

Lake Pleasant Watershed Assessment and Protection Plan

Prepared by

**Western Pennsylvania Conservancy
and
Argonne National Laboratory**

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Growing Greener Program**



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MISSION

Western Pennsylvania Conservancy's mission is to save the places we care about by connecting people to the natural world.

ACHIEVING OUR MISSION AT LAKE PLEASANT

Since the 1950s, Western Pennsylvania Conservancy (WPC) has recognized the uniqueness and need to protect the glacial region of northwest Pennsylvania for future generations to enjoy. Home to significant geological, archaeological, and ecological resources, this region holds treasures found nowhere else in the Commonwealth.

In the 1980s, scientists from WPC and the Cleveland Museum of Natural History studied the flora of lakes in northwest Pennsylvania. They documented only seven natural, glacially formed lakes in the region. These lakes contained unique native plant communities, or the remnants of historically diverse plant communities that had been impacted by decades of human abuse and exotic species invasion. Many of these natural lakes had fallen victim to incompatible land use, shoreline development, loss of wetlands, recreational overuse, water level manipulation, and pollution. In addition, most were overrun with invasive exotic plants and more recently, some have begun to see the introduction of zebra mussels. One of these lakes had managed to escape most of these threats and still retained the healthy ecological communities that early French trappers would have found over 250 years ago. This lake, still considered the jewel of northwest Pennsylvania glacial lakes, is Lake Pleasant.

Covering only 64 acres and draining less than 3-mi², Lake Pleasant is one of the smallest glacial lakes in northwest Pennsylvania. Its small size made it possible to protect Lake Pleasant through traditional land protection measures. Over two-dozen species of special concern and rare natural communities made it a priority for protection. In the early 1990s, WPC worked with several watershed landowners to begin purchasing land. Presently, WPC has purchased over 370 acres in the watershed, protected roughly 70 percent of Lake Pleasant's shoreline, and have another 200 acres under sales agreement. These properties are open for the public to enjoy and connect neighboring publicly owned lands to form corridors for the benefit of wildlife and outdoor enthusiasts.

In 2000, WPC established its Northwest Field Station on Lake Pleasant. On the site of a former church camp, WPC staffs an office, environmental education center, and conservation and research station. The Northwest Conservation Programs staff is dedicated to understanding and protecting Lake Pleasant. In 2003, we completed the Lake Pleasant Conservation Area Master Site Plan that focuses on connecting people to this natural treasure through educational programming, recreational activities, and conservation of land for future generations to enjoy.

The *Lake Pleasant Watershed Assessment and Protection Plan* is the result of our latest endeavor to work with our partners and neighbors to understand the threats to the health of Lake Pleasant. A comprehensive watershed assessment was necessary to understand the mechanisms at work in the Lake Pleasant watershed that govern water quality and quantity as well as the health of ecological communities. The information contained in this report will be used to guide restoration activities and further conservation in the Lake Pleasant watershed. The data collected will provide useful background information that can be used to gauge the health of the lake far into the future. Next steps include:

- continued water quality monitoring
- analysis of aquatic and wetland communities
- monitoring and management of invasive species
- landscape restoration on degraded areas throughout the watershed
- development of a publicly driven watershed conservation plan that incorporates scientific data, recreational improvement plans, restoration and habitat improvement plans, and environmental education programs at WPC's Northwest Field Station.

At Lake Pleasant, we are striving to protect this place we care about by connecting people to its natural wonders.

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Western Pennsylvania Conservancy would also like to thank the watershed stakeholder group comprised of landowners, scientists, local government officials, and outdoor enthusiasts that met to provide initial input on priorities for the Lake Pleasant Watershed Assessment. The complete list of stakeholders can be found in Appendix A. This group provided critical input on information sources, threats to Lake Pleasant, and priorities for protection of the lake and watershed.

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The views expressed herein are those of the authors and do not necessarily reflect the views of the Pennsylvania Department of Environmental Protection.

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ACRONYMS

ANL	Argonne National Laboratory
CCC	Criteria Continuous Concentration
CMC	Criteria Maximum Concentration
CMNH	Cleveland Museum of Natural History
CSM	Conceptual Site Model
DCNR	Pennsylvania Department of Conservation and Natural Resources
DEP	Pennsylvania Department of Environmental Protection
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
GPS	Global Positioning System
NOAA	National Oceanic and Atmospheric Administration
NRWQC	National Recommended Water Quality Criteria for Priority Toxic Pollutants
red-ox	Oxidation-Reduction
SQuiRT's	Screening Quick Reference Tables
TPP	Technical Planning Process
YSI	Yellow Springs Instrument
WPC	Western Pennsylvania Conservancy

EXECUTIVE SUMMARY

In 2001, Western Pennsylvania Conservancy began a comprehensive assessment of the health of Lake Pleasant and a documentation of threats to water quality and quantity, and the unique ecological communities found in the watershed. Driven by an urgent need to protect the best remaining example of an ecologically intact glacial lake in northwest Pennsylvania, WPC partnered with Argonne National Laboratory to develop the Lake Pleasant Watershed Protection Plan.

This report focuses on the analysis of information collected to fill existing data gaps, combined with existing data on the lake, to create a comprehensive analysis of the parameters that drive the lake's environmental processes. This report is organized by the environmental systems and mechanisms operating in the watershed:

- Brief introductory material is presented on Lake Pleasant and the study objectives.
- Descriptions of the geology and hydrology of the lake are provided.
- Study methods are described.
- Chemical constituents of groundwater, surface water, and lake are analyzed in detail and include a phosphorus budget, metals analysis, and assessment of the trophic state.

Watershed management and protection strategies for the Lake Pleasant watershed are provided, consistent with the goal of conserving the lake, its wetlands, and resident native species.

Discussion and recommendations in this report refer to the Lake Pleasant ecosystem. As an ecosystem, Lake Pleasant is a unique, discrete system that receives impacts from the outside, both natural and anthropogenic, and in turn impacts a larger external system, the French Creek watershed. It is imperative to consider the entire system that includes Lake Pleasant. The Lake Pleasant ecosystem must be the focus of conservation efforts if the lake and associated natural communities are to be protected. The lake cannot be protected without protecting hydrologically connected streams and wetlands, aquatic plants and fish cannot be protected without protecting upland groundwater recharge areas, and water quality cannot be protected without considering outside impacts like atmospheric deposition. While the latter may be difficult to address, we cannot fully conserve the Lake Pleasant ecosystem without addressing human impacts both from within the watershed and from a regional perspective.

Development of the Lake Pleasant Watershed Assessment and Protection Plan is documented online at <http://web.ead.anl.gov/wpc> or at www.paconserve.org. Raw data can be accessed using a spatial, internet-based, GIS tool. Background information, historical data, and WPC and Argonne staff contact information is available.

1. INTRODUCTION

Lake Pleasant stands as one of the best remaining examples of an intact glacial lake community in Pennsylvania. Located in Venango Township, Erie County, approximately 12 miles southwest of the city of Erie, this 64-acre lake is surrounded by wetlands to the north, west and south and supports 24 plant species and three fish species of special concern in Pennsylvania. This wide diversity of organisms depends strongly on the quality, quantity, flow and distribution of groundwater in the watershed; therefore, it is important to understand the hydrologic system and how it may be changing due to anthropogenic impacts.

Unlike many other large glacially formed lakes in Pennsylvania, Lake Pleasant has escaped the extensive development and water level manipulation that has claimed the integrity of many of its counterparts. It is the only natural lake in western Pennsylvania that has escaped habitation by Eurasian water-milfoil, a widely spread invasive species.

Although the lake is perceived to be in good condition in comparison with other lakes in the region, WPC scientists identified the need for a thorough, well-documented understanding of the hydrologic and chemical characteristics of the lake to aid protection efforts. Without well-documented historical chemical, biological, and physical information, it would be difficult to perform a diagnostic analysis of the lake if future undesirable changes, such as reductions in the numbers of rare species, pronounced algae blooms, or increased siltation of the lake bed occurred. For example, if a sudden onset of algae blooms was observed, changes in the water chemistry – perhaps, observable increases in phosphorus concentrations – or changes in the hydrology – perhaps, decreases in groundwater input – could be tracked and pin-pointed as a possible cause.

Due to the sparse amount of data that were available for Lake Pleasant, WPC initiated this study in 2001. The key potential threats to the watershed, identified in the early stages of the project, are:

- Non-point source pollution from agriculture and resource extraction.
- Invasion by exotic plant and animal species.
- Degradation of the immediate shoreline of the lake.

Western Pennsylvania Conservancy and Argonne National Laboratory (ANL) worked with other area stakeholders to assess the factors that impact the lake and to find ways to monitor and minimize them.

1.1 Study Approach (Development of an Adequate Data Set)

The first formal step taken in the investigation was the formation of a Conceptual Site Model (CSM) for the Lake and surrounding wetlands. The CSM is a constantly evolving description of the fundamental components of the watershed's physical and ecological systems. It is used to organize any existing information, place it into perspective relative to the Lake Pleasant watershed management goals and to identify key gaps in the understanding of the watershed's physical and ecological conditions.

Changes to the CSM are made throughout the investigation to reflect incoming data. By the close of the investigation, the revised CSM will present and interpret all existing data sets, serving as the most complete model of the lake and its wetlands to date. In essence, the CSM and the final report will ultimately become the same document.

The CSM was constructed to reflect and address the Lake Pleasant watershed management objectives:

- Minimizing shoreline erosion and degradation.
- Minimizing impacts to the ecosystem of the lake (watershed) from point and non-point source pollution.
- Inhibiting the introduction and spread of exotic species (or, maximizing the natural diversity of the plant and animal community).

1.1.1 Implementation of the Technical Project Planning Process

Once existing data sets were gathered and a basic CSM was developed, a Technical Project Planning (TPP) meeting was attended by WPC, ANL, and other area stakeholders (see Appendix A for a list of meeting attendees). The TPP meeting served to develop a common understanding of the CSM and the study objectives, and worked to establish the basic priorities, timing, and components of the study in a structured format.

Priorities flagged with the highest importance through the TPP meeting included:

- Establishing a hydrologic budget.
- Developing a phosphorus budget.
- Surveying the plant and fish communities of the lake and wetlands.
- Inventorying wells/septic systems.
- Assessing groundwater/surface water quality and chemistry.

1.1.2 Development of the Work Plan Using Adaptive Sampling and Analysis and the Data Quality Objectives Process

In order to achieve the above goals in a timely and organized manner, a work plan was developed for Lake Pleasant combining existing information from the CSM with the data needs identified by the TPP. The work plan described the process for establishing a baseline assessment of Lake Pleasant, its wetlands, and the watershed, with the primary focus on the lake and its water quality. Sources and types of pollution via non-point source pathways, the extent of watershed degradation from mining, and impacts from shoreline erosion were evaluated through qualitative and quantitative means. Sampling and data collection included parameters necessary to develop the hydrologic and phosphorus budgets and document the temporal and spatial variability of water quality in the lake, groundwater, and wetlands. Concurrent studies by WPC and partners documented the health of native aquatic and wetland plant communities, the degree of watershed invasion by exotic plant species, impacts to the lake from roadway runoff, and bird species within the watershed.

The work plan provided:

- The goals of the project.

- The type, timing, quality, and quantity of data needed.
- Decision guidelines to guide decision making on site.
- Field procedures to allow accurate data collection.
- Sampling and analysis strategy designed to reduce redundancy and support cost effectiveness of sampling effort.

Prior to initiating the data collection process, the team attempted to anticipate the kinds of analyses that would take place and the different ways in which the information and results would be portrayed. This allowed the data management process to be optimized from the very beginning of the study.

The work plan is dynamic and recognized that new concepts would be learned during the study and that different analytical tools may have been needed. Therefore, the work plan was subject to modification in order to accommodate such changes at any point in the study. For example, if a full metals analysis is performed on the lake water and no exceedances are found, the decision to terminate subsequent metals analyses can be made in the field to reduce cost and to redirect available resources to areas that may require more attention.

1.1.2.1 Adaptive Sampling and Analysis

Adaptive sampling and analysis takes advantage of screening technologies to focus sampling efforts. For example, a hand-held field meter was used to collect real-time field parameter data. One way this served to expedite the sampling process was by allowing the immediate availability of dissolved oxygen (DO) profiles to investigators in the field. Because concentrations of certain parameters are expected to exhibit spatial and temporal variability that correlates predictably with DO levels (red-ox dependant metals, for example), immediate knowledge of DO trends within the lake gave investigators the ability to accurately collect samples both in areas of high DO concentration and of low DO concentration. When DO is fairly uniform vertically, one sample was deemed sufficient. This process streamlined the sampling effort by saving time and associated laboratory costs.

1.1.2.2 Data Quality Objectives (DQOs)

The work plan described an optimized, systematic process for specifying the type, timing, quality, and quantity of data to be collected in order to achieve the study objectives. The United States Environmental Protection Agency (EPA) provides guidance known as the data quality objective (DQO) process, used to refine the data collection process in environmental studies. The plan also evaluates the detection limit of the analytical method to be sure that it is well below the level of concern.

The basic DQO process consists of seven steps that guide the data collection process to assure that the appropriate type, quantity, and quality of data are collected at the appropriate times. They are:

- Step 1: Define the Problem,
- Step 2: Identify the Decision(s),
- Step 3: Identify the Information Needed for the Decision(s),

- Step 4: Define the Boundaries of the Study,
- Step 5: Develop a Decision Rule,
- Step 6: Specify Tolerable Limits on Decision Errors, and
- Step 7: Optimize the Design for Obtaining Data.

The general concepts of the DQO process can be very powerful in how they are used to integrate the various components of data collection that must be performed in a study. For instance, phosphorus can enter the lake through many pathways. In order to perform a mass balance on phosphorus, it will be necessary to know the concentration in each pathway and the rate at which phosphorus enters the lake through that pathway. The degree of confidence required for understanding the phosphorus budget may determine how accurately the groundwater and storm water flow to the lake must be measured. It may also establish the range of flows that are contributing the bulk of the phosphorus to the lake and help to understand the relative importance of each flow condition in terms of its contribution of phosphorus to the lake.

Further explanation of the DQO process can be found online at <http://www.epa.gov/swerust1/cat/epaqag4.pdf>

1.2 Relationships Between Principal Study Components and Management Objectives

In order for the study to be implemented, the CSM was divided into components that could be described and tested by measurement. The most intensive work associated with this study is related to the management objective, minimizing impacts to the ecosystem from point and non-point source pollution.

The principle study components are:

- Topography and elevations of key features of the lake and its watershed.
- The hydrologic cycle (i.e., groundwater, surface water, precipitation, evapotranspiration, etc.).
- The phosphorus budget.
- The trophic index value of the lake.
- The presence and transport of metals and other chemicals in groundwater, surface water and sediment.

A related management objective is determining the number and distribution of native sensitive species and exotic species. The majority of this effort is being conducted concurrently by WPC and partner scientists or is planned for future work. WPC and Cleveland Museum of Natural History botanists are currently conducting a native plant inventory of the lake and surrounding wetlands. A discussion of those results is included in this report so that the integration of information and analyses between the two projects is as seamless as possible.

The third management objective, decreasing shoreline erosion will be addressed later in the report through further analysis of the geology, hydrology, and topography of the area.

Table 1. Relationship of Principal Study Components to Management Objectives

	<i>Study Components to be Addressed in Order to Satisfy Objectives</i>				
<i>Management Objectives</i>	Phosphorus Budget	Water and Sediment Chemistry	Geology	Climate and Hydrology	Topography and elevation data
Minimizing Impacts from Pollution	Define sources, sinks, and cycles of phosphorus	Determine nutrient balances, identify constituents that may be harmful to humans and the ecosystem	Understand the geologic composition of the watershed as it affects the fate and transport of pollutants	Understand magnitude, timing, and pathways of water movement in the watershed.	Topography drives the transport of pollutants. Accurate elevations of watershed features are essential.
Maximizing Species Diversity	Phosphorus may cause negative changes to the water, which many species depend on to thrive.	Understand the optimum water chemistry conditions for maximum species diversity.	Plants and animals are closely tied to the geologic substrate of the watershed.	The quality, quantity, availability, and movement of water are key to species distribution and survival.	Many species require very specific conditions, which are determined by their elevation relative to key watershed features such as the lake or groundwater surface.
Minimizing Shoreline Erosion	Indirectly, plant roots aid in keeping the shoreline intact by securing the soil and reducing wind shear.	Shoreline erosion contributes to sedimentation of the lake.	The composition of the shoreline is important to whether and how fast it erodes	The wave climate, degree of saturation, and freeze-thaw cycles affect shoreline erosion	Shorelines tend to be eroded by waves over very narrow elevation ranges.

1.2.1 Management Objective 1 – Minimizing the Impacts of Pollution on Lake Pleasant and its Wetlands

1.2.1.1 Principal Study Components

Principal Study Component 1

- Determine whether Non-Point Source (NPS) and Point Source (PS) pollution are contributing to the degradation of Lake Pleasant’s surface water.
 - Determine whether constituent levels of total phosphorus are elevated above 25 µg/L in the surface water of Lake Pleasant, and above 50 µg/L in the stream water at the point of entry into the lake.
 - If >10% of the samples for P in the lake at the sampling point center, fall above 25µg/L, then the lake will be considered to be at an increased risk for eutrophication. Continued monitoring for phosphorus, as part of a watershed management plan will be recommended.
 - If >10% of the samples for P at surface inflow points fall above 50µg/L, then the lake will be considered to be at an increased risk for eutrophication. A plan for reducing P inputs will be incorporated into a watershed management plan.
 - Determine whether constituent levels of metals and chemicals are elevated above national EPA standards for aquatic health in the lake and its wetlands.
 - If a measured one-hour average concentration of an EPA priority metal falls above its corresponding acute threshold value (CMC) more than once in a 3 year period, then the lake will be considered impaired in relation to the health of aquatic life for that constituent. (See section 4.4 for definitions of priority metal and threshold value)
 - If a measured four-day average concentration of an EPA priority metal falls above its corresponding chronic threshold value (CCC) more than once in a three year period, then the lake will be considered impaired in relation to the health of aquatic life for that constituent. (See section 4.4 for definitions of priority metal and threshold value)
 - Determine the pathways by which point source and non-point source pollution move through the watershed.
 - Determine sources and concentrations of P loading into and out of the lake through the construction of a phosphorus budget.

Principal Study Component 2

- Establish baseline conditions of the lake to determine whether future conditions will create pollution concerns. Because watershed management strategies extend over many years, it is necessary to establish baseline conditions against which the strategies can be judged periodically.
 - Prepare hydrologic budget for the lake, assessing groundwater, surface water, and lake water flow pathways.

- Sample and record concentrations of EPA priority metals: metals that have been shown to be significantly toxic to life or have the tendency to bioaccumulate in fish tissue.
- Create pH, DO, and temperature profiles for the lake, chronicling its spatial and temporal variability.
- Measure and record concentrations of the major cations and anions in groundwater and surface water.

Understanding the complex water chemistry of the lake is an important component of this study. The temporal changes in the lake can affect nutrient availability and uptake, metal toxicity and bio availability, and consequently, the quality of aquatic life. In order to satisfy Principal Study Component 2, the completion of a baseline assessment of Lake Pleasant, a thorough water quality assessment plan was constructed. Instrumental to the plan were:

- Optimization of sampling point selection in and around the lake ensures a complete data set while reducing sampling costs and labor.
- Selection of key parameters needed to supplement and support the existing water quality data by filling in existing data gaps.
- Identification of sampling methods and corresponding detection limits to ensure an effective balance between obtaining detection limits lower than or within corresponding threshold values and budget constraints.
- Determination of the timing (i.e. seasonal, diurnal) and quantity of samples collected.
- Establishment of a logical and easy to use sampling point nomenclature for effective data record keeping.

Data required to address Management Objective 1 include the phosphorus budget; metals and chemicals concentrations in precipitation, dry deposition, surface water and groundwater; hydrologic budget; and general water quality data.

1.2.2 Management Objective 2 – Maximize Native Species Diversity

1.2.2.1 Principal Study Components

Principal Study Component 3

- Inventory native species of plants and animals in the watershed to determine health of ecological communities.

Principal Study Component 4

- Inventory and assess impacts of exotic invasive species on the native plant and animal communities. Are existing exotic species contributing to an unfavorable environment for naturally occurring and rare species through shading, spreading, nutrient competition, predation, etc. and should control measures for exotics be taken?

1.2.3 Management Objective 3 – Evaluate the Potential for Shoreline Erosion and Degradation

1.2.3.1 Principal Study Components

Principal Study Component 5

Geology

- What is the composition of the shoreline? The composition of the shoreline is important to whether and how fast it erodes.

Principal Study Component 6

Hydrology

- The wave climate, degree of saturation, and freeze-thaw cycles affect shoreline erosion. Determine each of these parameters.

Principal Study Component 7

Topography

- Shorelines tend to be eroded by waves over very narrow elevation ranges. Detail the grading around the lake and determine the degree of erosion that is likely to occur.

The final analyses of all available data will be molded to obtain a current, comprehensive CSM for the lake and its environmental processes. Presentation of the data in this form will be inclusive of all data sets and will be demonstrative of the interrelations between watershed parameters. The report will begin with a discussion of the watershed geology and hydrologic processes governing the lake. A hydrologic budget will be developed through analysis of groundwater and surface water quantity, precipitation, and evaporation. Surface water and groundwater chemistry will then be addressed. First, analyses of field parameters will be presented, including temperature, dissolved oxygen (DO), pH, specific conductance, and oxidation-reduction potential for surface water and groundwater. The temporal variations observed due to seasonal lake processes will be discussed. Concentrations of anions and cations in the watershed will be analyzed along with a discussion of their impact on lake chemistry. A section concerning metals and corresponding threshold values in surface water, groundwater, and sediment will be presented along with the potential impacts on aquatic life. Finally, nutrient levels in the lake and the potential impacts to aquatic life will be detailed and includes: the results of nutrient analyses determining the limiting nutrient in the lake, identification and analysis of nutrient inputs and outflows, the cycling of phosphorus through the development of a phosphorus budget, the comparison of phosphorus values with threshold values indicative of P levels that correspond with eutrophic conditions, the comparison of lake nutrient parameters with other water bodies in the area, and the development of a trophic index for the lake based upon phosphorus, chlorophyll a (indicator of algal biomass), and Secchi disk (indicator of transparency).

The final section of the Lake Pleasant watershed assessment report is a discussion of current lake conditions, potential watershed threats, and management recommendations. It is hoped that these efforts will produce a Lake Pleasant Watershed Assessment and Protection Plan that can be utilized by conservation organizations, scientists, local municipalities, and environmental agencies working together to conserve the natural resources of this jewel of a lake, Lake Pleasant.

2. WATERSHED DESCRIPTION

2.1 Bathymetry and Surrounding Land Use

The landscape of the Lake Pleasant watershed and surrounding area is a mosaic of cover types including open fields, wooded lots, wetlands, and gravel quarries (Figure 1). A small asphalt industry, a dairy farm, single-family residences, seasonal cottages, and various outbuildings are situated throughout the watershed.



Figure 1. Land use surrounding Lake Pleasant

Lake Pleasant is roughly an oval-shaped “kettle” lake with a maximum depth of approximately 13.5 meters (~45 feet). Estimates of lake volume and areas associated with various depths are provided by Dr. Milt Ostrofsky, Allegheny College, Meadville, Pennsylvania (Figure 2, Ostrofsky *et al.*, 2000). The bathymetric map was produced by measurement of depths through ice cover with an electronic depth finder and is similar to a map produced in 1977 by Dr. E. C. Masteller, The Pennsylvania State University, Behrend College, Erie, Pa. Both published maps were verified through sounding with weighted lines during the 2002 field season.

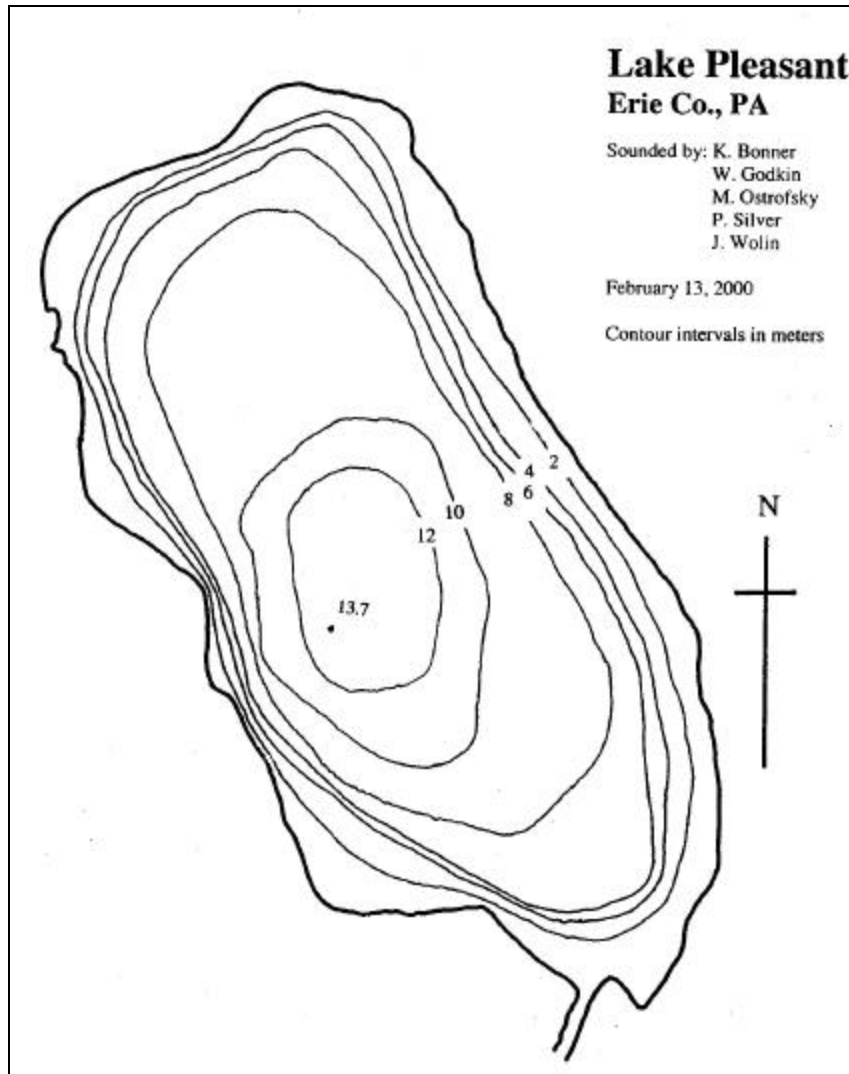


Figure 2. Bathymetric map of Lake Pleasant (Ostrofsky *et al.*, 2000)

2.2 Hydrogeologic Setting

Lake Pleasant (Figure 3), located south of the Lake Erie plain, is a 64-acre lake that lies within a 6-mi² tributary watershed of the French Creek drainage, Erie County, Pa. French Creek is part of the greater Ohio River basin.

The Lake Pleasant watershed is approximately two miles wide. The axis of the valley is oriented roughly northwest-southeast bounded by parallel ridges to the northeast and southwest. Surface water drains to the southeast. The ridges are formed in rock of the Devonian Venango formation, interbedded, coarse-grained sandstone and shale formation (Richards *et al.*, 1987). The bedrock of the valley is of the Devonian Chadokoin formation, an interbedded shale and sandstone, which is more easily eroded relative to the Venango formation.



Figure 3. Lake Pleasant

2.3 Geology

Lake Pleasant was formed as a result of Pleistocene glaciation. The valley is filled with sediments deposited by glacial ice and meltwater. Several major episodes of glaciation and de-glaciation occurred during the Pleistocene epoch. Each major episode contained a number of minor advances and retreats of the glacial front. The Lake Pleasant vicinity experienced between five and ten advances and retreats of the ice front in the last two major glaciations; the Illinoian (older) and Wisconsin (younger) glaciations. The two most recent minor advances and retreats known as the Kent and Lavery advances are responsible for the current valley surface topography and near-surface geologic configurations in the Lake Pleasant valley (White *et al.*, 1969). The Kent ice advance and retreat occurred between 20,000 and 25,000 years ago. The Lavery ice advance and retreat occurred between 15,000 and 20,000 years ago.

As the glaciers advanced, they carried and pushed clay, silt, sand, cobbles, and boulders. As they melted and retreated, they left the sediments and rocks behind in deposits known as glacial till. Till is typically a complex mix of clay, silt, sand, boulders, and cobbles (Figure 4). The till occurs in thin veneers a few feet thick on the ridges and their flanks. However, the till thickens toward the axis of the valley and is estimated to be at least 100 feet thick in the center of the valley beneath the lake and associated wetlands (Richards *et al.*, 1987).

Great discharges of water flowed from the glaciers as they melted, eroding a complex series of channels through the previously deposited till and laying down new deposits.

Meltwater deposits, known as glacial outwash deposits, are better sorted than till deposits. Relatively well sorted, deposits of clay, silt, sand, and gravel were laid down in the meltwater rivers depending on the velocity and depth of the water. Clays and silts were deposited in relatively quiet water, specifically in water where glacial ice and debris temporarily dammed the meltwater flow. Because of the multiple advances and retreats of the glaciers, a complex configuration of glacial sediments was deposited in the Lake Pleasant valley.



Figure 4. Glacial till

Tills were eroded by meltwater, which deposited outwash deposits, which were eroded by later glacial advances. Then, the remnants were covered with till from the latest glacial advance.

The description of Lake Pleasant as a “kettle” lake may not be accurate. Kettle lakes refer to lakes formed as a result of enormous blocks of ice breaking free from the leading edge of the glacier and being deposited in the outwash plain. Over time, these blocks of ice, which typically become buried by glacial outwash sediments, melt and leave a depression in the outwash plain known as a kettle. These kettles are common features of the landscape of glaciated areas and often fill with water to form lakes. Some scientists believe this process is how Lake Pleasant was formed. However, glacial lakes can form in a variety of other ways. Some are the result of valleys being dammed by glacial sediments and filling with water. Other lakes may be gauged out by the force of moving ice on the landscape. Lake Pleasant may have been formed as a result of an ice tongue advancing into the valley from the northwest during the most recent glacial advances. The ice remained in the valley while meltwater deposited glacial sediments around the ice and dammed the valley southeast of present-day Lake Pleasant. Eventually the ice in the Lake Pleasant basin melted, leaving it occupied by the current Lake Pleasant and associated wetlands (David S. Miller, pers. comm.).

2.3.1 Groundwater Drainage and Geochemistry

Sand and gravel deposits act as preferential groundwater flow pathways because water moves relatively easily through these porous and permeable materials. Wellington (1991) noted the absence of surface water sources to Lake Pleasant. This is a characteristic feature of geologic settings where the materials have high porosity and permeability. Virtually all of the water flowing to Lake Pleasant and its wetlands from the furthest reaches of its watershed must travel along subsurface pathways where it chemically equilibrates with the subsurface materials.

Rocks and minerals from far into Canada to nearby in Pennsylvania compose the till and outwash of the Lake Pleasant valley. An important aspect of the till and outwash in the

Lake Pleasant valley is they contain significant fractions of limestone and dolomite (carbonate rich rocks) (White *et al.*, 1969). During a field inspection of a gravel quarry southwest of Lake Pleasant, several lithified beds of outwash deposits were noted ranging in thickness from an inch or two to nearly three feet (Figures 5 and 6). The lithification was due to carbonate sediment as confirmed by effervescence upon contact with dilute hydrochloric acid.



Figure 5. Lithified beds of outwash deposits observed at Lake Pleasant

The carbonate content of the till and outwash is significant because virtually all of the water reaching Lake Pleasant and its wetlands must move through the carbonate rich ground to the lake and wetlands. Carbonate is a significant source of alkalinity and provides buffering capacity against the effects of acid deposition.



Figure 6. Lithified beds of outwash deposits observed at Lake Pleasant

The pH and dissolved oxygen of the water of Lake Pleasant was measured at one-meter depth intervals near the center of the lake in August 1991 (Wellington, 1991). Below 6 meters in depth, the pH ranged from 6.7 to 7.1 and the dissolved oxygen ranged from 0.6

to 1.7 ppm. In the top 6 meters of the water profile, the pH was very nearly constant between 8.1 and 8.2 except in the 5 to 6 meter interval where the pH was measured at 7.6. The dissolved oxygen ranged between 8.9 and 9.4 ppm in the top 5 meters of the water profile and was 6.7 ppm between 5 and 6 meters in depth. Additional information regarding water chemistry of Lake Pleasant can be found in section 5.