality in Red Rock Lake. Continued collection of water quality data should take place to determine if water quality standards are met.

It is also important to note that Curly-leaf Pondweed covers over half of the lake although it is not currently dense enough to suggest management is necessary. However, monitoring should continue in case Curly-leaf pondweed increases in density leading to potential water quality problems.

6.0 References

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Appendix A

Complete Visual Inspection Results for the Duck and Red Rock Lake Watersheds Basin Survey

Table A.1 Visual Inspection Results for the Duck and Red Rock lake Watersheds Basin Survey.

Water Body ID	Repairs Needed?	Water Body Type	Inventory Comments	Expr1006	Water Level	Structural Condition	Sedimentation	Debris Present?	Debris Type (primary)	Flow Conditions	Comments
05-22-A	No		-		Low		Slight	No		Open	
05-24-A	No	Wetland	Inlet @ 0100? Added to ArcMap 6/1/10		Low			Some	Yard Waste	Open	
05-33-A	Inlet @ 1130 has large willow growing inside	Wetland - Stormwater wetland	-	Duckweed	Normal		None	No		Open	Duckweed
05-34-B	No	Wetland - Stormwater wetland	-		Dry		Slight	No		Inhibited	
05-34-C	Yes - Work order pending	Wetland	work order made 11/13/09 (work pending)		Low		Slight	Some	Mixed materials	Inhibited	
06-11-C	No	Wetland	Yard waste on trashguard @ 0400. Also erosion above inlet @ 0400 - in 2010	Very slight shine	Normal		None	No		Open	Very slight shine
06-11-D	No	Wetland	-		Low		None	Some	Mixed materials	Open	
06-12-A	No	Wetland	Two inlets found and evaluated in 2009 Many inlets to sort out btwn databases. Inlet: 0615, 0645? 1100 and 1200? Possible inlet at 0530 needs to be inspected		Low		Slight	No		Open	
06-13-A		Wetland	Inlet @ 1000 (found July 2010)		Normal		None	Some	Yard Waste	Open	
06-21-C	No	Constructed Pond	-		Low		Slight	No		Open	
06-21-D	No	Wetland	-	Erosion from yardwaste blockage at 0600 forming a flow channel.	Dry		Moderate	Yes	Yard Waste	Open	Erosion from yardwaste blockage at 0600 forming a flow channel.
06-22-A	No	Wetland	-		Dry	Normal	None	Some	Mixed materials	Open	
06-23-A	Yes	Wetland	Trashguard is damaged and may need to be replaced. One inlet is partially crushed. However both are open and flowing. - 2010		Dry	Other	None	Yes	Mixed materials	Inhibited	
06-24-A	No	Wetland - Stormwater wetland	No easement		Dry	Normal	Slight	Some	Mixed materials	Open	
06-31-A	No	Constructed Pond	Both inlet and outlet of the pond have a structure in front of outfall. Pictures were taken and filed in 2009 folder. Outlet material is wooden and may need to be replanted or replaced in future.		Dry		Slight	No		Open	
06-33-A	No	Linear Water - Creek Segment	Part of Purgatory Creek between Tartan Curve and Duck Lake Trail.	No standing water	Dry		Slight	Some	Mixed materials	Open	No standing water

Water Body ID	Repairs Needed?	Water Body Type	Inventory Comments	Expr1006	Water Level	Structural Condition	Sedimentation	Debris Present?	Debris Type (primary)	Flow Conditions	Comments
06-33-B	No	Linear Water - Creek Segment	work order made 10/16/09 (work pending)	Cattails covered the pond basin	Dry			Yes	Mixed materials	Open	Cattails covered the pond basin
06-34-A	No	Linear Water - Creek Segment	Most of creek corridor on City property, remainder under drainage easement		Dry	Corroded		No		Open	
06-42-A	No	Constructed Pond	-		Normal		Moderate	No		Open	
06-42-B	No	Constructed Pond	-		Normal	Corroded	Slight	Some	Mixed materials	Restricted	
06-43-A	Yes	Wetland - Stormwater wetland	-Work order in 2010????		Normal	Eroded / Hanging	Moderate	No	None	Inhibited	
06-43-B		Wetland - Stormwater wetland	May be a constructed pond or excavated from adjoining wetland - need to check 2011- Berm obviously constructed - unknown where material is from.	Entirely covered in invasives -Garlic Mustard, creeping charlie, thistle. Branches a cement on hill	Dry	Normal	None	Some	Yard Waste	Open	Entirely covered in invasives -Garlic Mustard, creeping charlie, thistle. Branches a cement on hill
07-12-A	No	Wetland - Stormwater wetland	-	Wolfia and Lemna as well - Duckweed	Normal		None	No		Open	Wolfia and Lemna as well - Duckweed
07-12-B	No	Wetland - Stormwater wetland	-		Normal		Slight	No		Open	
07-12-C	Yes	Wetland - Constructed wetland	Piping for inlet has been exposed by erosion. Exposed pipe is approx. 6 to 8 feet long.		Normal		None	No	None	Inhibited	
07-23-A	Yes	Wetland - Stormwater wetland	Outlet 0500 in poor condition in 2004 and submerged in 2010.		Normal		Slight	Some	Mixed materials	Open	
07-24-A	No		-		Normal		Slight	Yes	Mixed materials	Open	
07-24-E	No		-		Dry		Slight	Yes	Mixed materials and yard waste	Open	
07-24-F	Yes	Wetland - Stormwater wetland	Work Order created for Inlet 0900 in 2010 as inlet (0900) corroding and the structure iin poor condition. It is difficult to tell where the structure begins and the rip-rap ends.		Normal	Spalling / Cracking	Moderate	Some	Mixed materials	Open	
07-32-A	No	Wetland - Stormwater wetland	-		Normal			No		Open	
08-12-A	No	Wetland	Work order made 6/12/09 (Completed 6/22/09) Possible inlet at 0300 needs to be inspected		Normal	Normal	Slight	Some	Mixed materials	Open	
16-31-A	No	Wetland	-		Low			No		Not applicable	
16-34-A	Yes	Wetland - Stormwater wetland	-		Normal		Slight	Some	Mixed materials	Open	

Water Body ID	Repairs Needed?	Water Body Type	Inventory Comments	Expr1006	Water Level	Structural Condition	Sedimentation	Debris Present?	Debris Type (primary)	Flow Conditions	Comments
16-42-A	No		3rd inlet @ 0500? Couldn't find inlets Aug 2010. Only found inlet 0200 in 2012.		Normal		Excessive	No		Open	
16-44-A	No		-		Dry	Spalling / Cracking	Moderate	No	None	Inhibited	
17-14-A	no	Constructed Pond	-		Low	Normal	None	Some	Mixed materials	Inhibited	
17-14-B	No	Constructed Pond	This water body is a rain garden near the south side of the entrance to the Dunn Brothers parking lot on Eden Prairie Road.		Dry		None	No		Open	
17-14-C	No	Constructed Pond	-		Dry		Excessive	No		Inhibited	
17-31-A	No		outlet not located		Normal	Normal	None	Slight		Open	
17-33-E		Wetland - Stormwater wetland	No easement		Low	Normal	Slight	Yes	Mixed materials and Yard Waste	Inhibited	
17-34-A	No	Wetland	Lot of vegetation and no standing water	no standing water, only upland and emergent vegetation	Dry		None	No		Open	no standing water, only upland and emergent vegetation
17-34-D	No	Constructed Pond	Field check for an in/outlet at 6:00		Dry	Eroded / Hanging	Slight	No		Inhibited	
17-34-F		BMP - Infiltration Trench	-			Normal	None	Slight	Mixed materials	Open	
17-41-A	No	Wetland	-		Normal	Normal	None	No	None	Open	
17-41-C	No	Wetland - Stormwater wetland	Inlets 0900 and 1000 were not found, may be submerged, in 2012.		Normal		Slight	Yes	Mixed materials and Plastics	Open	
17-42-A	No	Wetland - Stormwater wetland	Could not locate noted inlet 1000		Dry			No		None	
17-43-C	No	Constructed Pond	No easement		Low		None	No		Open	
17-44-B	No		-		Dry	Normal	Slight	Slight	Mixed materials	Open	
17-44-C		Constructed Pond	No easement	2011 -minmal erosion - channel - 1200	Low	Normal		Some	Mixed materials	None	2011 -minmal erosion - channel - 1200
20-11-A	No		-		Dry	Normal	Slight	Yes	Yard Waste	None	
20-11-B	Yes - Work order pending	Wetland	work order made 12/4/09 (work pending) - 2009	large palstic tots - 8668 Endicott, retaining wall blocks - 8656 Endicott	Normal	Normal	None	Slight	Mixed materials	Open	large palstic tots - 8668 Endicott, retaining wall blocks - 8656 Endicott
20-11-C	Yes - Work order pending	Wetland	work order made 12/4/09 (work pending)		Low		Moderate	Some	Yard Waste	Open	

Water Body ID	Repairs Needed?	Water Body Type	Inventory Comments	Expr1006	Water Level	Structural Condition	Sedimentation	Debris Present?	Debris Type (primary)	Flow Conditions	Comments
20-11-D	Yes, FES is 85% filled with sediment	BMP - Infiltration Trench	Work order sent 2/7/2012		Dry	Normal	Slight	Yes	Mixed materials	Restricted	
20-12-A	No	Wetland	Work order made 4/27/09 (Completed 5/1/09)		Normal		Slight	Yes	Mixed materials and Yardwaste	Open	
20-13-A	Yes - Work order pending	Wetland	Work order made 12/4/09 (work pending). Jim Schedin contacted about dumping in easement on 12/4/09, also conservation easement; erosion along stream bank, much organic debris in stream, 16617 Mayfield storing wood and dumping debris in easement		Normal	Normal	Excessive	No	None	Open	
20-13-B	No	Wetland	No inlets located. LOTS of Buckthorn.		Dry	Normal		No		Open	
20-13-C	No	Wetland - Stormwater wetland	-		Dry	Normal	No	No	None	Inhibited	
20-13-D	Yes		Last section of the outlet at 1:00 has disconnected from the rest of the pipe. - 2010		Dry	Normal		No		Open	
20-14-A	No	Wetland - Stormwater wetland	No easement	Veg mats	Normal	Normal	None	Yes	None	Open	Veg mats
20-21-A	No	Wetland - Stormwater wetland	-		Low	Normal	None	No	None	Open	
20-21-B	No	Wetland - Stormwater wetland	-		Normal	Normal	None	No	None	Open	
20-21-C	No	Wetland - Stormwater wetland	-	pond covered in dead pond weed and green scum	Normal	Normal	None	Some	Mixed materials	Open	pond covered in dead pond weed and green scum
20-22-B	Unknown	Wetland	Was unable to locate Outlet (0130). Buried? Return in spring.	wooded depression	Dry					Open	wooded depression
20-24-A	No	Wetland - Stormwater wetland	-	Curly Leaf Pond Weed - 60% of pond	Normal	Normal	None	Yes	Mixed materials	Open	Curly Leaf Pond Weed - 60% of pond
21-11-C	No		-		Normal	Eroded / Hanging	Excessive	Yes	Mixed materials	Inhibited	
21-31-A	No	Constructed Pond	-		Low		Slight	Yes	Mixed materials	Open	
21-32-A	No	Wetland	Inlets 0700 and 0900 about 1/2 full of sediment. Outlet overgrown with vegetation. - 2009		Low	Normal	None	Yes	Mixed materials	Open	
21-32-B	No	Constructed Pond	-		Dry	Normal	None	Slight	Mixed materials	Open	
21-32-C	No	Constructed Pond		Church property	Normal	Normal	None	No		Open	Church property

Appendix B

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Duck Lake and Red Rock Lake

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Duck Lake, Minnesota

27 January, 2013

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OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled oxic (i.e., aerobic) and anoxic (i.e., anaerobic) conditions and to quantify biologically-labile (i.e., subject to recycling) and refractory (i.e., biologically inert and subject to burial) P fractions for sediment collected in Duck Lake, Minnesota.

APPROACH

Laboratory-derived rates of P release from sediment under oxic and anoxic conditions: Sediment cores were collected by Wenck Associates from a centrally-located station in Duck Lake in November, 2012, for determination of rates of P release from sediment under oxic and anoxic conditions. Cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 to 25 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Sediment chemistry: The upper 10 cm of an additional core was sectioned for analysis of moisture content (%), sediment density (g/mL), loss on ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, aluminum-bound P, calcium-bound P, labile and refractory organic P, total P and total iron (Fe; all expressed at mg/g). A known volume of sediment was dried at 105 ^{o}C for determination of moisture content and sediment density and burned at 500 ^{o}C for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total P, Fe, Mn, and Ca using standard methods (APHA 2005 method 4500 P.f. and EPA method 200.7).

Phosphorus fractionation (Table 1) was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), sodium hydroxide-extractable P (i.e., aluminum-bound P), and hydrochloric acid-extractable P (i.e., calcium-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P. Refractory organic P was estimated as the difference between total P and the sum of the other fractions.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that result in desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fractions represent redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The sum of redox-sensitive P and labile organic P collectively represent biologically-labile P. This fraction is generally active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound, calcium-bound, and refractory organic P fractions are more chemically inert and subject to burial rather than recycling.

RESULTS AND INTERPRETATION

Rates of Phosphorus Release from Sediment

P mass and concentration increased rapidly and linearly in the overlying water column of sediment systems maintained under anoxic conditions (Figure 1). The mean P concentration maximum in the overlying water under anoxic conditions was 0.300 mg/L (± 0.047 standard error) at the end of the incubation period. The mean rate of P release under anoxic conditions was relatively high at 3.3 mg m^{-2} d^{-1} (Table 2), and indicative of eutrophic conditions (Nürnberg 1988).

Under oxic conditions, P mass and concentration in the overlying water column was near detection limits during the first 5 days of incubation (Figure 2). P mass and concentration increased modestly between day 5 and 15 of incubation and then leveled off. The mean rate of P release under oxic conditions was moderate at 0.54 mg m^{-2} d^{-1}

(Table 2). The maximum P concentration attained in the overlying water column toward the end of the incubation period was ~ 0.064 mg/L, which was moderate and could represent an important available P source for assimilation by algae. Overall, Duck Lake sediments exhibited moderately high rates of P release under oxic conditions, compared to some other lakes in the region (Figure 3). In contrast, anoxic P release rates were more moderate to low versus other lakes in the region (Figure 3).

Sediment Textural and Chemical Characteristics

The upper 10-cm sediment layer exhibited a moderately high moisture content and low bulk density, indicating fined-grained flocculent sediment (Table 3). Organic matter content was relatively high at ~25%. Concentrations of biologically-labile (i.e., subject to recycling back to the overlying water column; loosely-bound P, iron-bound P, and labile organic P) and refractory (i.e., aluminum-bound, calcium-bound, and refractory organic P) P concentrations were also moderate and fell within ranges observed for lakes in the region (Table 4 and Figure 4). Biologically-labile P represented ~ 30% while biologically-refractory P accounted for 70% of the sediment total P concentration (Table 5 and Figure 5).

Redox-sensitive P concentrations (i.e., the sum of loosely-bound and iron-bound P) were moderate compared to other lakes in the region (Figure 4) and accounted for ~ 39% of the biologically-labile P (Table 5). The anoxic P release rate for Duck Lake appeared to be correlated with iron-bound P (expressed on a mg P/g fresh sediment mass basis; Nürnberg 1988), suggesting that the iron-bound P concentration was an important factor in anoxic P release (Figure 6). Labile organic P, which can be recycled to the water column as a result of bacterial metabolic processes, also represented a significant portion of the biologically-labile P pool at 62%. The loosely-bound P fraction was relatively low and accounted for ~ 4% of the biologically-labile P and 10% of the redox-sensitive P. Loosely-bound P typically represents P in interstitial water and concentrations are usually low relative to other sediment P fractions.

Biologically-refractory P was dominated by the refractory organic P fraction (74% of the biologically-refractory P; Table 4 and Figure 5). Calcium-bound P (i.e., P associated with apatite minerals) represented ~ 15% and aluminum-bound P accounted for ~ 11% of the biologically-refractory P (Table 4).

The total sediment Fe concentration was moderate for Duck Lake (Table 6). It was also high relative to the concentration of total sediment P, resulting in an Fe:P ratio (mass:mass) of ~20:1. Ratios greater than 10:1 to 15:1 have been associated with regulation of P release from sediments under oxic (aerobic) conditions due to efficient binding of P onto iron oxyhydroxides in the sediment oxic microzone (Jensen et al. 1992). Strong and complete binding P at higher relative concentrations of Fe are suggested explanations for patterns reported by Jensen et al. At lower Fe:P ratios, Fe binding sites become increasingly saturated with P, allowing for diffusion of excess porewater P into the overlying water column, even in the presence of a sediment oxic microzone. Although the mean oxic P release rate was moderate for Duck Lake in conjunction with a high Fe:P ratio, a pattern that could be attributed to the Jensen et al. model, it was nevertheless high relative to other lakes in the region and represented a potential internal P loading source to the lake.

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Table 1. Sequential phosphorus (P) fractionation scheme, extractants used, and definitions of recycling potential.

Variable	Extractant	Recycling Potential
Loosely-bound P	1 M Ammonium Chloride	Biologically labile; Soluble P in interstitial water and adsorbed to $CaCO_3$; Recycled via direct diffusion, eH and pH reactions, and equilibrium processes
Iron-bound P	0.11 M Sodium Bicarbonate-dithionate	Biologically labile; P adsorbed to iron oxyhydroxides (Fe(OOH); Recycled via eH and pH reactions and equilibrium processes
Labile organic P	Persulfate digestion of the NaOH extraction	Biologically labile; Recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells
Aluminum-bound P	0.1 N Sodium Hydroxide	Biologically refractory; Al-P minerals with a low solubility product
Calcium-bound P	0.5 N Hydrochloric Acid	Biologically refractory; Represents Ca-P minerals such as apatite with a low solubility product
Refractory organic P	Determined by subtraction of other forms from total P	Biologically refractory; Organic P that isresistant to bacterial breakdown

Table 2. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under oxic (aerobic) and anoxic (anaerobic) conditions for sediments collected in Duck Lake.

Station	Diffusive P flux	
	Oxic ($mg\ m^{-2}\ d^{-1}$)	Anoxic ($mg\ m^{-2}\ d^{-1}$)
Central	0.54 (0.03)	3.3 (0.5)

Table 3. Textural characteristics for sediments collected in Duck Lake. 1 standard error in parentheses (n=3).

Station	Moisture Content (%)	Bulk Density (g/cm^3)	Sediment Density (g/cm^3)	Loss-on-ignition (%)
Central	87.2 (0.2)	1.063 (0.001)	0.156 (0.008)	25.0 (0.6)

Table 4. Concentrations of biologically labile and refractory P for sediments collected in Duck Lake. DW = dry mass, FW = fresh mass.

Station	Redox-sensitive and biologically labile P				Refractory P		
	Loosely-bound P (mg/g DW)	Iron-bound P (mg/g DW)	Iron-bound P (ug/g FW)	Labile organic P (mg/g DW)	Aluminum-bound P (mg/g DW)	Calcium-bound P (mg/g DW)	Refractory organic P (mg/g DW)
Central	0.010	0.086	10	0.153	0.064	0.085	0.429
	(<0.001)	(0.005)	(1)	(0.007)	(0.002)	(0.005)	

Table 5. Concentrations of sediment total phosphorus (P), redox-sensitive P (Redox P; the sum of the loosely-bound and iron-bound P fraction), biologically-labile P (Bio-labile P; the sum of redox-P and labile organic P), and refractory P (the sum of the aluminum-bound, calcium-bound, and refractory organic P fractions) for sediments collected in Duck Lake. DW = dry mass.

Station	Total P	Redox P		Bio-labile P		Refractory P	
	(mg/g DW)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)
Central	0.827	0.096	11.6%	0.249	30.1%	0.578	69.9%

Table 6. Concentrations of sediment total iron (Fe), manganese (Mn), and calcium (Ca) and the Fe:P ratio for sediments collected in Duck Lake. DW = dry mass.

Station	Total Fe (mg/g DW)	Total Mn (mg/g DW)	Total Ca (mg/g DW)	Fe:P
Central	16.81	0.44	12.50	20.3

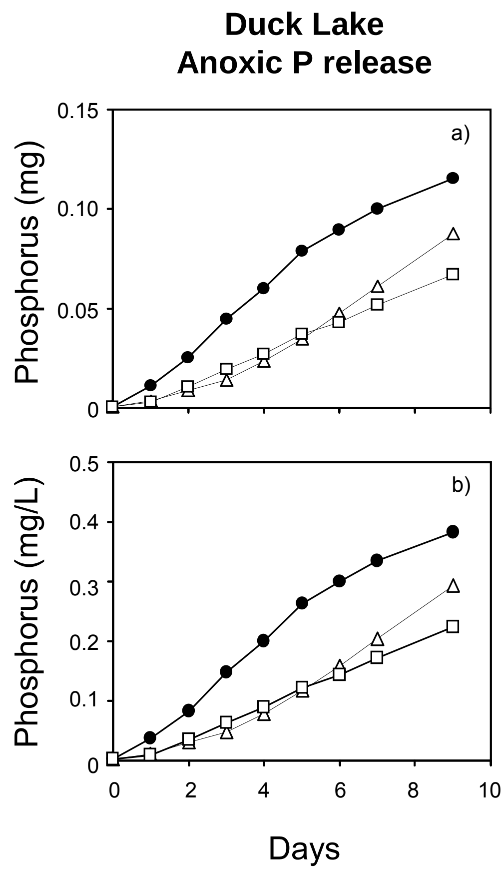

Figure 1. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in Duck Lake.

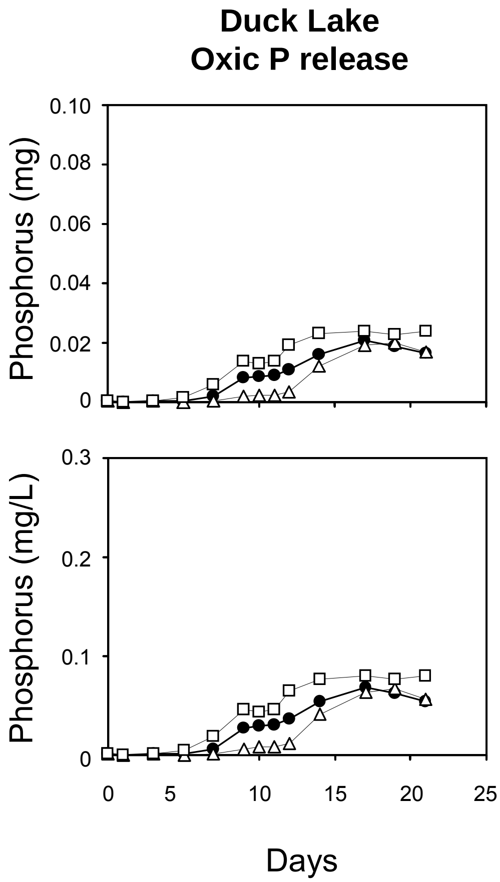

Figure 2. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in Duck Lake.

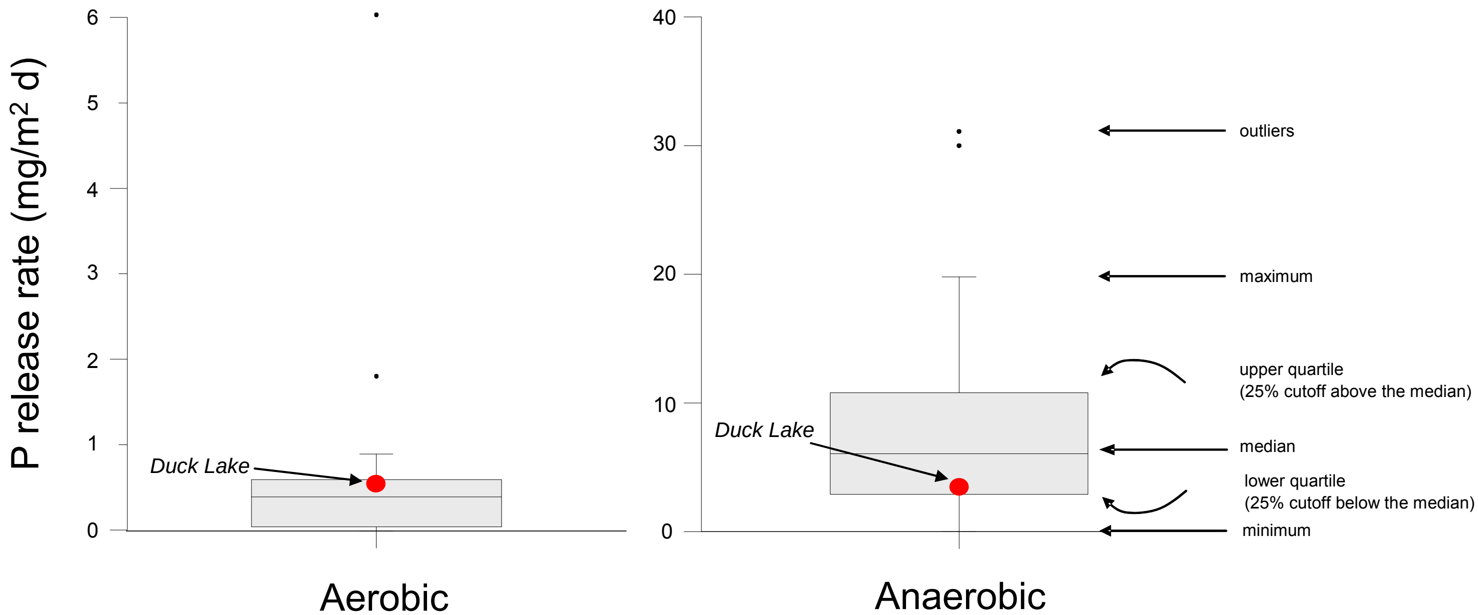

Figure 3. Box and whisker plot comparing theoxic and anoxic phosphorus (P) release rate measured for Duck Lake (red circles) with statistical ranges (n=50) for lakes in the State of Minnesota.

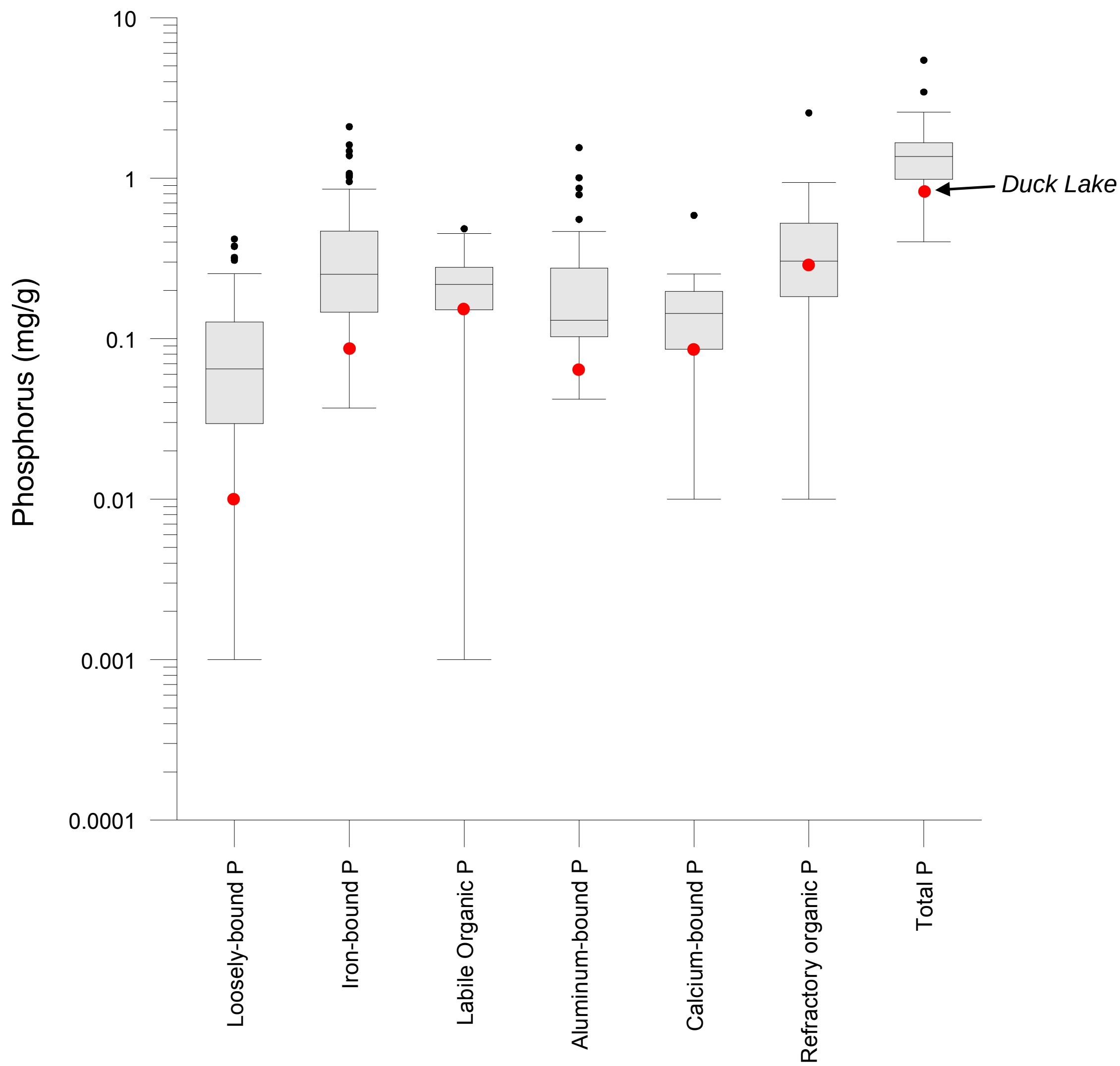

Figure 4. Box and whisker plots comparing various sediment phosphorus (P) fractions measured for Duck Lake (red circles) with statistical ranges (n=50) for lakes in the State of Minnesota. Loosely-bound, iron-bound, and labile organic P are biologically-labile (i.e., subject to recycling) and aluminum-bound, calcium-bound, and refractory organic P are more are more inert to transformation (i.e., subject to burial). Please note the logarithmic scale.

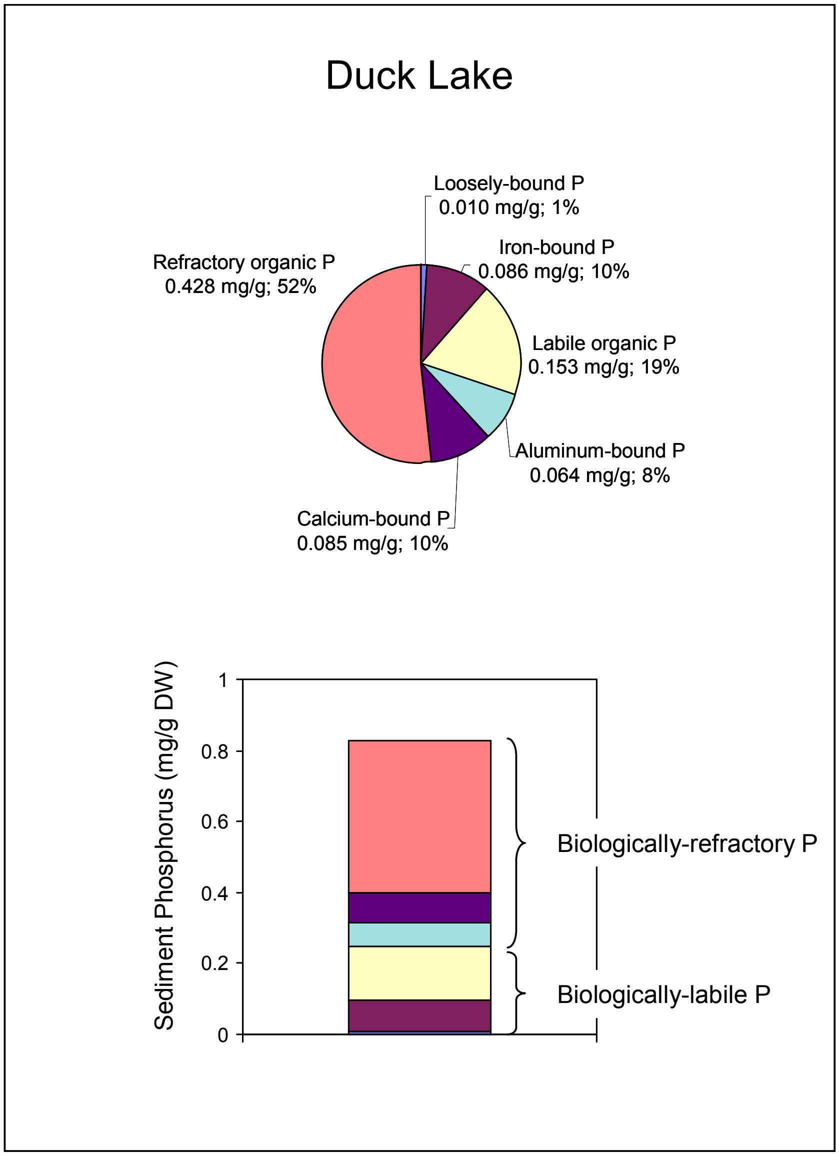

Figure 5. Total phosphorus (P) composition for sediment collected in Duck Lake. Loosely-bound, iron-bound, and labile organic P are biologically reactive (i.e., subject to recycling) while aluminum-bound, calcium-bound, and refractory organic P are more inert to transformation (i.e., subject to burial). Values next to each label represent concentration (mg·g^{-1}) and percent of the total sediment P concentration, respectively.

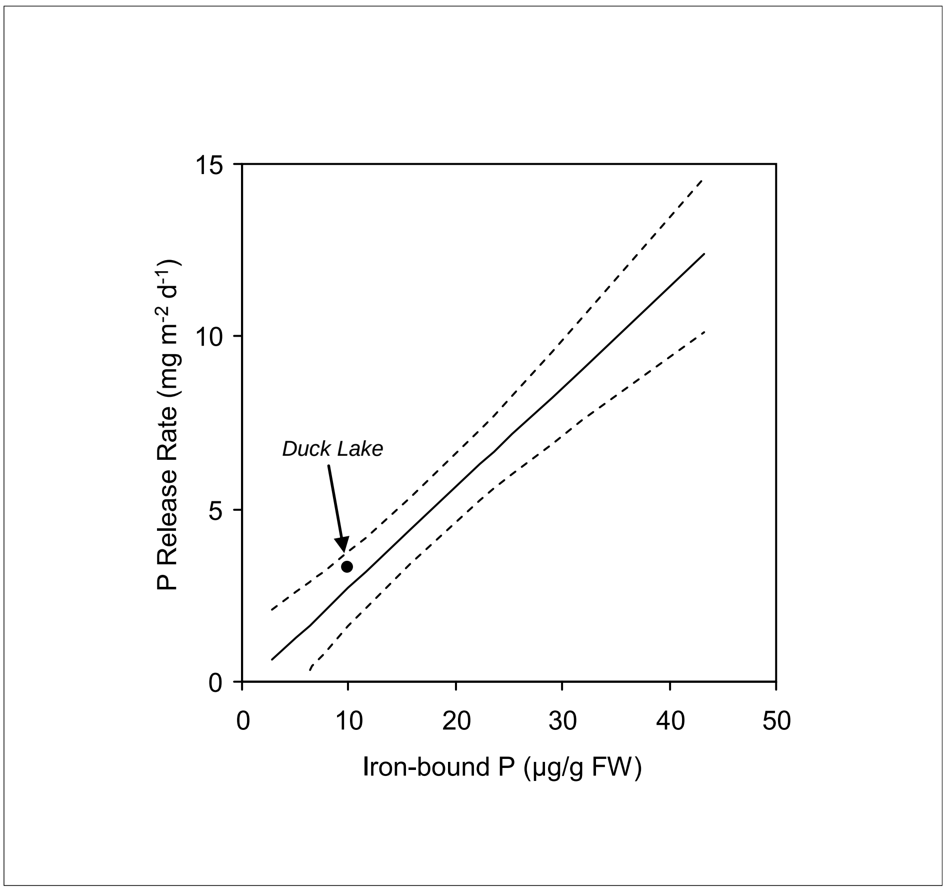

Figure 6. Relationships between iron-bound phosphorus (P; µg g^{-1} fresh sediment mass) and rates of P release from sediments under anoxic conditions. Regression line and 95% confidence intervals from Nürnberg (1988) are shown for comparison.

Internal Phosphorus Loading and Sediment Phosphorus Fractionation Analysis for Redrock Lake, Minnesota

27 January, 2013

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OBJECTIVES

The objectives of this investigation were to determine rates of phosphorus (P) release from sediments under laboratory-controlled oxic (i.e., aerobic) and anoxic (i.e., anaerobic) conditions and to quantify biologically-labile (i.e., subject to recycling) and refractory (i.e., biologically inert and subject to burial) P fractions for sediment collected in Redrock Lake, Minnesota.

APPROACH

Laboratory-derived rates of P release from sediment under oxic and anoxic conditions: Sediment cores were collected by Wenck Associates from a centrally-located station in Duck Lake in November, 2012, for determination of rates of P release from sediment under oxic and anoxic conditions. Cores were drained of overlying water and the upper 10 cm of sediment was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Surface water collected from the lake was filtered through a glass fiber filter (Gelman A-E), with 300 mL then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. They were placed in a darkened environmental chamber and incubated at a constant temperature (20 to 25 ^{o}C). The oxidation-reduction environment in the overlying water was controlled by gently bubbling air (oxic) or nitrogen (anoxic) through an air stone placed just above the sediment surface in each system. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.

Water samples for soluble reactive P were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter (Nalge). The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. Soluble reactive P was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of P release from the sediment (mg m^{-2} d^{-1}) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Sediment chemistry: The upper 10 cm of an additional core was sectioned for analysis of moisture content (%), sediment density (g/mL), loss on ignition (i.e., organic matter content, %), loosely-bound P, iron-bound P, aluminum-bound P, calcium-bound P, labile and refractory organic P, total P and total iron (Fe; all expressed at mg/g). A known volume of sediment was dried at 105 ^oC for determination of moisture content and sediment density and burned at 500 ^oC for determination of loss-on-ignition organic matter content (Håkanson and Jansson 2002). Additional sediment was dried to a constant weight, ground, and digested for analysis of total P, Fe, Mn, and Ca using standard methods (APHA 2005 method 4500 P.f. and EPA method 200.7).

Phosphorus fractionation (Table 1) was conducted according to Hieltjes and Lijklema (1980), Psenner and Puckso (1988), and Nürnberg (1988) for the determination of ammonium-chloride-extractable P (loosely-bound P), bicarbonate-dithionite-extractable P (i.e., iron-bound P), sodium hydroxide-extractable P (i.e., aluminum-bound P), and hydrochloric acid-extractable P (i.e., calcium-bound P). A subsample of the sodium hydroxide extract was digested with potassium persulfate to determine nonreactive sodium hydroxide-extractable P (Psenner and Puckso 1988). Labile organic P was calculated as the difference between reactive and nonreactive sodium hydroxide-extractable P. Refractory organic P was estimated as the difference between total P and the sum of the other fractions.

The loosely-bound and iron-bound P fractions are readily mobilized at the sediment-water interface as a result of anaerobic conditions that result in desorption of P from sediment and diffusion into the overlying water column (Mortimer 1971, Boström 1984, Nürnberg 1988). The sum of the loosely-bound and iron-bound P fractions represent redox-sensitive P (i.e., the P fraction that is active in P release under anaerobic and reducing conditions). In addition, labile organic P can be converted to soluble P via bacterial mineralization (Jensen and Andersen 1992) or hydrolysis of bacterial polyphosphates to soluble phosphate under anaerobic conditions (Gächter et al. 1988; Gächter and Meyer 1993; Hupfer et al. 1995). The sum of redox-sensitive P and labile organic P collectively represent biologically-labile P. This fraction is generally active in recycling pathways that result in exchanges of phosphate from the sediment to the overlying water column and potential assimilation by algae. In contrast, aluminum-bound, calcium-bound, and refractory organic P fractions are more chemically inert and subject to burial rather than recycling.

RESULTS AND INTERPRETATION

Rates of Phosphorus Release from Sediment

P mass and concentration increased rapidly and linearly in the overlying water column of sediment systems maintained under anoxic conditions (Figure 1). The mean P concentration maximum in the overlying water under anoxic conditions was 0.300 mg/L (± 0.047 standard error; S.E.) at the end of the incubation period. The mean rate of P release under anoxic conditions was relatively high at 2.4 mg m^{-2} d^{-1} (± 0.5 S.E.; Table 2), and indicative of eutrophic conditions (Nürnberg 1988).

Under oxic conditions, P mass and concentration in the overlying water column was near detection limits during the first 5 days of incubation (Figure 2). These variables then increased modestly between day 5 and 15 of incubation and leveled off to an asymptote until the end of the incubation period. The mean rate of P release under oxic conditions was moderately high at 0.82 mg m^{-2} d^{-1} (± 0.16 S.E.; Table 2). The maximum P concentration attained in the overlying water column toward the end of the incubation period was also high at 0.107 mg/L (±0.024 S.E.), representing a potentially important available P source for assimilation by algae. Overall, Redrock Lake sediments exhibited high rates of P release under oxic conditions, compared to some other lakes in the region (Figure 3). In contrast, anoxic P release rates were more moderate to low versus other lakes in the region (Figure 3).

Sediment Textural and Chemical Characteristics

The upper 10-cm sediment layer exhibited a moderately high moisture content and low bulk density, indicating fined-grained flocculent sediment (Table 3). Organic matter content was relatively high at ~34%. Concentrations of biologically-labile (i.e., subject to recycling back to the overlying water column; loosely-bound P, iron-bound P, and labile organic P) and refractory (i.e., aluminum-bound, calcium-bound, and refractory organic P) P concentrations were also high and fell within the upper ranges observed for lakes in the region (Table 4 and Figure 4). Biologically-labile P accounted for the majority of the sediment total P at ~ 58% while biologically-refractory P accounted for 42% of the sediment total P concentration (Table 5 and Figure 5).

Redox-sensitive P concentrations (i.e., the loosely-bound and iron-bound P fractions) fell within the high range compared to other lakes in the region (Figure 4) and accounted for ~ 88% of the biologically-labile P (Table 5). In particular, iron-bound P, which has been positively correlated with rates of P release under anoxic conditions (Nürnberg 1988), was very high in concentration at 1.611 mg/g DW (122 µg/g FW sediment) compared to other lakes in the region (Figure 4) and could play an important role in driving high rates of P release under anoxic conditions. In particular, this fraction overwhelmingly dominated both redox-sensitive and biologically-labile P fractions at 91% and 80%, respectively (Figure 5). However, the anoxic P release rate for Redrock Lake was low in relation to the iron-bound P concentration and did not conform to the Nürnberg (1988) regression relationships (Figure 6). Explanations for this discrepancy are currently unknown. Other factors such as microbial uptake and control of P release from sediment may be impacting rates. In addition, aluminum-bound P, a biologically-refractory P form, may be somehow important in regulating P release from the sediment under anoxic conditions since concentrations of this fraction were also very high (see below) in Redrock Lake sediments. Aluminum (as ($Al(OH)_3$) can play an important role in regulating (reducing) diffusive P flux from sediments when its concentration is high relative to that of iron (Kopáček et al. 2005). More research is needed to identify and better understand relationships between redox-sensitive P and rates of P release under anoxic conditions.

Although moderately high in concentration compared to other lakes in the region (Figure 4), labile organic P, which can be recycled to the water column as a result of bacterial metabolic processes, also represented a minor fraction of the biologically-labile P pool in Redrock Lake sediment at ~12% (Figure 5). The loosely-bound P fraction, also relatively high in concentration, only accounted for low and accounted for ~ 8% of the biologically-labile P and 9% of the redox-sensitive P. Loosely-bound P typically represents P in interstitial water and concentrations are usually low relative to other sediment P fractions.

Biologically-refractory P was dominated by the aluminum-bound P fraction (68% of the biologically-refractory P; Table 4 and Figure 5). As mentioned above, concentrations of aluminum-bound P were also very high relative to other lakes in the region (Figure 4). Calcium-bound P (i.e., P associated with apatite minerals) represented ~ 12% and refractory organic P accounted for ~ 20% of the biologically-refractory P (Table 4).

The total sediment Fe concentration was moderate for Redrock Lake (Table 6). It was moderately high relative to the concentration of total sediment P, resulting in an Fe:P ratio (mass:mass) of ~8:1. Ratios greater than 10:1 to 15:1 have been associated with regulation of P release from sediments under oxic (aerobic) conditions due to efficient binding of P onto iron oxyhydroxides in the sediment oxic microzone (Jensen et al. 1992). Strong and complete binding P at higher relative concentrations of Fe are suggested explanations for patterns reported by Jensen et al. At lower Fe:P ratios, Fe binding sites become increasingly saturated with P, allowing for diffusion of excess porewater P into the overlying water column, even in the presence of a sediment oxic microzone. The mean oxic P release rate was high for Redrock Lake in conjunction with a low Fe:P ratio, a pattern that could be attributed to the Jensen et al. model.

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Table 1. Sequential phosphorus (P) fractionation scheme, extractants used, and definitions of recycling potential.

Variable	Extractant	Recycling Potential
Loosely-bound P	1 M Ammonium Chloride	Biologically labile; Soluble P in interstitial water and adsorbed to $CaCO_3$; Recycled via direct diffusion, eH and pH reactions, and equilibrium processes
Iron-bound P	0.11 M Sodium Bicarbonate-dithionate	Biologically labile; P adsorbed to iron oxyhydroxides (Fe(OOH); Recycled via eH and pH reactions and equilibrium processes
Labile organic P	Persulfate digestion of the NaOH extraction	Biologically labile; Recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells
Aluminum-bound P	0.1 N Sodium Hydroxide	Biologically refractory; Al-P minerals with a low solubility product
Calcium-bound P	0.5 N Hydrochloric Acid	Biologically refractory; Represents Ca-P minerals such as apatite with a low solubility product
Refractory organic P	Determined by subtraction of other forms from total P	Biologically refractory; Organic P that isresistant to bacterial breakdown

Table 2. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under oxic (aerobic) and anoxic (anaerobic) conditions for sediments collected in Redrock Lake.

Station	Diffusive P flux	
	Oxic ($mg\ m^{-2}\ d^{-1}$)	Anoxic ($mg\ m^{-2}\ d^{-1}$)
Central	0.82 (0.16)	2.4 (0.5)

Table 3. Textural characteristics for sediments collected in Redrock Lake. 1 standard error in parentheses (n=3).

Station	Moisture Content (%)	Bulk Density (g/cm^3)	Sediment Density (g/cm^3)	Loss-on-ignition (%)
Central	92.4 (0.3)	1.032 (0.001)	0.088 (0.004)	33.9 (0.3)

Table 4. Concentrations of biologically labile and refractory P for sediments collected in Redrock Lake. DW = dry mass, FW = fresh mass.

Station	Redox-sensitive and biologically labile P				Refractory P		
	Loosely-bound P (mg/g DW)	Iron-bound P (mg/g DW)	Iron-bound P (ug/g FW)	Labile organic P (mg/g DW)	Aluminum-bound P (mg/g DW)	Calcium-bound P (mg/g DW)	Refractory organic P (mg/g DW)
Central	0.156 (0.047)	1.611 (0.167)	122 (10)	0.250 (0.036)	1.006 (0.177)	0.174 (0.011)	0.290

Table 5. Concentrations of sediment total phosphorus (P), redox-sensitive P (Redox P; the sum of the loosely-bound and iron-bound P fraction), biologically-labile P (Bio-labile P; the sum of redox-P and labile organic P), and refractory P (the sum of the aluminum-bound, calcium-bound, and refractory organic P fractions) for sediments collected in Redrock Lake. DW = dry mass.

Station	Total P	Redox P		Bio-labile P		Refractory P	
	(mg/g DW)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)	(mg/g DW)	(% total P)
Central	3.487	1.767	50.7%	2.017	57.8%	1.47	42.2%

Table 6. Concentrations of sediment total iron (Fe), manganese (Mn), and calcium (Ca) and the Fe:P ratio for sediments collected in Redrock Lake. DW = dry mass.

Station	Total Fe (mg/g DW)	Total Mn (mg/g DW)	Total Ca (mg/g DW)	Fe:P
Central	27.86	2.02	75.02	8.0

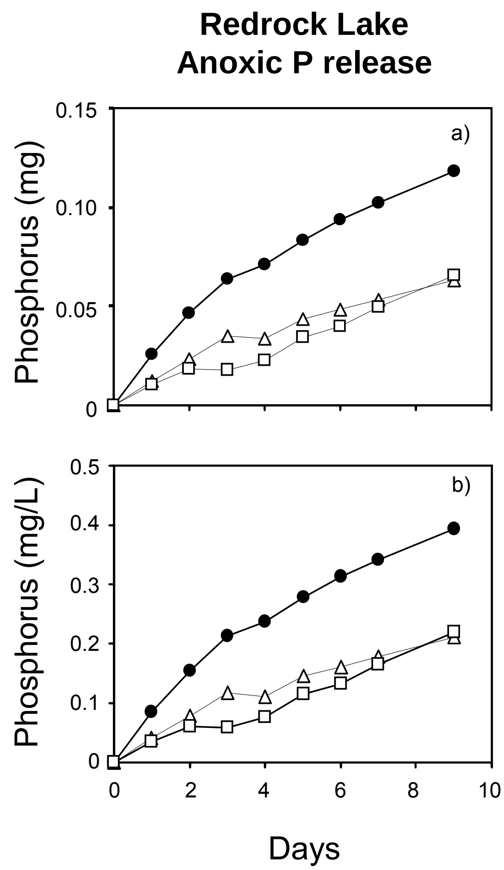

Figure 1. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under anoxic conditions versus time for sediment cores collected in Redrock Lake.

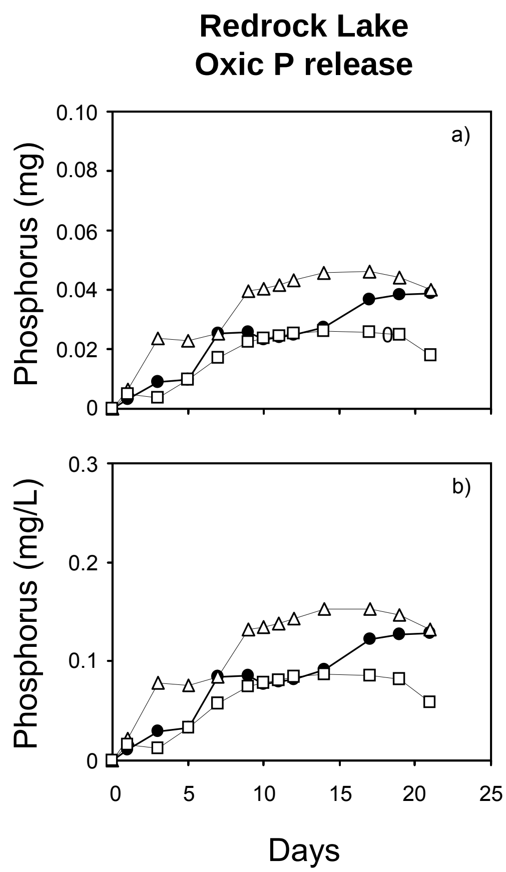

Figure 2. Changes in soluble reactive phosphorus mass (upper panel) and concentration (lower panel) in the overlying water column under oxic conditions versus time for sediment cores collected in Redrock Lake.

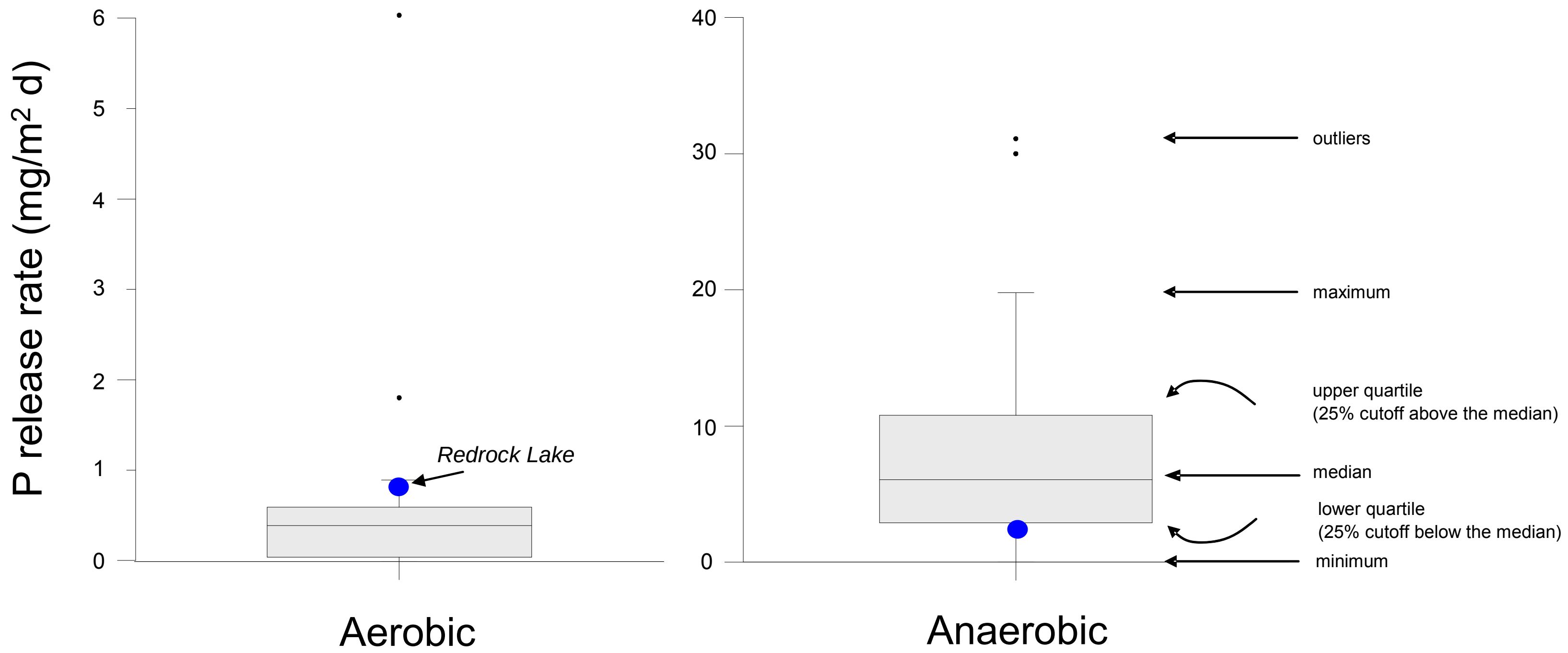

Figure 3. Box and whisker plot comparing the oxic and anoxic phosphorus (P) release rate measured for Redrock Lake (blue circles) with statistical ranges (n=50) for lakes in the State of Minnesota.

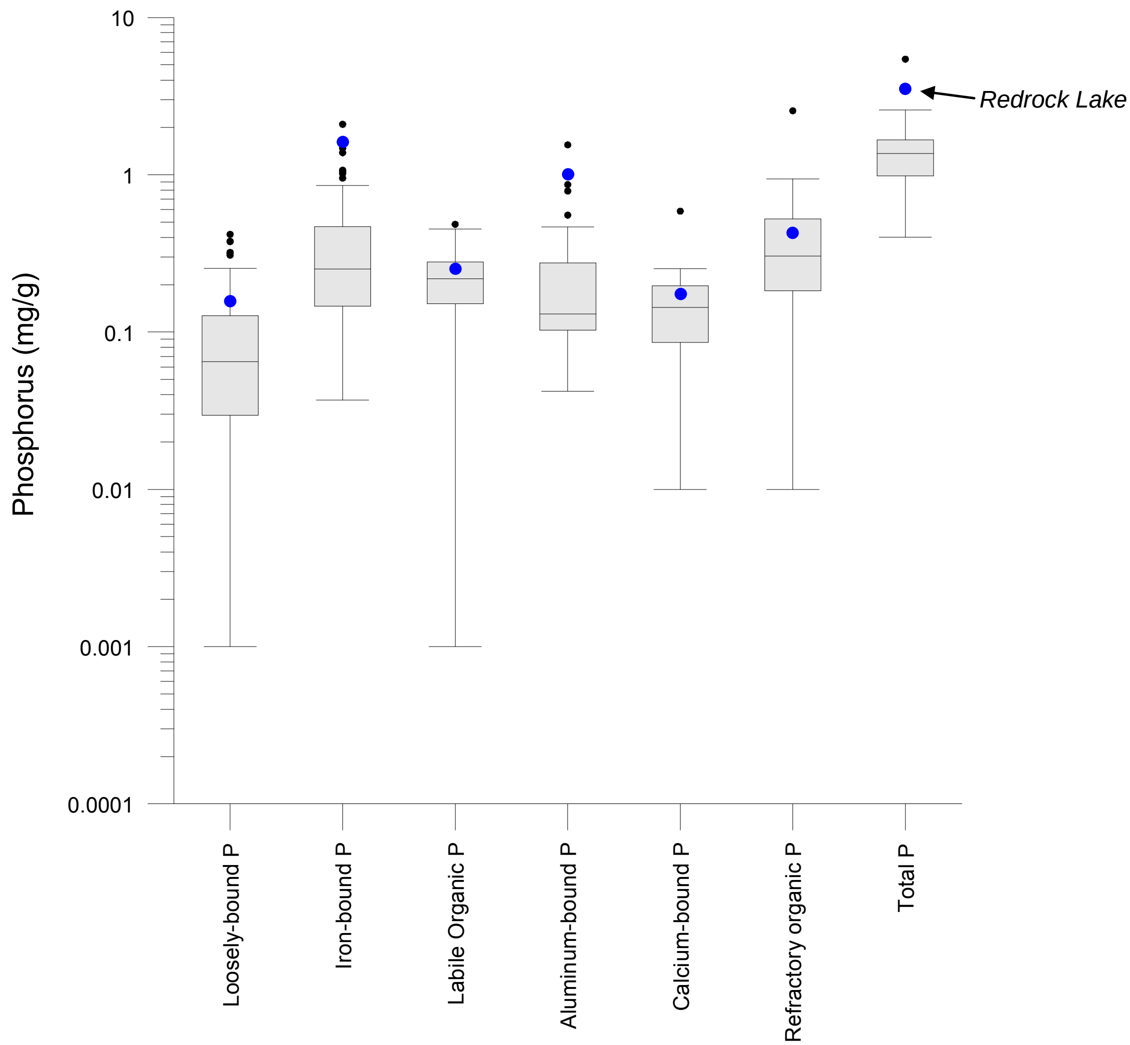

Figure 4. Box and whisker plots comparing various sediment phosphorus (P) fractions measured for Redrock Lake (blue circles) with statistical ranges (n=50) for lakes in the State of Minnesota. Loosely-bound, iron-bound, and labile organic P are biologically-labile (i.e., subject to recycling) and aluminum-bound, calcium-bound, and refractory organic P are more are more inert to transformation (i.e., subject to burial). Please note the logarithmic scale.

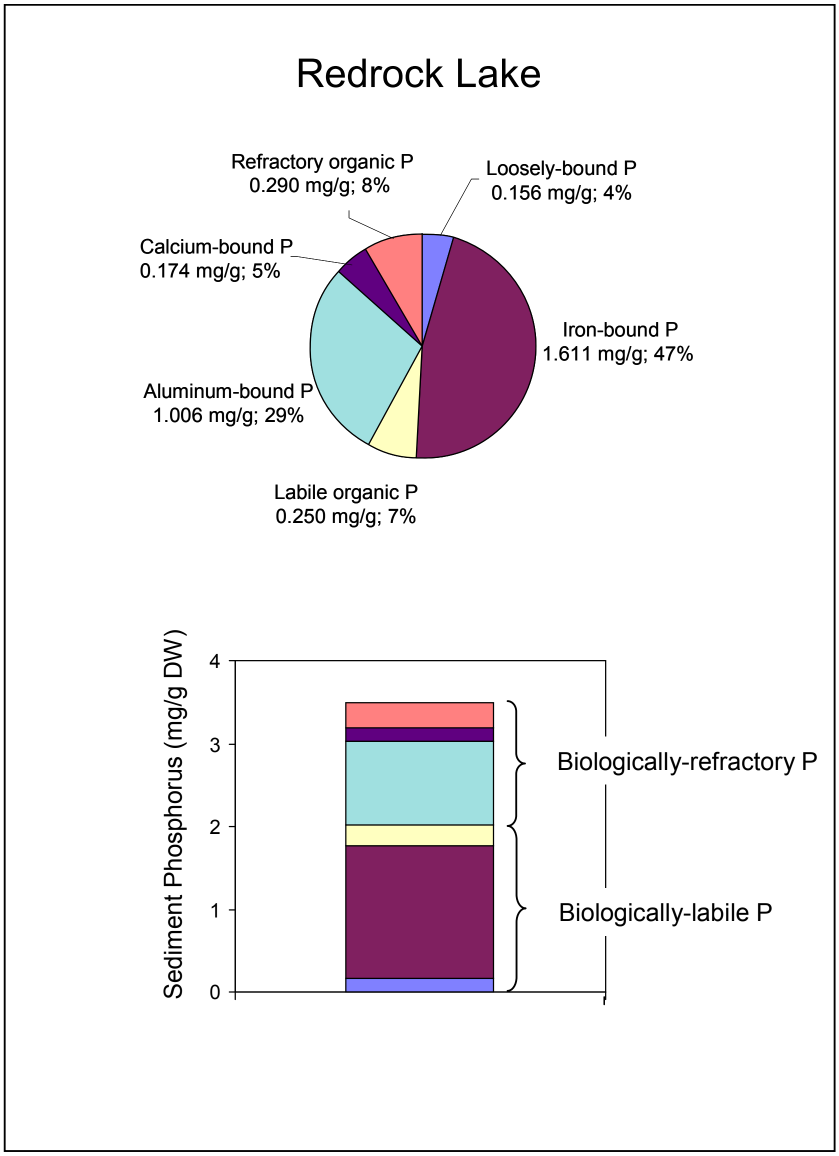

Figure 5. Total phosphorus (P) composition for sediment collected in Redrock Lake. Loosely-bound, iron-bound, and labile organic P are biologically reactive (i.e., subject to recycling) while aluminum-bound, calcium-bound, and refractory organic P are more inert to transformation (i.e., subject to burial). Values next to each label represent concentration ($mg \cdot g^{-1}$) and percent of the total sediment P concentration, respectively.

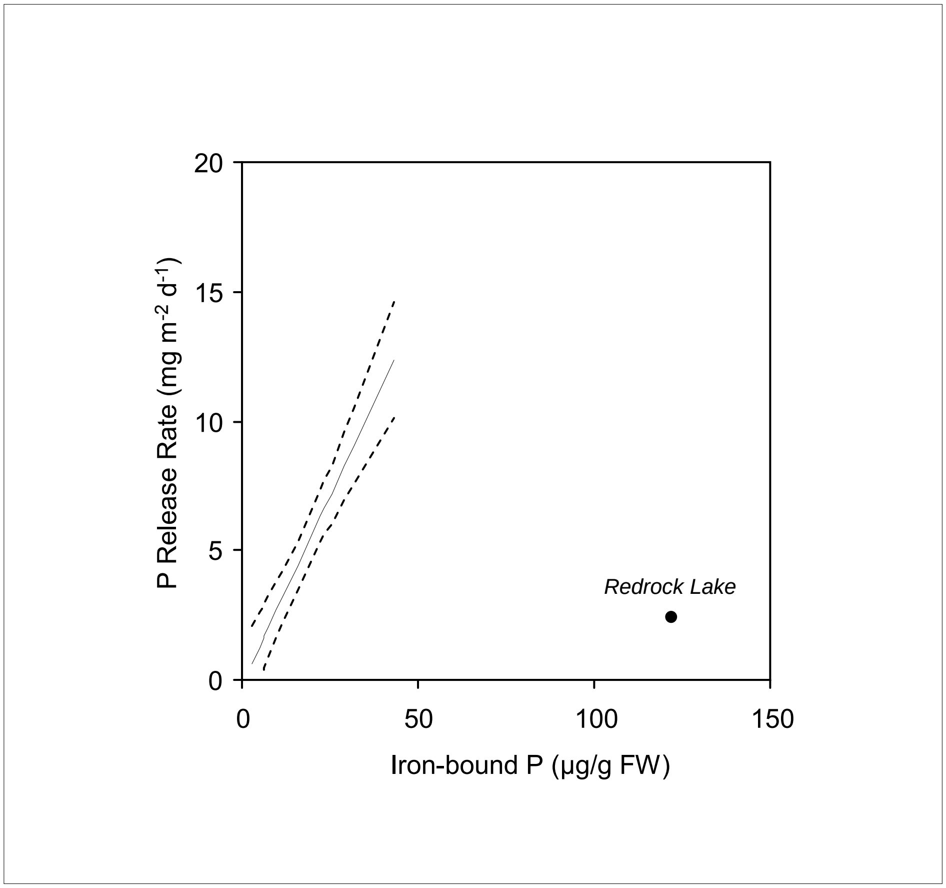

Figure 6. Relationships between iron-bound phosphorus (P; µg g^{-1} fresh sediment mass) and rates of P release from sediments under anoxic conditions. Regression line and 95% confidence intervals from Nürnberg (1988) are shown for comparison.