COMMUNITY ASSISTANCE
PLANNING REPORT NO. 58
(3RD EDITION)

A LAKE MANAGEMENT PLAN FOR PEWAUKEE LAKE

WAUKESHA COUNTY, WISCONSIN

SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

Special Acknowledgement is due to Dale J. Buser, PE, PH, Principal Specialist; Zofia Noe, Senior Specialist – Biologist; Dr. Justin Poinsatte, Senior Specialist –Biologist; Dr. Thomas Slawski, Chief Biologist; Megan Deau, Senior Graphic Designer; Dr. Jeffrey A. Thornton, PH, CLM, Former SEWRPC Principal Planner; Beverly Saunders, Former Senior Specialist; Anna Cisar, Former Research Analyst; and Emma Weiss-Burns, Former Environmental Planning Technician, for their contributions to the conduct of this study and the preparation of this report.

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WAUKESHA COUNTY, WISCONSIN

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The preparation of this publication was financed in part through a grant from the
Wisconsin Department of Natural Resources Lake Management Planning Grant Program

June 2020

A LAKE MANAGEMENT PLAN FOR PEWAUKEE LAKE

EXECUTIVE SUMMARY

A Management Plan for Pewaukee Lake and its Watershed

The Lake Management Plan for Pewaukee Lake (the Plan) is the third comprehensive management plan for this Lake and was developed to provide a set of targeted, specific recommendations to improve Pewaukee Lake, its tributaries, and ecological conditions throughout the watershed. This Plan supplements and builds upon previous plans and recommendations, such as the 1984 and 2003 lake management plans (see sewrpc.org); the 2017 aquatic plant management plan; and studies by the Wisconsin Department of Natural Resources (WDNR), the United States Geological Survey (USGS), and Wisconsin Lutheran College (WLC). Many recommended management measures from the previous editions of this Plan, such as educational programming, acquiring wetland parcels, promoting native aquatic species, and enhanced water quality monitoring, have been incorporated into past and ongoing Lake management practices.

Characteristics of Pewaukee Lake and its Watershed

Pewaukee Lake has long been renowned for its natural beauty and clear, clean water, as is historically evident by its robust ice harvesting business in the late 1800s. Currently, the Lake, one of the largest in southeastern Wisconsin, enjoys comparatively good water clarity, a healthy aquatic plant community, and is among the most popular musky fisheries in southeastern Wisconsin. Located in the metropolitan Milwaukee area, its visitors and residents engage in a wide variety of recreational pursuits including sailing, fishing, swimming, water-skiing, and other activities.

The Lake is fed by surface-water runoff draining from a 24.8 square mile watershed. The watershed is located entirely within Waukesha County but is divided between several cities, villages, and towns. Agricultural and residential land uses occupy the largest amount of land area within the watershed. Overall lake ecosystem health is commonly a direct reflection of watershed land use and management.

Four named tributaries (Audley, Coco, Meadowbrook, and Zion Creeks) and two unnamed tributaries contribute water to the Lake. Groundwater is also a significant source of water to the Lake, with springs being particularly common in the northwestern portion of the Lake and Coco Creek. As a consequence of abundant cold, mineral-rich groundwater discharge, Coco Creek is a coldwater stream hosting a population of trout, and the Lake has hard (mineral rich) water.

Pewaukee Lake is home to many recreational pursuits, including sailing, swimming, water-skiing, and fishing.

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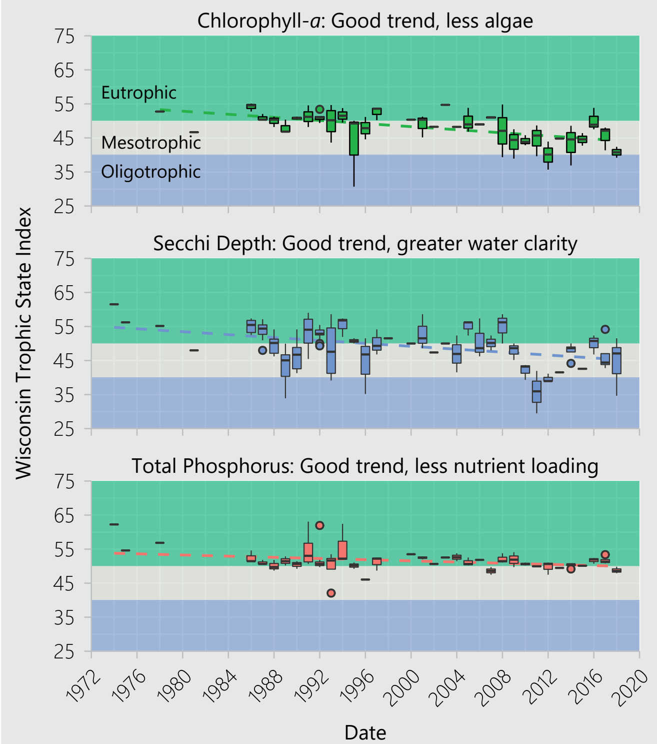
Justification for Plan

In spite of human-induced stressors, the Lake enjoys generally good water quality and conditions supporting a wide variety of use. Nevertheless, water resource features are commonly quite vulnerable to disturbance, a situation that can diminish the value of these high-value natural resource assets. In recognition of this concern, members of the Lake community are interested in evaluating topics that can be used to evaluate changes in the Lake's community value and ecological health. Many of these topics were evaluated as part of this plan. Examples of some topics of particular and widespread interest include the following:

- Water Quality Trends
- Aquatic Plant Management
- Water Level Regulation and Outlet Dam Operation
- Shoreline Stability, Riparian Buffers, and Floodplain Protection
- Restoring Natural Hydrology in a Changed Landscape

Water Quality Trends

In general, overall Lake water quality has improved since consistent monitoring began in the mid-1970s. Through this period, Lake water has become clearer, while total phosphorus and chlorophyll-*a* concentrations (indicators of algal abundance), have declined. Additionally, the extent of summertime anoxic (no oxygen) water near the lake bottom in the west basin has substantially decreased, providing more suitable habitat for aquatic organisms in the summer and helping alleviate conditions that promote phosphorus release from lake-bottom sediment. Although data is much more limited, water quality in most of the Lake's tributary streams' also appears to be stable or improving. These water quality improvements are a testament to the positive impact of active management conducted on the Lake and in the watershed.



Source: Wisconsin Department of Natural Resources and SEWRPC

Greater water clarity as well as reduced algal abundance and total phosphorus suggest improving water quality.

45 years of consistent water quality monitoring provides invaluable insight to the Lake's health. Continued monitoring is essential for tracking progress and identifying threats.

While great progress has been made toward improving water quality, conditions change and new threats often become evident. For example, chloride, a component of common rock salt, is injurious to freshwater organisms at relatively low concentrations. Chloride concentrations have been consistently increasing in Pewaukee Lake for decades. The 146 mg/l chloride concentration measured in 2018 is almost 30 times greater than the 5 mg/l observed in the early 1900s. This concentration is fast approaching regulatory limits and may already be high enough to diminish the success of certain sensitive desirable native species. In a more directly tangible vein, Lake water may begin to taste salty by the year 2070 unless action is taken to reduce chloride loads. Such water quality insights are only possible thanks to the 45 years of consistent monitoring, much of which conducted by volunteers.

Aquatic Plant Management

Pewaukee Lake's aquatic plants have been a management priority for decades. Excessive nuisance aquatic plants, especially exotic invasive species, can compromise the ability of the Lake to provide quality recreational opportunities and impede navigation. Well-planned and dedicated aquatic plant management completed in the recent past has protected native aquatic plant species, controlled nuisance species, and removed substantial amounts of phosphorus from the Lake. Muskgrass (*Chara* spp.), one of the most dominant native species, stabilizes lake bottom sediment, removes phosphorus from the water column, and should be protected wherever and whenever practical. Aquatic plant management efforts embrace this goal. Recent surveys reveal that muskgrass has become more widespread while the invasive Eurasian watermilfoil (*Myriophyllum spicatum*) is less widespread than it has been in the past. Since 1988, aquatic plant harvesting by the Lake Pewaukee Sanitary District (LPSD) and the Village of Pewaukee has removed up to 52,348 pounds of total phosphorus from the Lake, an amount equal to between 10 to 34 percent of the nonpoint source phosphorus loading to the Lake during this period. The Plan recommends actions to further refine aquatic plant management efficiency and effectiveness; the Village of Pewaukee and LPSD aquatic plant management coordination can be a substantial contributor to this goal.

Aquatic plant harvesting has removed up to 52,348 pounds of phosphorus from Pewaukee Lake since 1988.

Promoting Native Aquatic Plants:

The Lake's aquatic plant diversity is greater than measured anytime in the previous 25 years.

Water Level Regulation and Outlet Dam Operation

Pewaukee Lake's water level has been artificially elevated by a dam for nearly 180 years. The dam considerably increased water depth, changing the former marshy eastern basin into a shallow lake and submerging marshy areas around the Lake's shoreline. The former weir-type dams had very limited capacity to vary water discharge rates. The dam was rebuilt in 2010, incorporating a bottom draw gate that now allows the dam operator a high degree of control over dam discharge rates and Lake water levels. This modification enhances capacity to diminish the duration of slow-no-wake periods, retain excessive runoff, augment downstream dry weather flow, and influence a number of other factors of interest to the community and/or that affect waterbody ecology. It is important to note that the dam is not designated as a flood control structure.

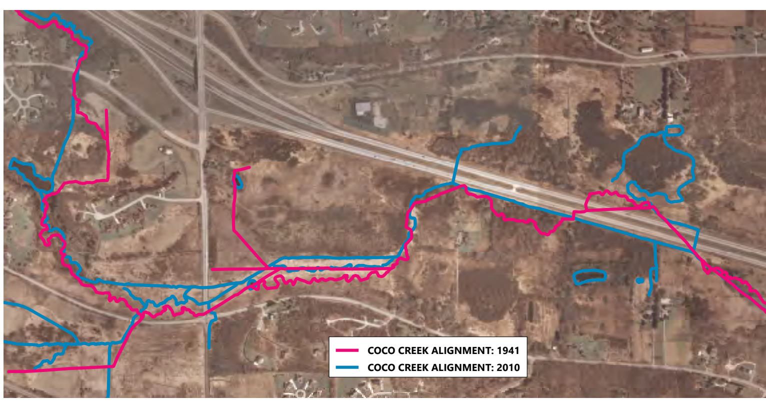
The Lake outlet dam was modified in 2010.

Balancing Lake elevation with outlet discharge rates can be a matter of controversy and concern, especially to those who have property and/or infrastructure near the Lake or the Pewaukee River downstream of the Lake. To help the dam operator select a discharge rate that considers multiple factors requires input from and compromise amongst many stakeholders. The current Plan provides data and suggests approaches to help balance the needs and desires of Lake users/riparians, downstream property owners, the ecological health of the Lake and River, and dam design/operation realities. For example, the plan stresses the importance of maintaining operable gates and gate discharge capacity during all seasons and suggests measures that promote reliable all season, all condition gate operability.

Pewaukee Lake's shoreline has many opportunities (left image) to expand vegetated buffers (right image). Buffers help reduce phosphorus and sediment loading as well as protect the shoreline from erosion. Native aquatic vegetation can reduce erosive wave force and enhance fish and wildlife habitat.

Shoreline Stability, Riparian Buffers, and Floodplain Protection

Protecting and enhancing wetland parcels as well as implementing best management practices (BMPs) within the watershed has helped contribute to reduced waterbody pollutant loads and improved water quality. Expanded/improved vegetative shoreline protection and riparian buffers can further improve water quality, protect shorelines from wave erosion, and enhance fish and wildlife habitat throughout the watershed. Management attention should prioritize actions that reconnect floodplains which, in turn, enhances floodwater detention, helps mitigate downstream flooding, and generally decreases wet-weather runoff nutrient and sediment loads. A comprehensive inventory of priority areas and parcels for riparian and shoreline buffers as well as storm drainage systems is provided in the Plan.



Southeastern Wisconsin streams were heavily channelized. For example, long reaches of Coco Creek were ditched between 1941 (pink line) and 2010 (blue line). Channelization contributes to loss of fish and wildlife habitat, reduced ability to store and filter floodwaters, and increased capacity to carry eroded sediment to the Lake.

Restoring Natural Hydrology in a Changed Landscape

Prior to European settlement, lands draining to Pewaukee Lake were covered with oak savanna, oak forest, and wetlands. Agricultural and residential land uses now dominate the watershed. Urban development is expected to comprise 57 percent of the watershed by 2050. Land conversion has changed the way precipitation falling upon the watershed behaves. In general, less water soaks into the ground, less is detained on the surface, more water exits stream basins as surface-water runoff, and runoff leaves the landscape more quickly. These factors amplify both the minimum and maximum streamflow. Some of the factors changing the watershed's hydrology include deforestation, stream channelization, dam construction, wetland draining/filling, and an ever increasing proportion of the land surface covered by impervious surfaces (e.g., buildings, roads, parking lots).

Examples of Key Management Strategies to Protect and Enhance Pewaukee Lake and its Watershed

- **Enhance stakeholder coordination and cooperation to foster even greater improvements in operational efficiency, funding availability, water quality, recreational potential, and ecological health**
- **Adopt dam operation guidance that benefits waterbody users, waterbody ecology, and property owners located both upstream and downstream of the outlet dam. Resolve dam operational problems (e.g., ensure reliable all-season, all-condition operation)**
- **Actively promote and financially support buffers, rain gardens, and other best management practices (BMPs) along shorelines and riparian areas as well as modern agricultural practices (e.g., cover crops) in upland areas**
- **Preserve groundwater infiltration areas to regulate runoff, maintain water supply, and protect critical habitat in Lake tributaries**

Overall, hydrologic changes reduce the landscape's ability to capture, filter, detain, and retain precipitation, particularly of excessive rainfall events. Consequently, the landscape is prone to more frequent and severe floods and less capable of maintaining adequate water supplies that support water quality/ecology, potable water demands, and recreational needs. The recommendations in this Plan suggests actions that can help communities protect drinking water supply, water quality, ecological integrity, and recreational use.

Funding and Partnerships

Developing, expanding, maintaining and enhancing partnerships are essential elements to efficiently achieving lake and watershed management goals. The Pewaukee Lake area is home to a wide variety of organizations that are interested and oftentimes involved in the betterment of the Lake and its watershed. In addition to several governmental agencies with missions that include promoting and protecting the Lake, examples of organizations that focus on the Lake and its watershed include the Pewaukee Women's Club, the Pewaukee River Partnership, the Pewaukee Chapter of Walleyes for Tomorrow, the Pewaukee Kiwanis Club, the Pewaukee School District, the Boy Scouts of America, and the Badger's Fisherman League. An example of interagency cooperation includes cooperation between the LPSD, local land trusts, and private landowners to preserve land through conservation easements, land purchases, and land donations. Restoration, education, and outreach efforts will continue to be instrumental in promoting a culture of waterbody protection.

Established partnerships and actionable plans enhance funding opportunities to implement Plan elements. For example, interested municipalities and certain other organizations can sponsor Healthy Lakes Program grants, allowing shoreline owners to apply for funding to implement recommended BMPs such as fish sticks, rain gardens, native vegetation buffers, diversions, and rock infiltration areas. Implementing only the Healthy Lake BMPs on at least 75 percent of the shoreline properties would tangibly reduce Lake pollutant loading all while improving fish and wildlife habitat. A variety of federal and state funding sources promote conservation practices and protect water quality, including programs by the Natural Resource Conservation Service (NRCS) and the Wisconsin Department of Agriculture, Trade and Consumer Protection.

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The Lake Pewaukee Sanitary District and the Pewaukee Chapter of Walleyes for Tomorrow have lead several habitat restoration and education efforts. Examples include invasive species removal from streambanks (left) and installing fish sticks in the Lake (right).

Conclusion: Focused Management Improves Conditions for All

Pewaukee Lake and its watershed have significant economic, aesthetic, quality-of-life, and ecological value. Dedicated management continues to improve water quality and enhance the aquatic plant community within the Lake. All opportunities are enhanced through active partnering with others interested in the Lake, its watershed, and the community that has grown up in the midst of these valuable natural resource assets. Widespread Plan endorsement and/or Plan adoption can be used to demonstrate the broader community's united resolve to achieve tangible goals, a situation that commonly results in greater execution efficiency and which can help foster receipt of grant funding.

The measures presented in this Plan primarily focus on those that can be implemented through collaboration between local organizations and individuals, such as the LPSD; Lake residents; the Pewaukee chapter of Walleyes for Tomorrow; Waukesha County; the WDNR; the Cities of Delafield, Pewaukee, and Waukesha; the Towns of Delafield, Lisbon, and Merton; and the Villages of Hartland, Pewaukee, and Sussex. The plan must be adaptable to addresses challenges that will arise during implementation. Watershed implementation is primarily a volunteer effort, but this effort needs support from targeted technical and financial assistance. All communities within the watershed must commit and collaborate to reach compliance with existing regulations, which in turn help improve the Lake's condition.

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INTRODUCTION 1

Credit: SEWRPC Staff

Pewaukee Lake lies within U.S. Public Land Survey Sections 7, 8, 17, and 18 of Township 7 North, Range 19 East and Sections 12, 13, 14, 15, 22, 23, and 24 of Township 7 North, Range 18 East in north-central Waukesha County, Wisconsin. The eastern end of the Lake is located partially in the Village of Pewaukee and partially in the City of Pewaukee. The Lake's western basin lies entirely in the Town of Delafield. Pewaukee Lake, together with its associated watershed and wetlands, is an important high-quality natural resource and is a substantial asset to the local and regional community. For this reason, preserving and enhancing the Lake's health is an issue of considerable interest to resource managers, Lake residents, Lake users, and others who benefit from the Lake's recreational, ecological, and aesthetic value.

1.1 HISTORICAL CONTEXT

Pewaukee Lake offers a remarkable variety of water based recreational opportunities and has been the focus of the surrounding lake-oriented communities for well over a century. Over the years, the Lake has experienced various management challenges including excessive aquatic plant growth, recreational use conflicts, water quality related use limitations, and public concerns over perceived aesthetic degradation. The Lake is located in the Milwaukee metropolitan area, a situation contributing to high demand for more urban development (particularly residential development) in the Lake's watershed. Past, ongoing, and probable future development stresses the natural environment and places increasing demands on the Lake to provide for a wide variety of oftentimes intensive water-based recreational opportunities.

Residents of the Pewaukee Lake community have historically made decisions to protect and improve the Lake's water quality and ecology. This included forming the Lake Pewaukee Sanitary District (LPSD), and using the LPSD as a mechanism to collect, coordinate, and disseminate information on the Lake and its watershed. Pewaukee Lake residents have become increasingly concerned about present and future impacts of pressures on the Lake and its ecosystem. These concerns relate to observations and perceptions such as decreased water clarity, increased aquatic plant growth, Lake water deterioration from nonpoint source pollution, and user-related aesthetic degradation and use conflicts. A brief timeline of the history of Pewaukee Lake is included in Table 1.1.

Table 1.1
Timeline of Pewaukee Lake Management Events

Date	Event	Source[a]
1838	First dam constructed to provide power for a mill; Pewaukee Lake created	CAPR 58-2 SEWRPC report
1848	Construction begins on plank road	LP Historical Charlie Shong (former LPSD Manager)
	Village of Pewaukee incorporated	CAPR 58-2 SEWRPC report
1855	Railroad completed in Pewaukee Lake area; led to increase in population of area	LP Historical Charlie Shong (former LPSD Manager)
1873	First large passenger boat; Lady of the Lake sidewheeler	LP Historical Charlie Shong (former LPSD Manager)
1878	First commercial icehouse built on north shore of Pewaukee Lake (Best Brewery, Milwaukee)	LP Historical Charlie Shong (former LPSD Manager)
1886	Carp delivered to Pewaukee Lake for stocking purposes	WI Commissioner of Fisheries Biennial Report
1888	Christopher Starke uses steam dredge to create Peninsula (1st dredging on lake)	LPSD files
	Aquatic plants cut to allow operation of mail boat	LPSD files
1890	Most of west end shoreland developed for residential (agriculture still dominant in watershed)	LP Historical Charlie Shong (former LPSD Manager)
	Meadowbrook stream ditched to aid building electric railway	LP Historical Charlie Shong (former LPSD Manager)
1894	Waukesha Beach amusement park opens/Milwaukee Electrical provides rail service (until 1948)	LP Historical Charlie Shong (former LPSD Manager)
1898	Steam-powered weed cutter used by ice companies	LP Historical Charlie Shong (former LPSD Manager)
1899	White bass and walleye planted in Pewaukee Lake	WI Commissioner of Fisheries Biennial Report
1900	Beginning of significant urban development in Pewaukee Lake watershed	CAPR 58-2 SEWRPC report
	Wisconsin Geological and Natural History Survey studies Lake's genesis and morphology	CAPR 58-2 SEWRPC report
1901	Rainbow trout planted in Pewaukee Lake	WI Commissioner of Fisheries Biennial Report
1906	Armour ice house burns; end of large scale commercial ice industry	LP Historical Charlie Shong (former LPSD Manager)
1920	WDNR 1992 core samples indicate increase in sedimentation from 1920s	LP Historical Charlie Shong (former LPSD Manager)
	Almost all of shoreline developed by this date; decline in water quality	LP Historical Charlie Shong (former LPSD Manager)
1937	A single haul removes 10,000 pounds of gar from Pewaukee Lake	CAPR 58-2 SEWRPC report
1937-1949	WDNR annual fish stocking	CAPR 58-2 SEWRPC report
1930	Public sanitary service provided to Lake area	CAPR 58-2 SEWRPC report
1938	Lake residents begin to organize in response to water quality and algae issues	LP Historical Charlie Shong (former LPSD Manager)
1944	Formation of Lake Pewaukee Sanitary District	CAPR 58-2 SEWRPC report
	LPSD begins cutting of aquatic plants on Lake	MR 56 SEWRPC report
	Wisconsin Conservation Department starts intermittently collecting water quality data	CAPR 58-2 SEWRPC report
1945	Chemical herbicide (sodium arsenite) treatments begin	LPSD files
	Septic systems inspections begin	LP Historical Charlie Shong (former LPSD Manager)
1946	State requires Pewaukee to remove cut weeds from Lake	LPSD files
1947	LPSD begins harvesting aquatic plants	LPSD files
1950-2000	Spreadsheet data DNR fish stocking records	SEWRPC file FISH
1950-1967	Aquatic plant chemical controls used	WDNR FX-2 report
1951-1952	WDNR annual fish stocking	CAPR 58-2 SEWRPC report
1962	LPSD begins use of 2,4-D to control aquatic plants	LPSD files
1963	LPSD discontinues use of sodium arsenite	LPSD files
	Water Quality analysis by WDNR	WDNR FX-2 report
1965	Boat survey	WDNR FX-2 report

Table continued on next page.

Table 1.1 (Continued)

Date	Event	Source[a]
1966	Eurasian Watermilfoil (EWM) first observed in the Lake	LPSD files
	US Soil Conservation Service conducts soil survey of PL area	SEWRPC PR 8 report
	Water Quality analysis by WDNR	WDNR FX-2 report
1967	Lake Hydrography and Morphology compiled	WDNR FX-2 report
	Aquatic species abundance list	SEWRPC file AQ PL
	Recommendations by WDNR	WDNR FX-2 report
1967-1981	WDNR annual musky stocking	MR 56 SEWRPC report
1975	Curly-leaf pondweed first identified in the Lake	Online WDNR
1976	Sanitary sewers begin to be installed around lake perimeter homes	LPSD files
	Plant survey	CAPR 58-2 SEWRPC report
1976-1977	Phytoplankton survey	CAPR 58-2 SEWRPC report
1978	Wisconsin Legislature mandates Wisconsin Wetlands Inventory	CAPR 58-2 SEWRPC report
1983	Village decides not to modify dam	SEWRPC file NEWS
1984	SEWRPC publishes CAPR 58 1st Ed. WQMP (first lake/watershed plan)	SEWRPC file box
1985-2004	Native aquatic plant populations increase; milfoil density decreases	LPSD files
1985	Chemical herbicide treatments discontinued	LPSD files
1986	WDNR Starts Long Term Trend Water Quality Monitoring Program	CAPR 58-2 SEWRPC report
	Citizen Volunteer Enrolled in Self-Help Monitoring Program	CAPR 58-2 SEWRPC report
1988	LPSD Starts Keeping Plant Harvesting Data	CAPR 58-2 SEWRPC report
1990	LPSD begins buying wetlands in watershed	SEWRPC file Rec/Cons
1991	WDNR survey finds musky, largemouth bass, northern pike, panfsh common	FM-800-91 WDNR publication
	LPSD receives $10K grant from WDNR for WQ study (inflow study)	SEWRPC file NEWS
1992	LPSD plant survey finds EWM widespread and abundant/dominant	MR 56 SEWRPC report
	LPSD develops Aquatic Plant Management Plan for the Lake	SEWRPC file Reports
	Core samples taken of lake sediment (WDNR)	LPSD files / WDNR files
1994	WDNR prepares nonpoint source pollution control report for Upper Fox River basin	WDNR PUBL-WR-366-94
	WDNR 1994 Sensitive Area Assessment	SEWRPC file Reports
1995	SEWRPC boat survey	CAPR 58-2 SEWRPC report
	SEWRPC conducts lake use surveys	MR 56 SEWRPC report
1999	City of Pewaukee incorporated	CAPR 58-2 SEWRPC report
2000	Summer fish kill due to bacteria (WDNR)- newspaper report	SEWRPC file FISH
2002	City of Pewaukee attempts to do their own aquatic plant control	LP Historical Charlie Shong (former LPSD Manager)
2003	Blue-green algae issues	SEWRPC file NEWS
	Phosphorus ban proposed	SEWRPC file NEWS
2004	Zebra mussels first identified in the Lake	Online WDNR
	WDNR decision to allow 2,4-D use on the Lake	LPSD files
2010	Chinese mystery snail first identified in the Lake	Online WDNR
2011	E. coli analyses from UW-Milwaukee School of Freshwater Sciences	LPSD file
2014	2014 LPSD Harvesting Report	LPSD file
	E. coli analyses from UW-Milwaukee School of Freshwater Sciences	LPSD file
2016	Wisconsin Lutheran College aquatic plant survey	CAPR-58
2019	Starry stonewort first identified in the Lake	Online WDNR

[a] *The category of each source is designated with the following colors:*

History · Water Quality · Lake Physical
Fish · Pollution Control · Recommendations
Aquatic Plants · Recreation · Reports
Land Use · Invasives · Conservation
Geology · Soil

Source: Lake Pewaukee Sanitary District, Wisconsin Department of Natural Resources, and SEWRPC

The public's interest in sustainable land use, quality of life, and water quality has led to numerous reports that either focus on Pewaukee Lake and its watershed, or contain information of interest to Lake management. The following list provides a few examples of the kinds of documents that provide information useful to managing Pewaukee Lake.

Federal Reports

- 1836 – Federal land survey
- 1892 and 1909 – U. S. Geological Survey (USGS) 15-minute topographic maps covering the Lake and its watershed
- 1966 – U.S. Soil Conservation Service soil survey that included the Pewaukee Lake area
- 1975 – U.S. Environmental Protection Agency (USEPA) produced a National Eutrophication Study that included Pewaukee Lake
- 2012 – USGS report describing a groundwater/surface water flow model for the upper Fox River basin, including Pewaukee Lake and its tributaries
- 2014 – Federal Emergency Management Agency (FEMA) updates flood insurance rate maps for portions of the watershed. These maps illustrate the extent of flooding under a range of flood severity.

State Reports

- 1886 – Wisconsin Commissioners of Fisheries biennial report on fish culture and fish stocking, including stocking in Pewaukee Lake
- 1963 – Wisconsin Conservation Department Surface Water Resources of Waukesha County
- 1967 – John Batha, UW-Madison, limnological study of Pewaukee Lake
- 1970 – Wisconsin Department of Natural Resources (WDNR) Lake Use Report No. FX-2 on Pewaukee Lake
- 1975 – Wisconsin Geological and Natural History Survey (WGNHS) Ground-Water Resources of Waukesha County, Wisconsin
- 1994 – WDNR Sensitive Areas Assessment Report for Pewaukee Lake
- 2001 – WGNHS Pleistocene Geology of Waukesha County, Wisconsin
- 2004 – WGNHS Preliminary Bedrock Geologic Map of Waukesha County, Wisconsin
- 2013 – WDNR comprehensive fishery survey report of the Lake
- 2019 – WDNR preliminary report about 2018 fishery survey of the Lake

Local Reports

- SEWRPC
    - 1969 – Planning Report No. 12, *A Comprehensive Plan for the Fox River Watershed*
    - 1977 – Planning Report No. 27, *A Park and Open Space Plan for Southeastern Wisconsin*
    - 1979 – Planning Report No. 30, *A Regional Water Quality Management Plan*

    - 1980 – Community Assistance Planning Report (CAPR) No. 42, *A Park and Open Space Plan for the Town and Village of Pewaukee*
    - 1984 – CAPR No. 58, *A Water Quality Management Plan for Pewaukee Lake*
    - 1989 – CAPR No. 137, *A Park and Open Space Plan for Waukesha County*
    - 1992 – Planning Report No. 40, *A Regional Land Use Plan*
    - 1996 – Memorandum Report No. 56, *A Lakefront Recreational Use and Waterway Protection Plan*
    - 2003 – CAPR No. 58 (2nd edition), *A Water Quality Management Plan for Pewaukee Lake*
- Wisconsin Lutheran College
    - 2000 – Biological Evaluation report
    - 2005 – *Pewaukee Lake Phosphorus Monitoring 2003-2004*
    - 2006 – Minnow and Small Fish Assemblages of Pewaukee Lake
    - Reports on aquatic plant surveys conducted by Wisconsin Lutheran College for years 2002, 2004, 2006, 2007, 2008, 2009, 2010, 2011, 2013, 2014, and 2016
- Other Local Organizations
    - 1971 – Aqua Tech report on Pewaukee Lake water quality, aquatic plants, and related topics
    - 1992 – LPSD developed *An Aquatic Plant Management Plan for Pewaukee Lake*
    - 1992 – Pewaukee Lake Citizens Advisory Committee report on aquatic plant management
    - 1997 – LPSD report on purchases made as part of their Wetland Conservancy Fund
    - 1998 – Milwaukee Zoological Society report on area bird species
    - 2007 – Eco-Resource Consulting report for LPSD on aquatic plants of Pewaukee Lake

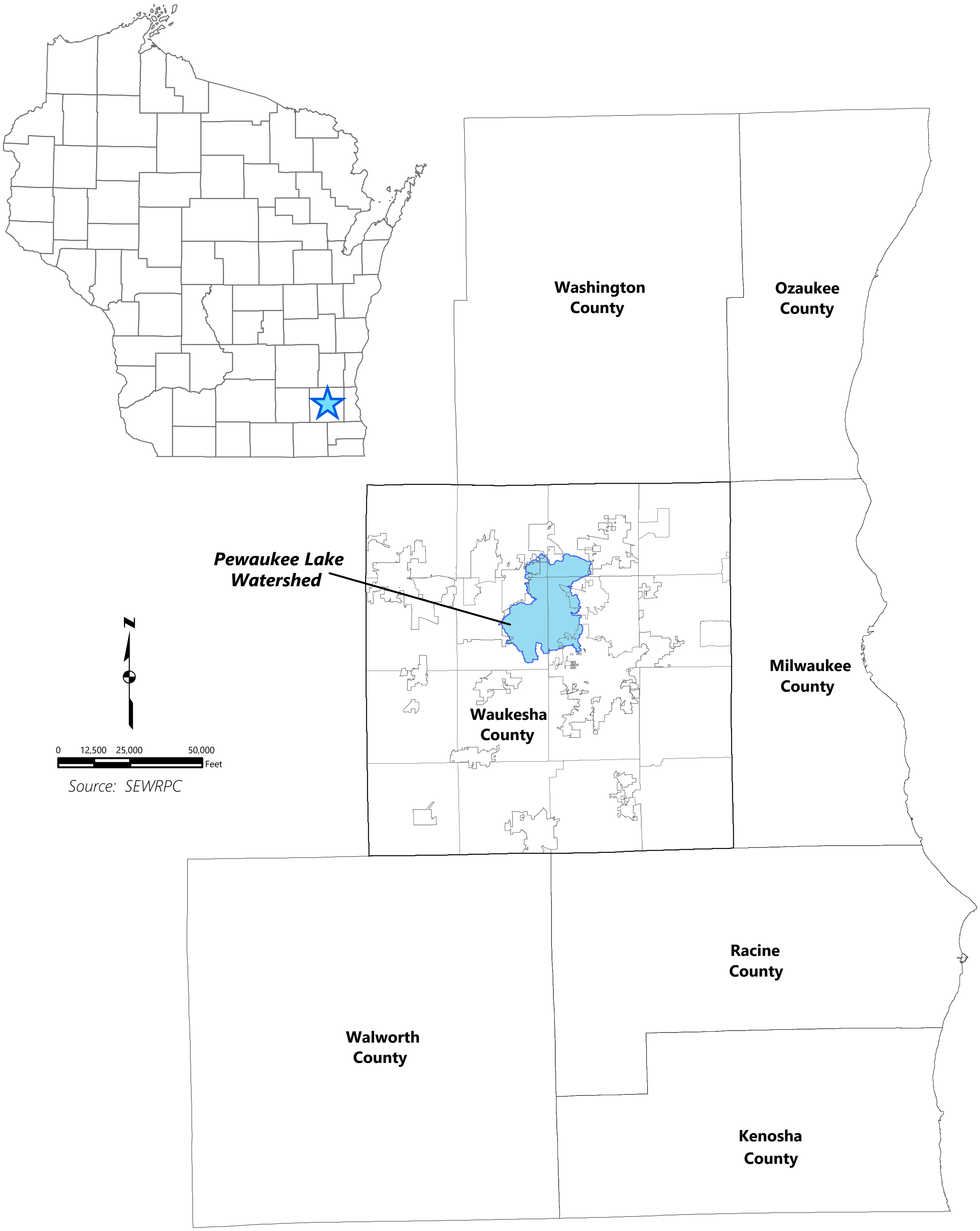
1.2 PLAN PURPOSE, ORGANIZATION, AND FOCUS

Located in the north-central portion of Waukesha County (see Map 1.1), Pewaukee Lake provides a unique warmwater system that remains healthy despite a long history of intensive use as well as intensive and extensive past, ongoing, and projected future urbanization within its watershed. The Lake's continued vitality is a testament to the benefits of proactive and well-planned Lake management.

Pewaukee Lake is a premier water resource asset in the Milwaukee Metropolitan area. Development of the plan program described in this report was funded in part by a WDNR grant awarded to the LPSD through the *Wisconsin Administrative Code* Chapter NR 190, "Lake Management Planning Grants" program. Examples of major grant program deliverables include the following items.

- Compile watershed and water quality information. Examine trends and implications. The morphometry of the Lake and the hydrology of the Lake and its watershed must also be closely examined and related to observed or potential future conditions.
- Estimate nutrient, sediment, and pollutant loads to the Lake. This requires detailed study of land uses within the area where surface water runoff drains to the Lake.

Map 1.1
Location of the Pewaukee Lake Watershed Study Area



Source: SEWRPC

- Identify sensitive areas and critical species areas.
- Evaluate Lake tributaries, with particular attention paid to streambank erosion.
- Examine the aquatic plant community, and identify appropriate management actions that further the goals of Lake users and Lake health.
- Assist the LPSD with a survey of Lake resident concerns. This will help identify topics of most interest and/or that are poorly understood by Lake residents.
- Develop recommendations that help the LPSD monitor the Lake's overall condition, help protect water quality, foster public participation and understanding, preserve or enhance recreational use, and safeguard the ecology of the Lake.
- Prepare a comprehensive written report and present the findings at a public meeting. The inventory and aquatic plant management plan elements presented in this report conform to requirements and standards set forth in relevant *Wisconsin Administrative Codes*.[1]

This protection plan is the third in a series of lake management plans developed for Pewaukee Lake by the Southeastern Wisconsin Regional Planning Commission (SEWRPC). The first plan was published in 1984 with an amended version published in 2003.[2,3] This plan represents the continuing commitment of government agencies, non-governmental organizations, municipalities, and citizens to diligent lake planning and natural resource protection.

This plan is divided into three chapters. Chapter One briefly outlines the plan's purpose, summarizes basic Lake characteristics and assets, and describes general goals and objectives. Chapter Two presents and interprets information needed to understand Lake conditions and the factors that could imperil Lake health. Finally, Chapter Three discusses approaches to protect and enhance the Lake and its watershed. Chapter Three recommendations aim to enhance and preserve Pewaukee Lake's native plant community, ecology, and water quality, while allowing Lake users and watershed residents opportunities for safe and enjoyable recreation within the Lake and the Lake's watershed.

The health of a lake or stream is usually a direct reflection of land use and management within the lake's watershed (the land surrounding a lake that slopes toward the lake or a tributary stream, and that contributes runoff to the lake).[4] In the face of human-induced change, active intervention is often necessary to stabilize, maintain, or enhance resource conditions. This protection plan focuses on what can be done to *protect* critical resources from human-induced deterioration and *prevent* future water pollution or resource degradation. This plan complements other existing programs and ongoing management actions in the Pewaukee Lake watershed and represents the continuing commitments of government agencies, municipalities, and citizens to diligent land use planning and natural resource protection. This plan recommends appropriate and feasible watershed management measures to help enhance and preserve the water quality, aesthetics, and ecological integrity of Pewaukee Lake and its tributaries and provide the public with opportunities for safe and enjoyable recreation within Pewaukee Lake and its watershed. This document's primary purpose is to review and analyze available data and provide an updated management framework with specific recommendations. Such information enables organizations to take appropriate measures to protect the health and use value of Pewaukee Lake.

[1] *This plan has been prepared pursuant to the standards and requirements set forth in the following chapters of the* Wisconsin Administrative Code*: Chapter NR 1, "Public Access Policy for Waterways;" Chapter NR 40, "Invasive Species Identification, Classification and Control;" Chapter NR 103, "Water Quality Standards for Wetlands;" Chapter NR 107, "Aquatic Plant Management;" and Chapter NR 109, "Aquatic Plants Introduction, Manual Removal and Mechanical Control Regulations."*

[2] *SEWRPC Community Assistance Planning Report No. 58,* A Water Quality Management Plan for Pewaukee Lake, Waukesha County, Wisconsin*, March 1984.*

[3] *SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* A Lake Management Plan for Pewaukee Lake, Waukesha County, Wisconsin*, May 2003.*

[4] *In Pewaukee Lake's case, runoff from roughly 25 square miles drains to the Lake. The watershed is densely populated and is intensively used for various residential and commercial purposes.*

This protection plan provides practical guidance for maintaining or enhancing water quality within the Pewaukee Lake watershed and for managing lands that drain directly and indirectly to the Lake and its tributary streams. The plan is developed to assist units of government, nongovernmental organizations, businesses, and citizens in developing strategies benefiting the natural assets of Pewaukee Lake and protecting sensitive and other high-value habitats within its watershed. By applying the strategies outlined in this plan, the natural environment will be enriched and preserved. In addition, carefully planned urban development can preserve ecological benefits that directly benefit human habitation. For example, planning can create and maintain desirable aesthetics, groundwater recharge areas, and wildlife corridors, all of which benefit Pewaukee Lake's ecology, watershed residents and businesses, and visitors.

1.3 GENERAL CHARACTERISTICS OF PEWAUKEE LAKE AND ITS WATERSHED

Although Pewaukee Lake is classified by the WDNR as a drainage lake, the Lake has a relatively small watershed given its large open-water surface area. Several small tributaries enter the Lake, all of which are classified as headwater streams. The Lake's outlet is located at the extreme eastern end of the Lake and is dammed, raising the Lake's water elevation and substantially increasing the extent of open water. The Lake's outlet flows into the Pewaukee River. The Pewaukee River joins the Fox River just north of the City of Waukesha. The Fox River flows in a southerly direction through Waukesha, Racine, and Kenosha Counties; crosses the Wisconsin-Illinois state line; and then flows through the northern Illinois Chain-of-Lakes, discharging to the Illinois River near Ottawa, Illinois. From there, the Illinois River flows to the southwest, entering the Mississippi River north of the City of Saint Louis, Missouri. Water from Pewaukee Lake and its watershed ultimately discharges to the Gulf of Mexico.

Even though Pewaukee Lake has a large areal extent and is one of Waukesha County's largest lakes by volume, much of the Lake is relatively shallow. The Lake and its watershed cover nearly 25 square miles. Chapter Two provides more detail regarding the morphometry, morphology, and hydrology of Pewaukee Lake and its tributary streams and relates these characteristics to water quality, aquatic plants, fisheries, recreation, and overall Lake management.

Pewaukee Lake and its watershed provide numerous, widely varying, recreational assets. Prominent public access points and recreational features include Lakefront Park in the Village of Pewaukee at the Lake's extreme east end and the Pewaukee Boat Launch (owned by the Waukesha County Department of Parks and Land Use) at the extreme west end of the Lake. Large swaths of wetland have been protected in the watershed and can be accessed by the public. For example, the LPSD owns several tracts just north of the Lake and in the Coco Creek subwatershed. Other parcels are also open for public use (e.g., shoreline bait shops and boat liveries). Finally, a large numbers of homes surround the Lake, residences that typically focus on the Lake and its recreational opportunities and the aesthetic appeal it provides.

The Lake successfully supports a spectrum of recreational interests as evidenced by boat counts and observations completed by SEWRPC staff during summer 2016 (see Chapter 2 for more details). Lake users engage in full-body contact uses (such as swimming and water skiing) as well as pleasure cruising, high-speed boating, fishing, and other activities. Additionally, as is further described in Chapter 2, the Lake's watershed contains critical species habitat areas and a variety of wetlands, uplands, and woodlands. The watershed likely supports a large number of resident animal species, including several species of reptiles and amphibians; small and large mammals, insects, and invertebrates; and a number of transient bird species that may be found in the area during seasonal migrations.[5]

[5] *These estimates are based on bird, amphibian, and reptile databases for the Region.*

1.4 LAKE PROTECTION GOALS

General lake protection goals that aim to maintain and enhance the Lake's assets were developed as a part of this planning process. The goals listed below were developed in consultation with the WDNR, LPSD, the City of Pewaukee, the Village of Pewaukee, the Town of Delafield, and the public. The goals also directly address goals established in the Waukesha County Comprehensive Development Plan and the Waukesha County Land and Water Resources Management Plan.[6,7]

- Examine the Lake's aquatic plant community
  - Document the status of the Lake's aquatic plant community, with particular emphasis on the occurrence and distribution of nonnative species. Use this information to better understand the changes and dynamics of the Lake's aquatic plant community.
  - Evaluate the impact of aquatic plants on Lake use and habitat value.
  - Identify measures and methods useful to reduce the extent and abundance of nonnative aquatic plant species.
  - Reduce the risk of nonnative aquatic species spreading to other waterbodies.
  - Provide the bulk of the information needed to successfully apply for an aquatic plant management permit.
- Update descriptions of watershed conditions. This includes identifying and quantifying potential point and nonpoint sources of pollution, nutrient and sediment inputs, and nutrient and contaminant balances. Also, provide conceptual examples of projects that could be undertaken to mitigate the impact of identified sediment and pollution sources.
- Identify the extent of existing and potential future water quality problems likely to be experienced in the Lake. This includes examining the Lake's water quality using physicochemical monitoring data collected as part of ongoing water quality monitoring programs. In addition, estimate future water quality changes and provide advice regarding appropriate future monitoring activity.
- Assess the degree and intensity of recreational water use in and around Pewaukee Lake.
- Formulate appropriate management objectives, action plans, public information and education strategies, ordinances, and other possible responses to the identified threats and problems.
- Provide advice and concepts describing management, enhancement, and restoration measures that address identified issues of concern and could improve current and future Lake health and ecological resilience/resistance. This likely will include active measures as well as outreach and education.

Conscientiously implementing the actions recommended herein should provide an important step toward achieving the LPSD's desired Lake use/protection objectives over time.

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[6] *Waukesha County Department of Parks and Land Use,* A Comprehensive Development Plan for Waukesha County, Waukesha, Wisconsin*, February 24, 2009, www.waukeshacounty.gov/defaultwc.aspx?id=39496.*

[7] *Waukesha County Department of Parks and Land Use,* Waukesha County Land and Water Resource Management Plan*, 2012.*

Credit: SEWRPC Staff

RESOURCE INVENTORY 2

2.1 INTRODUCTION

Even though Pewaukee Lake (the Lake) is a treasured community and ecological resource, human activity in and around the Lake and within its watershed inadvertently contributes to management challenges and could lead to future problems and concerns. To better define and understand these issues, and to help maintain water body characteristics supporting quality recreational use and the Lake's great latent ecological value, the Lake Pewaukee Sanitary District (LPSD) and the Southeastern Wisconsin Regional Planning Commission (Commission) executed an agreement to identify community concerns, evaluate Lake and watershed resource conditions, conduct informational meetings, and develop a management plan addressing these concerns.

As a part of the planning process, issues of most concern were identified through various means, including an initial informational workshop with members of the Lake community, meetings of the LPSD, investigation by Commission staff, and polling of Lake user sentiments and concerns.[8,9] Table 2.1 lists priority issues identified by this process.

These issues are the basis for the topics addressed in this management plan. This chapter provides information and interpretations that will 1) help answer questions posed by the LPSD and concerned community members, and 2) help with development of concepts to safeguard long-term Lake health and human-based values.

Table 2.1
Issues and Concerns

Issues and Concerns	
1	Water Quantity
2	Water Quality
3	Pollutant and Sediment Sources and Loads
4	Aquatic Plants
5	Floating Algae and Cyanobacteria
6	Shoreline Condition and Habitat Value
7	Recreational Use and Facilities
8	Fish and Wildlife
9	Plan Implementation

Source: SEWRPC

[8] *Pewaukee Lake Improvement Association,* Perceptions and Priorities for Pewaukee Lake – 2005 Survey Results*, undated questionnaire distributed April 2005.*

[9] *SEWRPC,* Pewaukee Lake Watershed Questionnaire*, distributed August 2014.*

2.2 LAKE AND WATERSHED PHYSIOGRAPHY

The condition and overall health of a waterbody is directly related to the natural and human-induced characteristics and natural features within the area draining to the waterbody. This assemblage of unique natural features and processes can be collectively referred to as physiography. This section describes the Lake and watershed physiography including the shape and arrangement of landscape features, the composition and arrangement of soil and rock, tributary streams and Lake basin shapes, how water moves through the area, and how humans influence the landscape.

The landscape characteristics and land use practices around a lake control a lake's water quality and overall character. Therefore, it is important to characterize the area draining to a lake—its watershed—to understand natural resource elements, human manipulation, potential pollution sources and risks to the lake's water quality. Several items need to be examined in order to complete this characterization, including:

1. **The location and extent of a lake's watershed**—Before characterizing watershed features, its extent must be quantified. The delineation process involves carefully examining land surface elevation data to delineate the area from which water draining from the land surface eventually reaches a waterbody. This analysis provides the basis for determining whether potential pollutant sources threaten a waterbody. For example, if a pollution source is near a waterbody but outside the watershed, contaminated surface runoff from that source would not reach the waterbody, and, therefore, may not be an issue of concern in terms of water quality.

2. **Natural resource factors**—The arrangement and composition of soil and rock, climatic variables, vegetation, and other factors dictate much of a lake's overall character. Therefore, it is important to understand the topography, geology, hydrology, and climate prevailing in the lake's watershed.

3. **Existing land use types and distribution**—The extent and location of various land uses within the watershed can help predict the type and amount of pollution reaching a waterbody. Land use conditions can be represented with models to estimate total pollutant loads entering a waterbody, evaluate the relative contribution of certain land uses or areas, and predict consequences of land use change. Once loads are estimated, management efforts can be efficiently focused on those areas generating the greatest loads. For example, if agriculture is predicted to be the primary source of phosphorus to a water body, initial pollution reduction efforts may be focused on this land use.

4. **Historical land use types and distribution**—Being aware of past land use changes can provide context for understanding what caused past waterbody health issues, particularly when considered with contemporaneous water quality monitoring data or well-documented historical issues. For example, if a long-term lake property owner remembers or recorded the years of heavy aquatic plant growth, large algal blooms, or low or high water levels, those conditions can be correlated with historical land use changes to examine if something changed to cause an issue (such as an increase in impermeable surfaces or installation of stormwater infrastructure). This information can help offer insight into how a waterbody may react to similar future changes and situations.

5. **Future planned land use types and distribution**—In addition to past and current land use in a watershed, planned land use changes can help estimate future conditions. This information helps target areas that may need active or pre-emptive management in the future, as well as estimate the potential type and magnitude of future pollution issues.

6. **The nature and locations of pollutant sources (if applicable)**—Many human activities contribute pollutants to waterbodies. Many potential pollutant sources are stringently regulated. However, some may continue to be significant pollution sources. An example is private onsite wastewater treatment systems (POWTS), commonly known as septic systems. POWTS can be a significant source of phosphorus when not properly maintained and are usually a substantial source of chloride. Consequently, it is important to investigate whether POWTS exist within a watershed.

Watershed Extent and Topography

Pewaukee Lake covers 2,446 acres and receives runoff from a 13,432 acre watershed draining north-central Waukesha County.[10] Most of the watershed's runoff is delivered to the Lake through four named tributaries (Audley, Coco, Meadowbrook, and Zion Creeks).

The ground-surface elevation in the Pewaukee Lake watershed varies by roughly 280 feet, with elevations of approximately 852 feet above National Geodetic Vertical Datum, 1929 adjustment (NGVD 29) found along the Lake's shoreline to elevations of almost 1130 feet above NGVD 29 at the crest of prominent hills and ridges in the northern and southwestern portions of the watershed (see Map 2.1). Nevertheless, almost two-thirds of the watershed is less than 100 feet higher than the Lake water surface.

Areas of significant topographic relief are prone to long and/or steep slopes. Steeply sloping areas are less likely to store or infiltrate water and are more likely to experience significant erosion, especially when actively cropped, developed, or urbanized. Eroded sediments are transported to lakes, streams, and wetlands where they settle and have the potential to cover desirable granular substrates. Furthermore, sediments often contain significant amounts of nutrients, and can contain a variety of pollutants. Slopes in the Pewaukee Lake watershed range from less than 1 percent to greater than 20 percent. As shown on Map 2.2, most areas within the Pewaukee Lake watershed are relatively level, with 39 percent of the watershed underlain by land surfaces sloping at 2.5 percent or less, and 72 percent sloping at 6 percent or less. Nevertheless, steeply sloping land is found throughout the watershed, including areas close to the Lake. Steeply sloping land is found along the Lake's northwestern shoreline and in areas set well back from the Lake's shoreline draining to Audley, Coco, and Zion Creeks.

The topography of land surfaces, as well as the composition and layering of underlying soil, can significantly affect the type and amount of pollutants and sediment washed into the lakes, streams, and wetlands by rainfall and snowmelt. Generally, less permeable soils and steeper slopes translate to more erosive potential and a greater ability to carry pollutants and sediment to receiving waters. This situation can be exacerbated if slopes are unvegetated, paved, or relatively impermeable. Runoff volume reportedly increases rapidly as slopes increase from zero to about 3 percent. Further increases in slope only slightly increase runoff volume.[11] However, the same study found that soil erosion increased only gradually up to a slope of 4 percent. Soil erosion significantly increased when slopes were greater than 4 percent.

Weather and Climate

Weather and climate describe the same parameters: atmospheric temperature, precipitation, humidity, wind speed, cloud cover, and other conditions. However, weather and climate are not synonymous. The term "weather" generally refers to conditions over short periods of time (e.g., minutes, hours, days, weeks). In contrast, the term "climate" describes long term weather averages, and typically considers time periods of decades or longer. Long periods of weather data allow climate estimates to be made, and allow changes to climate to be noted. Weather conditions have been recorded in Waukesha County for well over 100 years. The average monthly temperatures, precipitation, snowfall, and snow depth recorded at the Waukesha Water Works between 1893 and 2016 are provided in Table 2.2.

Climate is dynamic and has changed many times over the Earth's history. Wisconsin climate data is based on weather observations that extend back at most only about 180 years. "Long-term" precipitation and temperature trends are often based on records spanning a few decades (generally from about the 1970s or 1980s to the present). The available data indicate that Wisconsin's climate is changing.[12] Many aspects of the landscape's water resource asset base respond to climate and can serve as indicators of climate change at various temporal and spatial scales. Historical data analysis demonstrates that water resources are intimately linked to local and regional climate conditions. Long-term records of lake water levels, lake-

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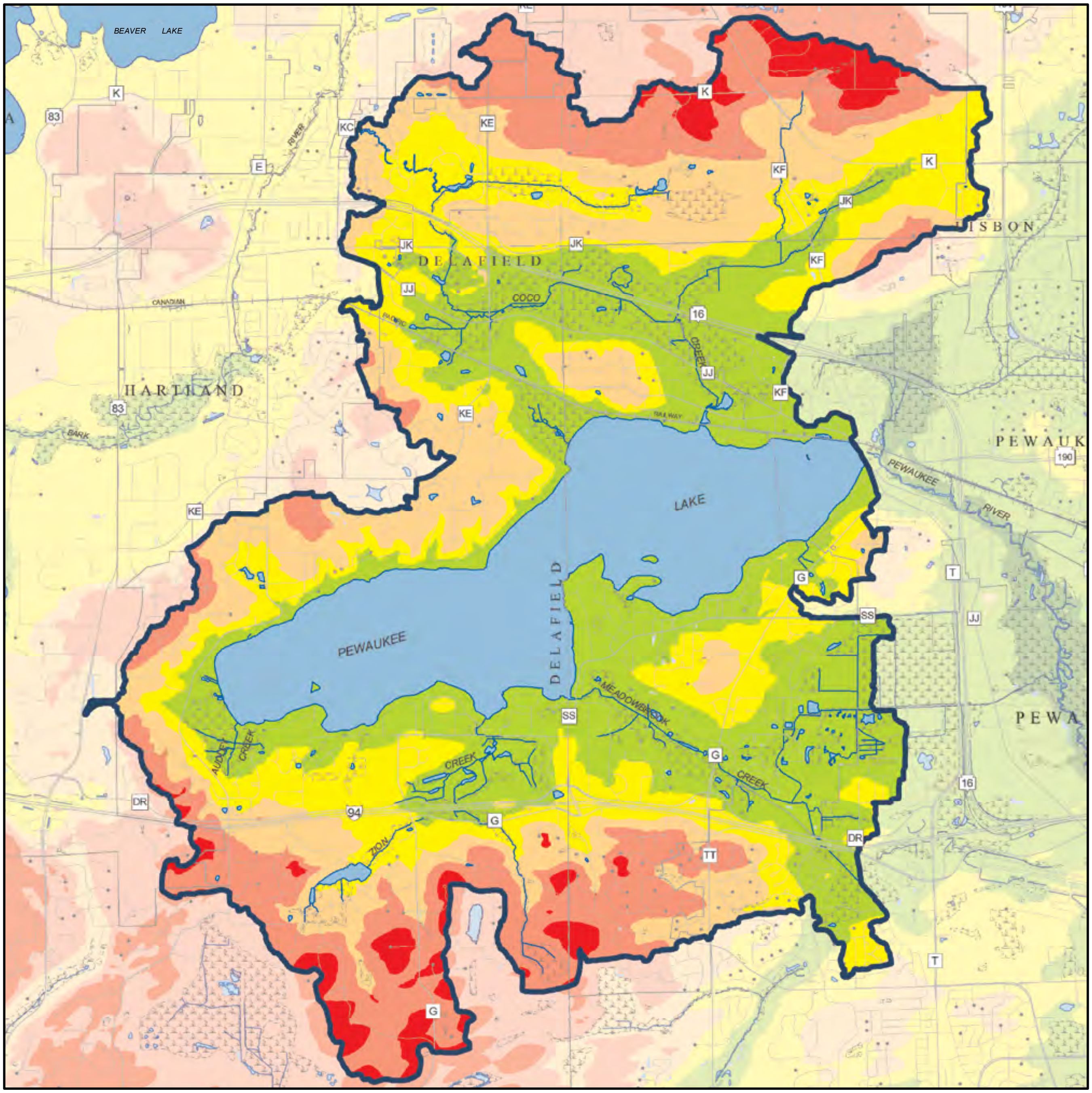
[10] *The Pewaukee Lake watershed boundary was delineated using two-foot interval ground elevation contours developed from a 2003 digital terrain model.*

[11] *F.L. Duley and O.E. Hays, "The Effects of Degree of Slope on Run-off and Soil Erosion,"* Journal of Agricultural Research, *45(6): 349-360, 1982.*

[12] *C.J. Kucharik, S.P. Serbin, S. Vavrus, E.J. Hopkins, and M.M. Motew, "Patterns of Climate Change Across Wisconsin from 1950 to 2006,"* Physical Geography, *31(1): 1-28, 2010.*

Map 2.1
Pewaukee Lake Watershed Physiography



ELEVATION (IN FEET)

- 800-850
- 850-900
- 900-950
- 950-1000
- 1000-1050
- 1050-1125

- SURFACE WATER
- WETLAND
- STREAM
- WATERSHED BOUNDARY

Note: Elevation in feet above National Geodetic Vertical Datum, 1929 Adjustment.

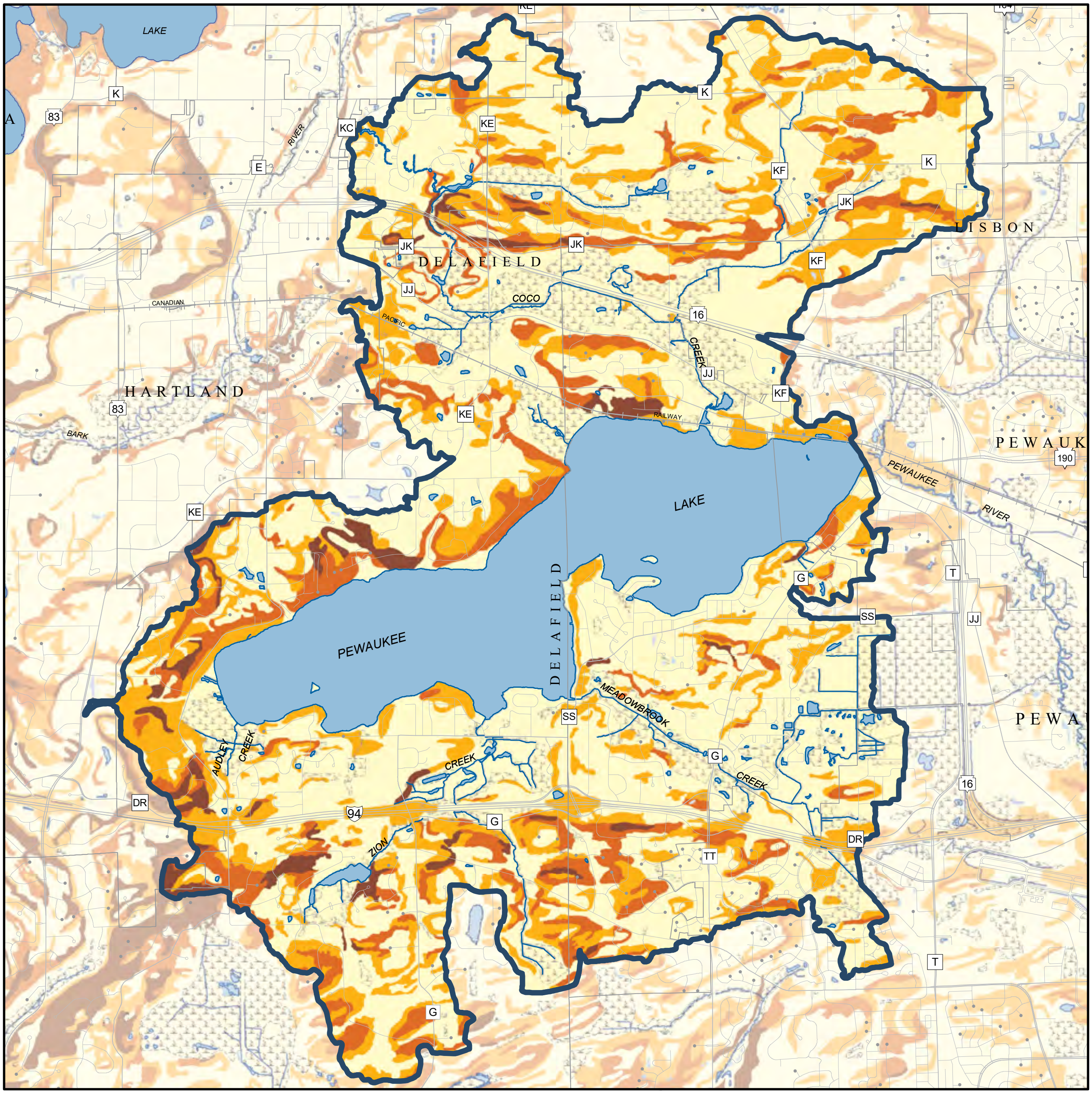
Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Map 2.2
Land Surface Slope Within the Pewaukee Lake Watershed



SOILS HAVING SLOPES RANGING FROM 0 TO 6 PERCENT

SOILS HAVING SLOPES RANGING FROM GREATER THAN 6 TO 12 PERCENT

SOILS HAVING SLOPES RANGING FROM GREATER THAN 12 TO 20 PERCENT

SOILS HAVING SLOPES OF GREATER THAN 20 PERCENT

SURFACE WATER

WETLAND

STREAM

WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: Natural Resources Conservation Service and SEWRPC

Table 2.2
Period of Record Monthly Climate Summary: 1893-2016

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (°F)	27.20	30.60	41.70	56.00	68.10	77.90	83.00	80.70	72.90	60.9	44.90	31.60	56.30
Average Min. Temperature (°F)	11.30	14.40	24.50	35.80	45.80	55.50	60.80	59.30	51.60	40.90	29.00	17.10	37.20
Average Total Precipitation (in.)	1.50	1.27	2.17	3.03	3.50	3.75	3.44	3.560	3.42	2.43	2.18	1.66	31.91
Average Total Snowfall (in.)	11.00	7.80	8.10	2.00	0.20	0.00	0.00	0.00	0.00	0.30	2.70	8.50	40.60
Average Snow Depth (in.)	5.00	4.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.00	1.00

Source: Western Regional Climate Center

ice duration, groundwater levels, and stream baseflow are correlated with long-term trends in atmospheric temperature and precipitation.[13]

The Wisconsin Initiative on Climate Change Impacts (WICCI) concludes that projected future climate change will affect Wisconsin's water resource quantity and quality.[14] However, WICCI also found clear evidence from analysis of past and probable future climate trends that different geographic regions of Wisconsin will respond differently to climate change (see Figure 2.1). These differences reflect local variation in land use, soil type, groundwater characteristics, and runoff and seepage response to precipitation. This illustrates the importance of including existing and future conditions as part of the watershed protection plan strategy.

Climate change seems to be altering water availability (volume and timing), distribution and intensity of rainfall over time, and whether precipitation falls as rain or snow, each of which affects water's movement through the water cycle. As shown in Figure 2.2, water entering the landscape arrives as precipitation (rain and snowfall) that either falls directly on waterbodies; runs off the land surface and enters streams, river, wetlands, and lakes; or percolates through the soil, recharging groundwater that flows underground and re-emerges as springs, seeps, or human well discharge, all which can feed lakes, wetlands, and streams.

Even absent climate change, when portions of the hydrologic cycle change, the surface-water and groundwater system may be affected. For example, intense groundwater pumping and consumptive use can reduce or completely deplete flow in local streams (see the "Groundwater Resources" subsection below). Climate change may expose the vulnerabilities of water supplies within a given natural system or human community, and this vulnerability is commonly proportional to how much humans have altered the water cycle. Water supply vulnerability is often most evident during protracted dry weather while flooding and infrastructure failure are most evident during extremely wet weather.

The WICCI Water Resources Working Group (WRWG) incorporated WICCI's 1980-2055 temperature, precipitation (including occurrence of events), and changes in snowfall projection to evaluate potential hydrologic process and resource impacts.[15] This team of experts identified and prioritized the most serious potential water resource problems related to anticipated climate change, and proposed strategic adaptation

[13] *Wisconsin Initiative on Climate Change Impacts (WICCI), Wisconsin's Changing Climate: Impacts and Adaptation, Nelson Institute for Environmental Studies, University of Wisconsin-Madison, and Wisconsin Department of Natural Resources, February 2011.*

[14] *Wisconsin Initiative on Climate Change Impacts, February 2011,* op. cit.

[15] *The Water Resources Working Group (WRWG) included 25 members representing the Federal government, State government, the University of Wisconsin System, the Great Lakes Indian Fish and Wildlife Commission, and the Wisconsin Wetlands Association. Members were considered experts in the fields of aquatic biology, hydrology, hydrogeology, limnology, engineering, and wetland ecology in Wisconsin. Over the course of a year, the group convened to discuss current climate-related water resources research, potential climate change impacts, possible adaptation strategies, and future research and monitoring needs across the entire State of Wisconsin. For more details on climate change, impacts, adaptation, and resources visit www.wicci.wisc.edu/water-resources-working-group.php.*

strategies to address those impacts across the State of Wisconsin (see below). The WRWG offers the following guidance to help local communities develop adaptation strategies:[16]

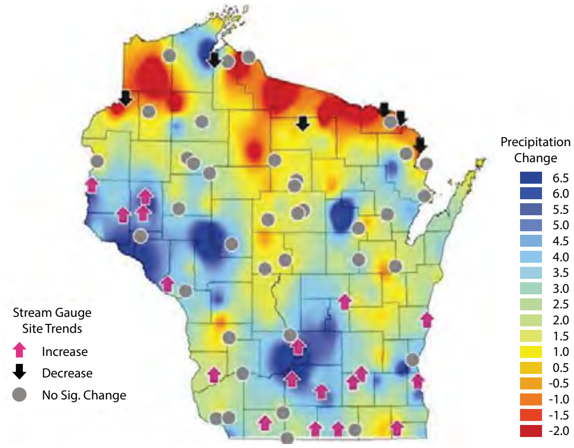
Minimize threats to public health and safety by anticipating and managing for extreme events-floods and droughts. *We cannot know when and where the next flooding event will occur or be able to forecast drought conditions beyond a few months, but we do know that these extreme events may become more frequent in Wisconsin in the face of climate change. More effective planning and preparing for extreme events is an adaptation priority.*

Increase resiliency of aquatic ecosystems to buffer the impacts of future climate changes by restoring or simulating natural processes, ensuring adequate habitat availability, and limiting human impacts on resources. *A more extreme and variable climate (both in temperature and precipitation) may mean a shift in how we manage aquatic ecosystems. We need to try to adapt to the changes rather than try to resist them. Examples include managing water levels to mimic pre-development conditions at dams and other water level structures, limiting groundwater and surface water withdrawals, restoring or reconnecting floodplains and wetlands, and maintaining or providing migration corridors for fish and other aquatic organisms.*

Stabilize future variations in water quantity and availability by managing water as an integrated resource, keeping water "local" and supporting sustainable and efficient water use. *Many of our water management decisions are made under separate rules, statutory authorities, administrative frameworks, and even different government entities. This can lead to conflicting and inconsistent outcomes. In the face of climate change, the more we can do to integrate these decisions at the appropriate geographic scale, the better adapted and ready for change we will be. In addition, treating our water as a finite resource and knowing that supply will not always match demand will allow for more sustainable water use in the future.*

Maintain, improve, or restore water quality under a changing climate regime by promoting actions to reduce nutrient and sediment loading. *Water quality initiatives will need to be redoubled under a changing climate in order to minimize worse-case scenarios such as fish kills, harmful blue-green algae blooms, or mobilization of sediments and nutrients and to prevent exacerbation of existing problems.*

Figure 2.1
River Baseflow and Precipitation Change in Wisconsin: 1960-2006



From 1950-2006, Wisconsin as a whole became wetter, with an increase in annual precipitation of 3.1 inches. This increase has primarily occurred in southern and western Wisconsin, while northern Wisconsin experienced some drying. Concomitantly, stream baseflow increased in wetter areas.

Source: Water Resources Working Group of the Wisconsin Initiative on Climate Change Impacts and SEWRPC

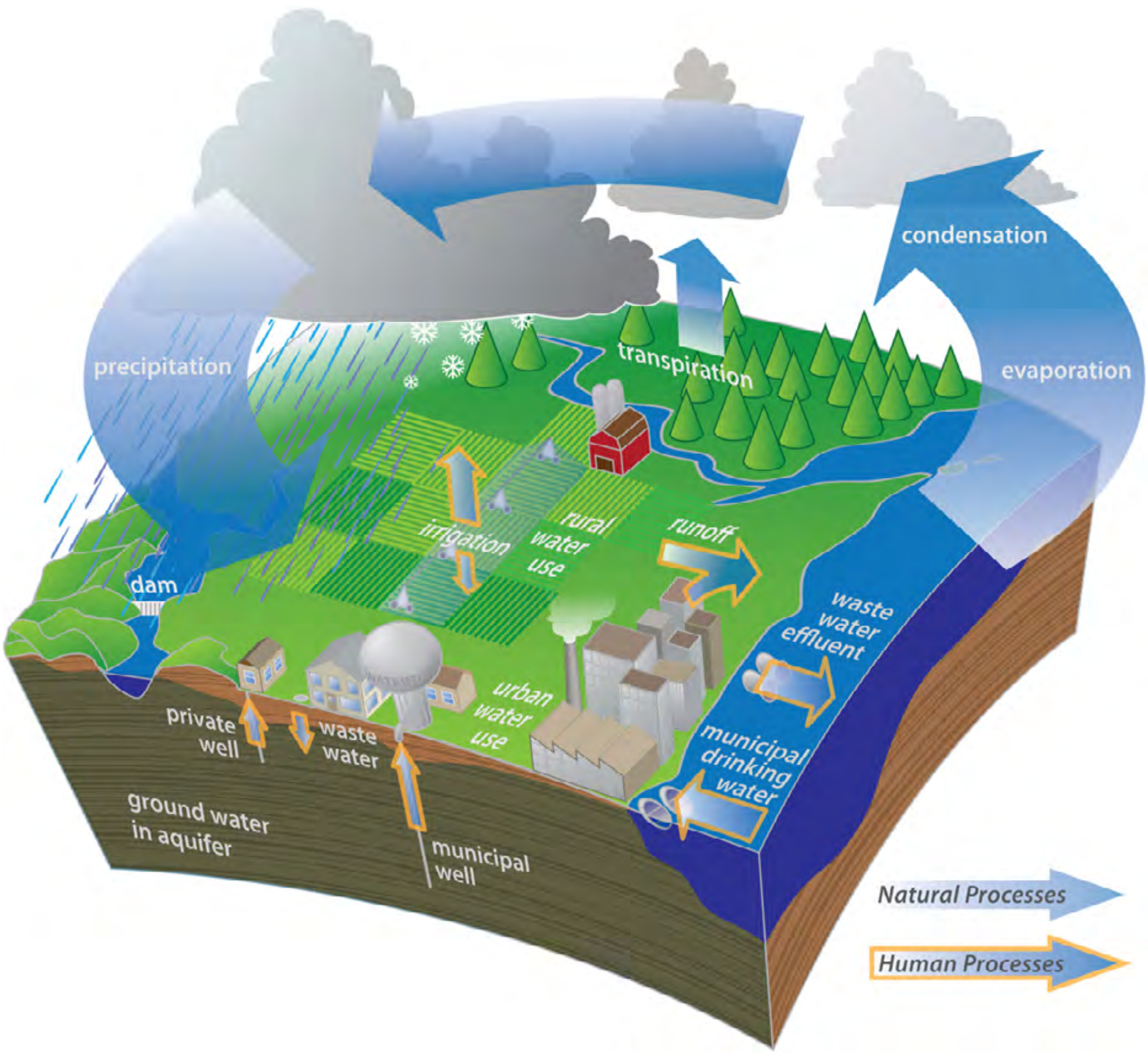
Studies in the Pewaukee River basin have evaluated local climatic change.[17] Overall, available data suggest that the local climate is becoming increasingly warm and wet. Most additional precipitation is falling in the fall and winter, and wetter than normal spring weather is often a harbinger of greater than normal annual precipitation. Records of ice thaw have been collected at Pewaukee Lake since 1936.[18] In that time, the average ice thaw date on the Lake has shifted from April 3rd to March 26th, consistent with trends from

[16] *Wisconsin Initiative on Climate Change Impacts, February 2011,* op. cit.

[17] *For a more detailed description of perceived climate change in the local area, and descriptions of the possible effect of climate change on flora, fauna, water resources, and other factors, see SEWRPC Community Assistance Report No. 313,* Pewaukee River Watershed Protection Plan*, December 2013.*

[18] *Ice records at Pewaukee Lake provided by Bill Browns and Dick Nowacki.*

Figure 2.2
Human Influence on Hydrologic Cycle



This schematic shows how human processes associated with land use development affect how water moves through the hydrologic cycle. Water returns to the atmosphere through evaporation (process by which water is changed from liquid to vapor), sublimation (direct evaporation by snow and ice), and transpiration (process by which plants give off water vapor through their leaves).

Source: Water Resources Working Group of the Wisconsin Initiative on Climate Change Impacts and SEWRPC

Geneva Lake in Walworth County as well as Lake Mendota and Lake Monona in Dane County.[19] Changes in patterns of precipitation and ice cover can impact dam operation (see Section 2.4, "Lake Level Manipulation and Management") as well as the growth of aquatic plants (see Section 2.7, "Aquatic Plants"). Such insight should be integrated into water resource management planning and water infrastructure design.

Geology and Soils

Essentially all of Waukesha County was covered by glacial ice until approximately 15,000 years ago. Eastern Waukesha County was overridden by glaciers flowing southwest out of the Lake Michigan Basin, depositing sediment now known as the Oak Creek Formation and the New Berlin Member of the Holy Hill Formation. Glaciers overriding western Waukesha County followed Green Bay, Lake Winnebago, and other lowlands,

[19] *Information on changes in lake ice is provided at www.epa.gov/climate-indicators/climate-change-indicators-lake-ice.*

and entered Waukesha County from the northwest depositing sediments known as the Horicon Member of the Holy Hill Formation. The two lobes of glacial ice met and formed the prominent ridges of the Kettle Interlobate Moraine (commonly referred to as the "Kettle Moraine").

Glaciers transported vast quantities of unsorted sediment (diamicton) to the area and deposited these sediments under and at the distal end of glacial ice. When glacial diamicton is deposited directly by glacial ice, it is referred to as till. Till deposited under glacial ice is termed ground moraine, while that deposited near the wasting end of a glacier forms a terminal moraine. Melting glaciers released enormous volumes of water, and this water flowed away from the glacier transporting and sorting sediment. Sorted glacial sediment is commonly referred to as glaciofluvial sediment (outwash) when deposited by flowing water or glaciolacustrine sediment (glacial lake deposits) when deposited in still water. The chaotic and rapidly changing environment near melting glacial ice commonly creates complexly interlayered assemblages of till and water-lain sediment. Ice blocks can separate from the main body of ice and can be buried in sediment. When the buried ice block melts, an irregular land surface marked by conspicuous steep-walled depressions ("kettles") results.

Unlike the other large lakes of northwestern Waukesha County formed in the Kettle Interlobate Moraine (an area rich in permeable glaciofluvial sediment), Pewaukee Lake is found in fine-grained ground moraine of the Holy Hill Formation. This means that the Pewaukee Lake watershed generally has gentler slopes, less relief, and generally finer grained, less permeable sediment than many of the other large lakes of Waukesha County. The conspicuous hills found to the north and south of the Lake are drumlins, features deposited under relatively thick glacial ice, and often incorporating layers of impermeable clayey sediment. This also contrasts to the hills surround the other large lakes, which are commonly composed of permeable sand and gravel. Pewaukee Lake is believed to be a result of erosion created by glacial meltwater, while many of the other lakes have basins formed by melting of large blocks of buried glacial ice.

Despite its position on a northeast-southwest trending buried bedrock ridge composed of erosion resistant Silurian-age Niagara Dolomite, bedrock is buried by glacial sediment throughout almost all of the Pewaukee Lake watershed. A few bedrock outcroppings are known, including areas about a half mile south of the Lake and east of Elmhurst Road, just west of Zion Creek, and several areas at and near the northeastern corner of the watershed (see Map 2.3). Most of the Lake, much of lower Coco Creek Watershed, and the upland area immediately north of the central portion of the Lake occupy a comparatively low area on the buried bedrock ridge. In these low areas, the dolomitic bedrock has been eroded away exposing the older underlying soft and easily eroded Ordovician-age Maquoketa Shale or even older Ordovician-age dolomite. Meadowbrook Creek generally parallels the path of a northwest-southeast bedrock fault that is mapped to being in the middle of the Lake.[20]

Soils are the uppermost layers of terrestrial sediment and are the result of weathering and biological activity. The type of soil underlying the area depends on several factors including landscape position and slope, parent material, hydrology, and the types of plants and animals present. Soils of the Hocheim-Theresa Association dominate the Pewaukee Lake watershed, covering over 95 percent of its area (see Map 2.4). Hocheim-Theresa Association soils are generally well drained, have a subsoil consisting of clay loam and silty clay loam, with parent materials being glacial till and loess (wind-deposited silt). Limited portions of the watershed just south of the Lake's west basin and at the extreme northeast corner of the watershed are occupied by soils of the Pella association. These soils are formed in glacial till, are poorly to well drained, and may have a relatively thin silty clay and clay loam soil with bedrock found at shallow depth. Only a few feet of unconsolidated sediment are present in some areas and bedrock outcroppings can occur. A very small area of Rodman-Casco association soils is found at the very edge of the watershed west and southwest of the Lake. Soils of the Rodman-Casco association are typically well drained, with subsoils often dominated by sand and gravel although clay and silt layers are found. The Rodman-Casco association soils are typical of the Kettle Moraine and are commonly found in areas of irregular topography and great topographic relief.[21]

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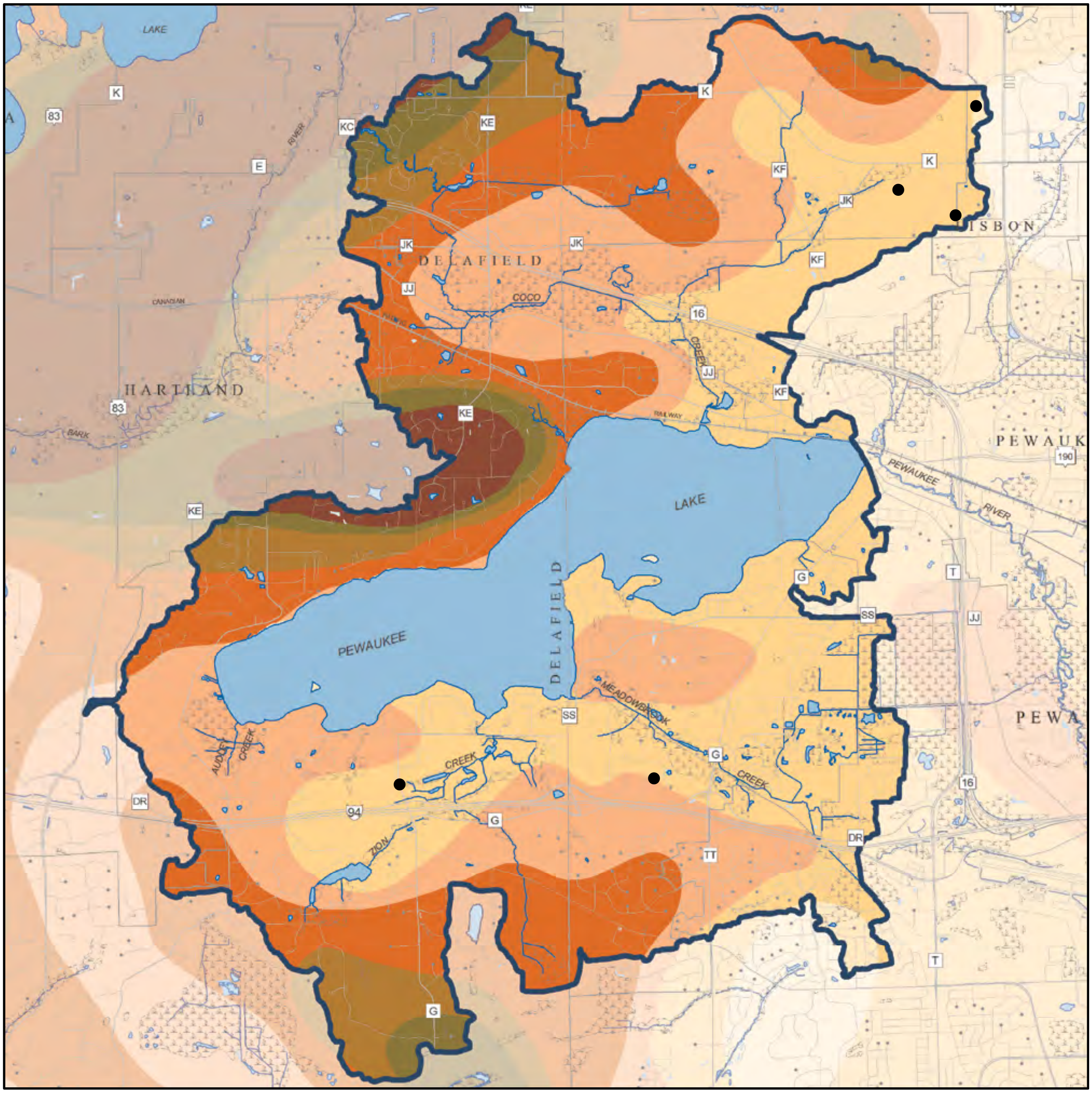
[20] *K.M. Massie-Ferch and R.M. Peters,* Preliminary Bedrock Geology of Waukesha County, Wisconsin, *Wisconsin Geological and Natural History Survey Open-File Report 2004-15B, 2004.*

[21] *J.A. Steingraeber and C.A. Reynolds,* Soil Survey of Waukesha County, Wisconsin*, United States Department of Agriculture, 1971.*

Map 2.3
Unconsolidated Sediment Thickness Within the Pewaukee Lake Watershed



DEPTH TO BEDROCK (IN FEET)

- 0-25
- 25-50
- 50-100
- 100-150
- 150-200
- 200-250
- 250-400
- BEDROCK OUTCROPPING
- SURFACE WATER
- WETLAND
- STREAM
- WATERSHED BOUNDARY

Note: The information shown on this map is general in nature, and may not reflect localized variations.

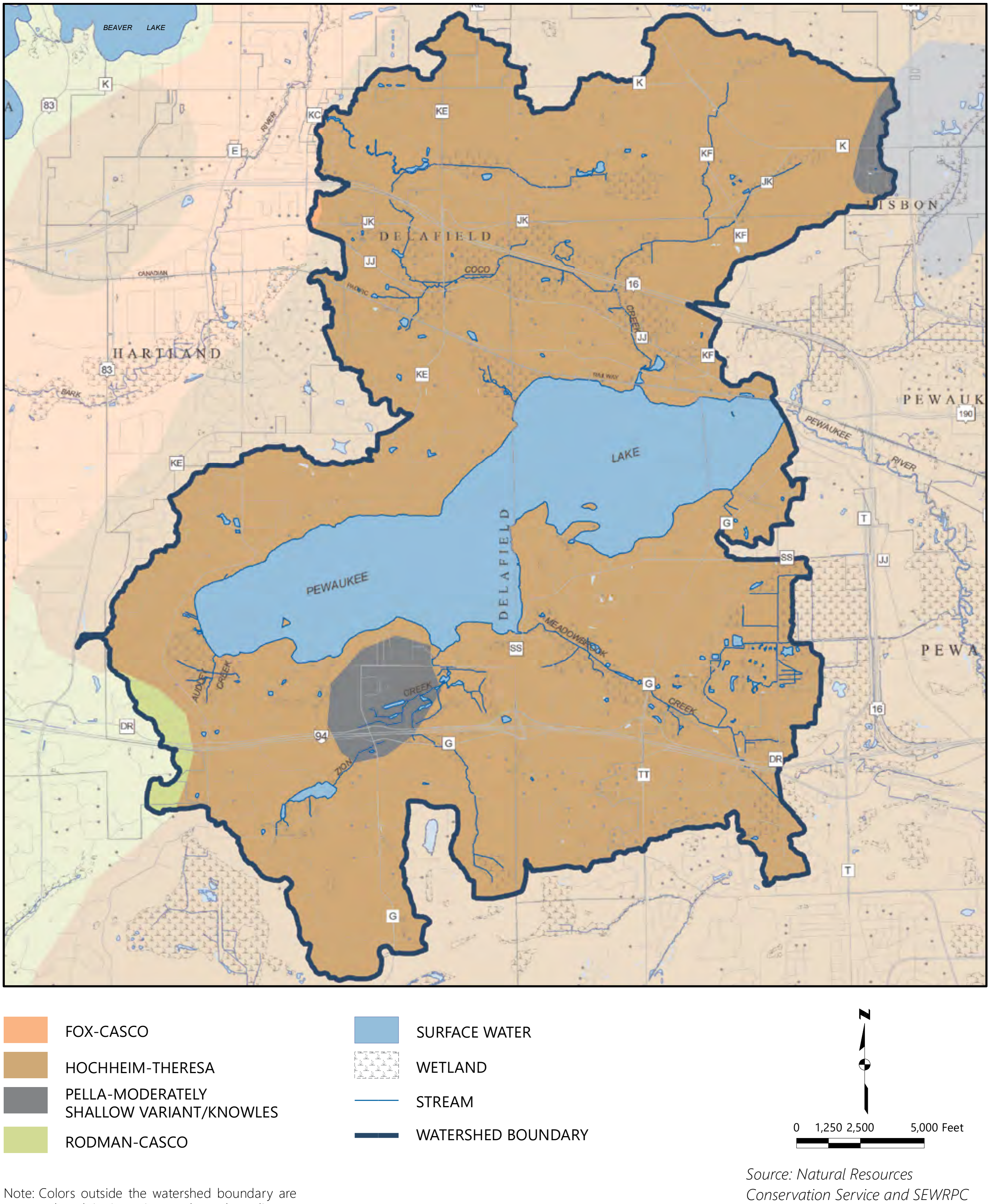
Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: Wisconsin Geological Natural History Survey and SEWRPC

Map 2.4
Pewaukee Lake Watershed Soil Associations



Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

Source: Natural Resources Conservation Service and SEWRPC

Hydric soils are formed when soils are saturated for extended periods of time. Hydric soils indicate groundwater near the land surface, ponding, or extended flooding and are commonly associated with wetlands areas. One-quarter of the Pewaukee Lake watershed is underlain by soils exhibiting some hydric characteristics. Most of these areas are located in wetlands paralleling major tributaries and in embayments along Pewaukee Lake's shoreline (see Map 2.5). Many hydric soil areas were likely drained for human use or were inundated shortly after the dam was built and Lake level increased about 180 years ago. Hydric soil areas often are sites of physical and biological processes that protect and sustain a lake's water quality and ecology and therefore warrant protection.

Vegetation

Before European settlement, oak savanna was the dominant vegetation assemblage in the Pewaukee Lake watershed (see Map 2.6). Oak savanna is a prairie environment with scattered oak trees. In general, oak savannas have at least one tree per acre but have less than half the land area covered by tree canopy. White, bur, and black oaks were particularly common in oak savannas. Modest-sized tracts of oak forest were found along the Lake's southern and eastern shorelines and in the uplands to the north of the Lake. Wetlands fringed many of the Lake's tributary streams and low elevation shorelines. After European settlement, native vegetation throughout the watershed was largely removed and supplanted by vegetation associated with agricultural or urban land uses, although some pockets of native vegetation remain.

Water Resources

Pewaukee Lake and its contributing watershed form a major headwater of the Pewaukee River, a fourth order river that joins the Fox River just upstream of Waukesha, Wisconsin.[22] The Pewaukee River's headwaters receive water from surface-water and groundwater sources. Four named streams, several small unnamed streams and ditches, broad wetland areas, ponds, and reservoirs occupy lands draining to Pewaukee Lake. This section provides information regarding the hydrology, morphometry, general characteristics, and management issues related to lakes, streams, floodplains, wetlands, and groundwater in the Pewaukee Lake watershed.

Pewaukee Lake

In its modern configuration, Pewaukee Lake is the largest lake in Waukesha County. The Lake's west basin is a natural lake, however, the eastern basin was created when the Pewaukee River was dammed. Without the dam, open water areas would be roughly half of the current size, and would be almost exclusively confined to the West Basin. Please see Section 2.4, "Lake Level Manipulation and Management," for more information regarding human water level manipulation.

<u>Origins</u>

The prominent valley in which Pewaukee Lake lies was formed by erosion caused by glacial meltwater flowing west under and away from glaciers moving out of the lowland that is now Lake Michigan. Pewaukee Lake's genesis is believed to be similar to several of Southeastern Wisconsin's largest lakes (e.g., Geneva Lake, Lake Como, and Delavan Lake). An early version of Pewaukee Lake formed when glaciers were still present in the local area and water drained out of the present Lake's northwest corner. This early lake had a water surface elevation well over 100 feet higher than the Lake's present water surface elevation. As glacial ice retreated further to the east, water began to drain out of the Lake's eastern basin in the headwater area of Coco Creek, and later out of the south via Pebble Creek.[23] After glacial ice completely left the area, lower discharge points became available and Pewaukee Lake began to drain to the east via the Pewaukee River as it does today. After leaving the Lake, water draining from the Lake now flows about 4.4 miles down the Pewaukee River where it joins the Fox River.

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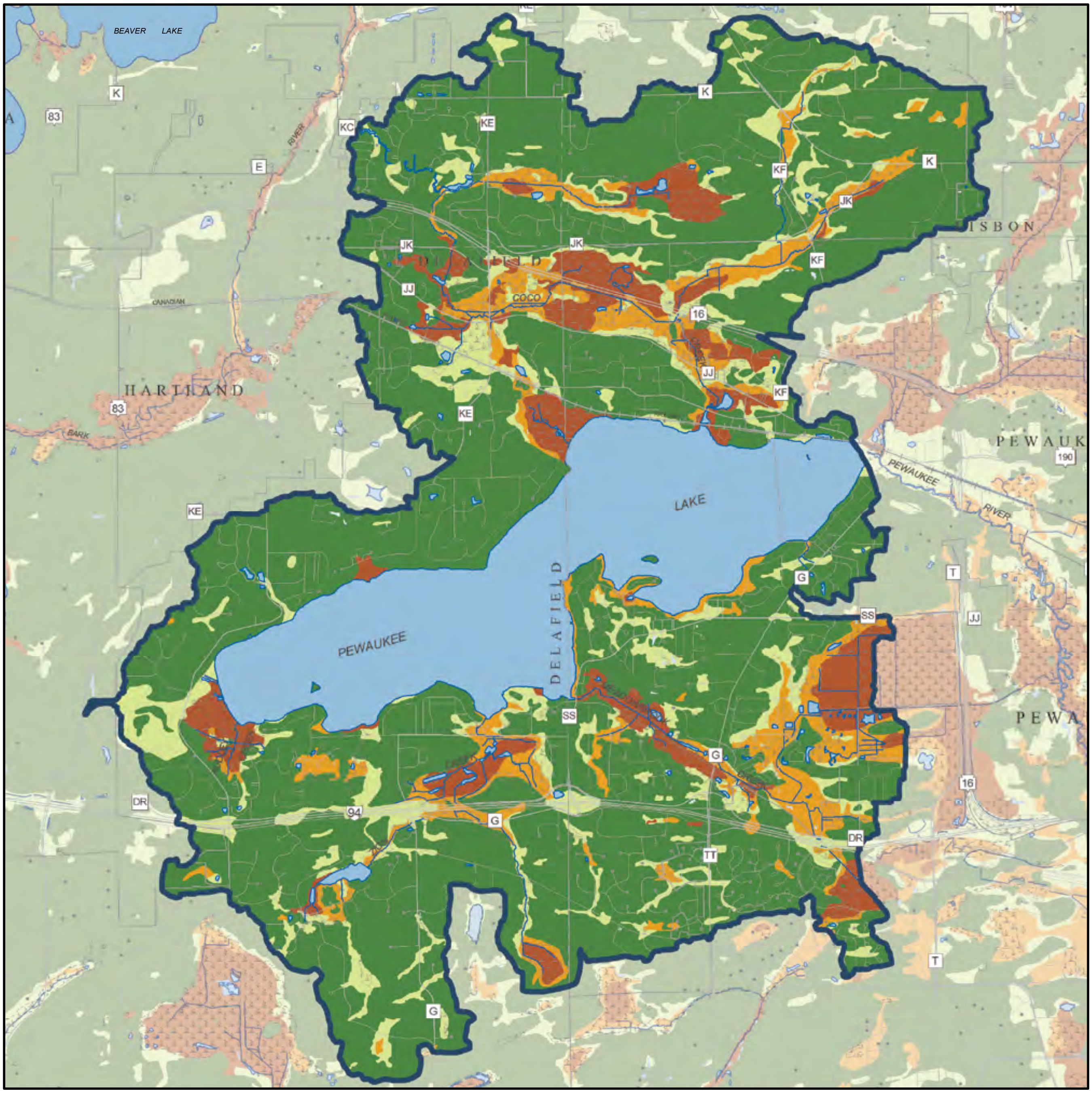
[22] *Stream order refers to a stream classification concept developed by Arthur Strahler and Robert Horton during the 1940s and 1950s. Headwater perennial tributaries are assigned a stream order of 1 and are labelled first order streams. When two first order streams converge, a second order stream is formed, when two second order streams converge, a third order stream is formed, and so on. When a lesser order stream converges with a higher order stream, the larger stream's order remains unchanged.*

[23] *L. Clayton,* Pleistocene Geology of Waukesha County, Wisconsin*, Wisconsin Geological and Natural History Survey, Bulletin 99, 2001.*

Map 2.5
Hydric Soils Within the Pewaukee Lake Watershed



HYDRIC

PREDOMINANTLY HYDRIC

PREDOMINANTLY NON-HYDRIC

NON-HYDRIC

SURFACE WATER

WETLAND

STREAM

WATERSHED BOUNDARY

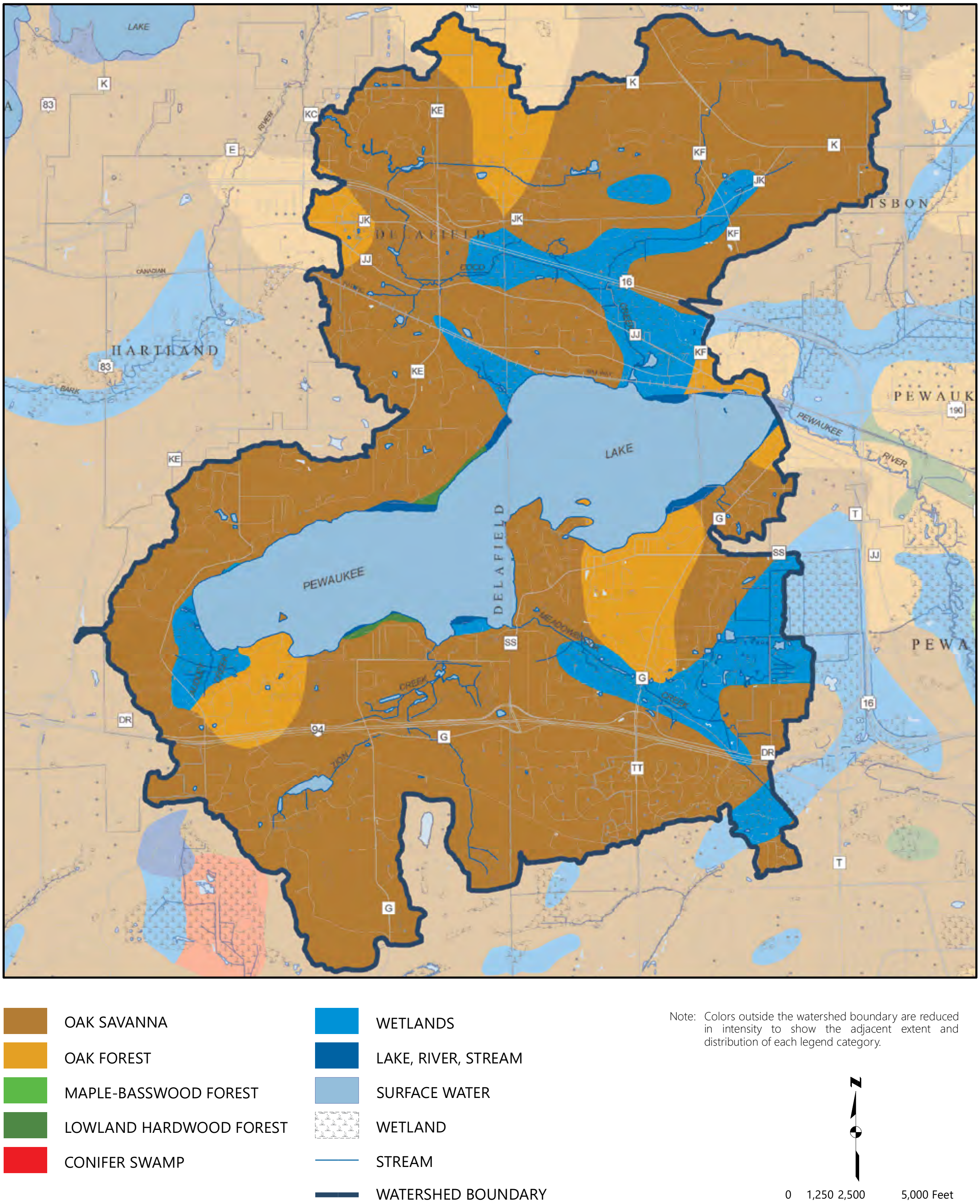
Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: Natural Resources Conservation Service and SEWRPC

Map 2.6
Presettlement Vegetation Within the Pewaukee Lake Watershed: 1836

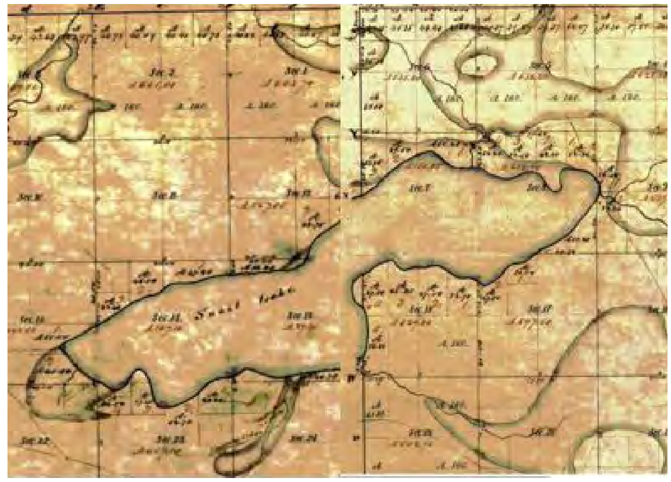


Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

Source: SEWRPC

The first US Public Land Survey was completed in the Pewaukee area during 1836 (see Figure 2.3). This survey identifies the western half of the Lake as "Snail Lake," while the eastern portion of the Lake was identified as marshland with water depths ranging between 0.5 and 1.0 foot. In 1842, the territorial government granted Asa Clark permission to construct a dam on the "Little Fox River" just downstream of the marshland portion of the Lake to power a mill.[24] The dam raised the Lake's natural water elevation approximately six feet. As a result, the large marshland just east of Snail Lake and lands along the perimeter of the Snail Lake were inundated, doubling the Lake's open water surface area, and forming what is today known as Pewaukee Lake. Water power was used for a variety of purposes, including milling feed and producing electricity for lighting.[25] Although the dam no longer produces power, Lake water elevations are still controlled by the dam at the east end of the Lake.

Figure 2.3
1836 Public Land Survey Sketch Map



Source: University of Wisconsin Digital Collections and SEWRPC

Morphometry and Hydrology

As it exists today, Pewaukee Lake covers 2,446 acres (see Table 2.3). The Lake contains approximately 34,000 acre-feet of water at normal Lake elevation and is oriented with its long axis running roughly east-west. The Lake measures roughly 4.5 miles long and 1.4 miles wide at its widest point and has about 12.8 miles of shoreline. About 16 percent of the Lake area is less than five feet deep, 62 percent has a water depth between five and 20 feet, and about 22 percent of the Lake is greater than 20 feet deep. Silt and muck are the predominant lake bottom materials. Coarser grained sediments (sand, gravel, boulders) are found primarily along shorelines.

The Wisconsin Department of Natural Resources (WDNR) classifies Pewaukee Lake as a drainage (flow-through) lake, which means that the Lake has both a defined inflow and outflow. Pewaukee Lake has two distinct basins: the deep natural lake to the west (45 foot maximum water depth), and the shallow former marsh that was inundated by the outlet dam over 175 years ago (10 foot maximum water depth). Refer to Map 2.7 for details regarding Lake bathymetry. Although the Lake's two basins are nearly equal in areal extent (i.e., the west basin covers about 1290 acres, while the east basin covers about 1156 acres), almost four-fifths of the Lake's total water volume is found in the Lake's western basin. Both the east and west Lake basin have several tributary streams. The Lake has a single outlet at the eastern extreme of the Lake's shallow eastern basin. Three islands are present in the Lake: one in the western basin and two in the eastern basin.

The volume of water entering and leaving the lake varies depending upon changes in precipitation, evaporation, and dam operation. According to a U.S. Geological Survey (USGS) study,[26] precipitation falling directly upon the Lake accounts for approximately 57 percent of the Lake's water supply. Streams and direct surface water runoff contributes about 27 percent of the Lake's water supply, while groundwater discharging to the Lake contributes the remaining 16 percent. The amount of water that the USGS predicts is contributed by surface-water runoff closely mirrors the average estimated discharge of the individual streams entering the Lake. Many of these streams are fed by groundwater, which increases the actual importance of groundwater to the Lake's overall water budget. Groundwater is critical to sustain dry weather water levels and critical habitat types, and its importance should not be underestimated. No wastewater, industrial process, cooling, or

[24] *L.S. Smith,* The Water Powers of Wisconsin*, Wisconsin Geological and Natural History Survey, Bulletin No. XX, Economics Series No. 18, 1908.*

[25] *Ibid.*

[26] *D.T. Feinstein, M.N. Fienen, J.L. Kennedy, C.A. Buchwald, and M.M. Greenwood,* Development and Application of a Groundwater/Surface-Water Flow Model Using MODFLOW-NWT for the Upper Fox River Basin, Southeastern Wisconsin*, U.S. Geological Survey Scientific Investigations Report 2012-5108, 2012.*

other artificial point sources are known to contribute water to the Lake or its tributary streams. Over half (52 percent) of the water leaving Pewaukee Lake is evaporated into the atmosphere. Less than 1 percent of the water leaving the Lake leaves the Lake via groundwater. The Pewaukee River receives the bulk of the remaining water leaving the Lake, with approximately 47 percent of the Lake's water exiting via the outlet dam.

According to the U.S. Geological Survey study, Pewaukee Lake's outflow over the outlet dam averages about 7.5 cubic feet per second, less than the value predicted by WDNR's PRESTO-Lite tool (10.1 cubic feet per second) and reported by the Village of Pewaukee.[27] Water volumes leaving the Lake via the Pewaukee River were also estimated using data from the USGS stream gaging station on the Fox River in Waukesha. The gaging station data was used to determine the average water yield for areas upstream of Waukesha, and the water yield that can be expected 90 percent of the time. While these values are not specific to the Pewaukee Lake watershed, they are representative of typical conditions in the local area. This exercise determined that annual water yield averages 12.2 inches, ranging as low as 4.1 inches during very dry years and as high as 21.0 inches per year during very wet years. This translates to an average annual watershed outflow of 20.6 cubic feet per second, a value substantially higher than the values estimated by the USGS or WDNR. During very dry years, average watershed outflow can fall to 3.9 cubic feet per second, and during wet years, average annual flow can increase to 35.7 cubic feet per second. During very dry years, the volume of water evaporated from the Lake's surface can exceed that contributed by precipitation falling upon the Lake's surface.

Several morphologic and hydrologic parameters are used to judge the potential impact of human influence on a lake. These parameters are described below.

Watershed/Lake Area Ratio contrasts the size of a lake to its contributing watershed. Lakes with higher ratios are typically considered more vulnerable to human influence and prone to water quality problems. However, the way the watershed is used can greatly influence the amount of pollutants carried to the Lake. As a rule of thumb, lakes with a watershed/lake ratio greater than 10:1 often experience some water quality issues. Pewaukee Lake's watershed/lake area ratio is approximately 5.5:1, while the typical Wisconsin inland lake has a watershed/lake area ratio of 7:1.[28] This finding suggests that the Lake is slightly less vulnerable to human influence and land use than a typical Wisconsin lake.

Table 2.3
Hydrology and Morphometry of Pewaukee Lake

Parameter	Pewaukee Lake
Size and Shape	
Open Water Surface Area	2,446 acres
Watershed Area[a]	13,432 acres
Shoreline Length	14.0 miles
General Lake Orientation	E-W
General Shape	Irregular elongated oval, two distinct lobes
Maximum Length	4.5 mile
Maximum Width	1.4 mile
Shoreline Development Factor[b]	2.02
Depth	
Maximum Depth	45 feet
Mean Depth	14 feet
Lake area with <5 feet water depth	393 acres
Lake area with water depths between 5 and 20 feet	1,528 acres
Lake area with > 20 feet water depth	525 acres
Hydrology	
Lake Volume	34,000 acre-feet
Lake Type	Drainage
Residence Time[c]	
Average weather	2.3 years
Prolonged dry weather	12 years
Prolonged wet weather	1.3 years

[a] *This watershed area is based on the most current elevation refinements made possible through Commission digital terrain modeling analysis. The watershed area includes all areas that slope toward the lake, but does not include the Lake itself.*

[b] *Shoreline development factor (SDF) is the ratio of the Lake's measured shoreline length to the circumference of a circle of the same area. Values close to one indicate a nearly circular lake. SDF can be used as an indicator of biological activity (i.e. the higher the value, the more likely the lake will be to have a productive biological community). Lakes with high SDF's have more shoreline per acre of surface area, and are prone to heavy human pressure.*

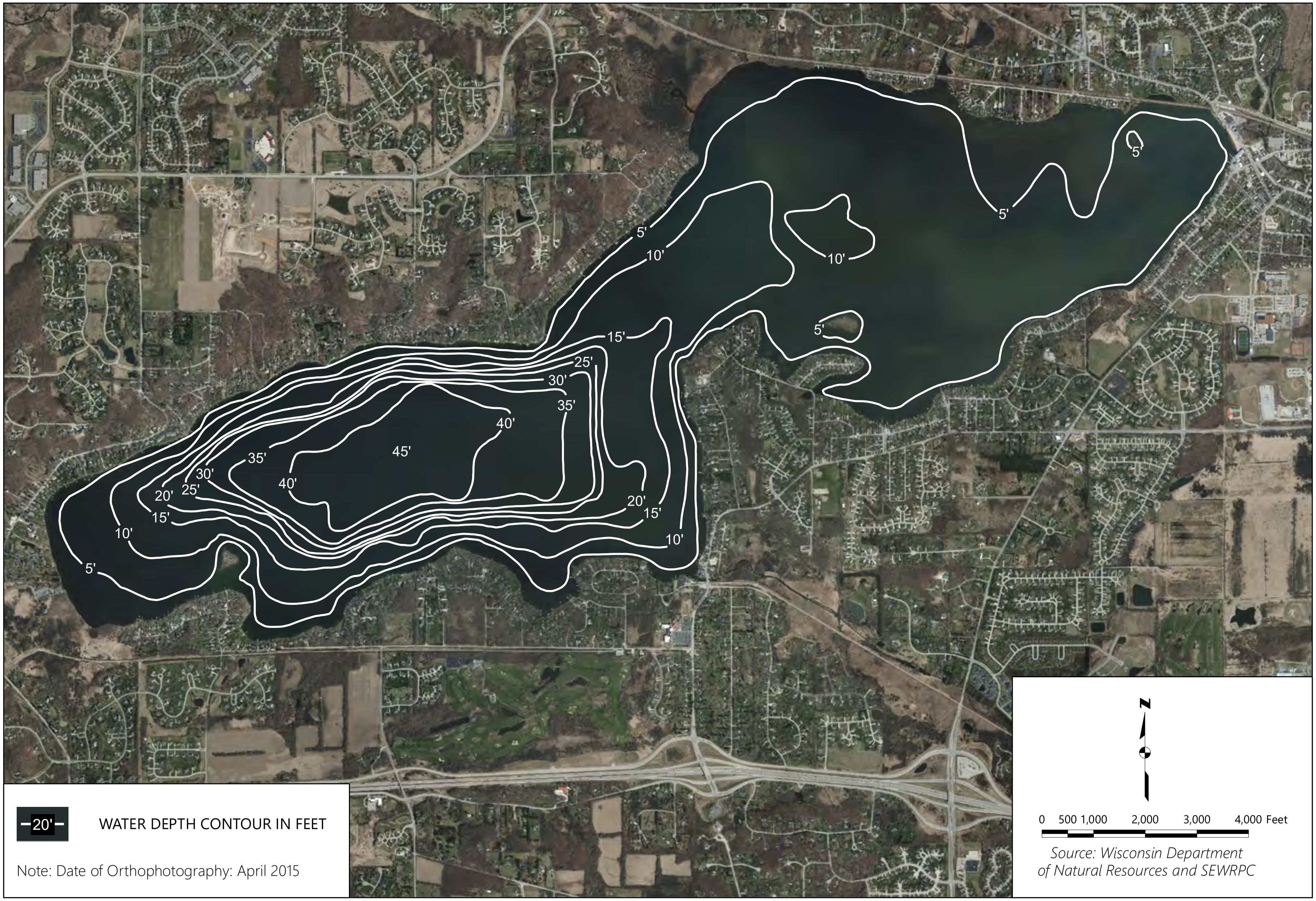
[c] *Residence time is the number of years required for natural water sources under typical weather conditions to fill the lake one time. Natural water sources include runoff from surrounding areas, precipitation falling directly upon a lake, water entering from tributary streams, and water contributed to a lake by groundwater. The calculation uses unit area runoff values representative of the Fox River upstream of Waukesha Wisconsin. Wet and dry values are based upon transient flows, and are not meant to represent long-term sustained conditions.*

Source: Wisconsin Department of Natural Resources and SEWRPC

[27] *D.J. Naze,* Operation and Maintenance Plan, *Pewaukee Lam Dam, Village of Pewaukee, Wisconsin, 2018.*

[28] *R.A. Lillie and J.W. Mason,* Limnological Characteristics of Wisconsin Lakes*, Wisconsin Department of Natural Resources Bulletin No. 138, 1983.*

Map 2.7
Pewaukee Lake Water Depth Contours



20' WATER DEPTH CONTOUR IN FEET

Note: Date of Orthophotography: April 2015

Source: Wisconsin Department of Natural Resources and SEWRPC

Retention Time refers to the average length of time needed to replace the lake's entire water volume.[29] In general, lakes with larger watershed/lake area ratios have shorter retention times. Retention time can help determine how quickly transient pollutant loads can be flushed from a lake. For example, if retention times are short, pollutants are flushed out of a lake fairly quickly. In such cases, management efforts can likely focus on pollutant and nutrient loads contributed to the lake from the watershed. In contrast, lakes with long retention times tend to accumulate nutrients and pollutants. These can eventually become concentrated in bottom sediments as opposed to flushed downstream. In this case, in addition to preventing external pollution from entering a lake, it also may be necessary to employ in-lake water quality management efforts to address pollutants not readily flushed from the lake.

With a lake-wide retention time averaging 2.3 years, Pewaukee Lake's flushing rate is slightly slower than Wisconsin statewide averages.[30] As such, apparent water quality may improve slowly if nutrients inputs to the Lake decrease. The deeper western portion of the Lake likely has a greater retention time than the overall average, reinforcing this situation in the deep western basin. Whatever the case, when it comes to maintaining or improving water quality, the importance of management actions that limit nutrient inflow from the watershed into the Lake cannot be over emphasized.

Shoreline Development Factor compares the length of a lake's shoreline to the perimeter of a perfect circle of identical area. Higher values result when lakes exhibit irregular shapes including such features as bays and peninsulas. Lakes with high shoreline development factors are commonly more biologically productive and have larger proportions of shallow nearshore areas (or *littoral zone*). Extensive littoral zones are conducive to aquatic plant growth which can grow to nuisance levels and which may impede navigation. The littoral zone generally represents the most productive habitat for plant and animal life in a lake. All other things being equal, a lake with a large shoreline development factor would be expected to have more plant and animal life than a lake having a low development factor. Given their longer shoreline lengths per acre of surface water, lakes with high shoreline development factors also commonly have greater numbers of residential lots per surface area of lake and therefore can be subjected to heavy human use pressure.

Pewaukee Lake has a shoreline development factor of 2.02, meaning that the Lake has about twice as much shoreline when compared to a perfectly circular lake. Nearby Nagawicka Lake has a similar form and a similar shoreline development factor. However, Okauchee Lake has a very irregular shape with many bays and points, and consequently has a shoreline development factor of over 3.0. The Lake's shoreline is nearly entirely developed by residential lots. Thus, the Lake is subject to significant human use pressure with a high number of lots per acre of Lake surface area.

Lake-basin bathymetry and bottom sediment composition can also influence a lake's biological productivity. To illustrate, lakes with large, nearly flat, shallows covered with soft bottom sediments are generally more biologically productive than uniformly deep lakes with rocky bottoms. As shown on Map 2.7, water depths throughout Pewaukee Lake's eastern basin are quite shallow. The eastern basin's bottom is quite flat and is composed primarily of soft sediment (silt and muck). Given these factors, Pewaukee Lake (especially the eastern half) would be expected to have moderately high biological productivity, relatively nutrient-rich water, and the ability to support abundant aquatic plant growth and a productive warmwater fishery.

Small Lakes, Wetlands, Streams, and Floodplains

Although Pewaukee Lake is the dominant surface-water feature of Waukesha County, it is not the only aquatic environment in the Pewaukee Lake watershed. A few small lakes exist in the watershed, including

[29] *The terms "flushing rate" and "hydraulic residence time" are also commonly used to describe the amount of time runoff takes to replace one lake volume. Flushing rate is the mathematic reciprocal of retention time, while hydraulic residence time is the same value as retention time. Therefore, while residence and retention time are expressed in years and have units of time, flushing rate is typically expressed as the number of times lake water is completely replaced by runoff in one year, and is therefore a rate (units/time).*

[30] *Retention times vary with prevailing weather conditions. During periods of heavy precipitation, a lake may have a lower retention time. Conversely, during drought, retention times can be longer. In Pewaukee Lake's case, the retention time may be as low at 1.3 years during prolonged wet weather and 12 years during prolonged dry weather. These values are instantaneous rate estimates at a discrete point in time. Weather conditions change, and with changing weather conditions, retention times frequently increase or decrease.*

a 3.8 acre semi-natural lake located a short distance upstream of the mouth of Coco Creek that likely formed after dam construction. Artificial lakes and ponds have been created throughout the watershed for aesthetic purposes, recreational use, stormwater management, and erosion control. These include a 14.4 acre, 16-foot deep reservoir near the headwater area of Zion Creek sometimes referred to as Salow Lake, ponds excavated within a wetland area along the lower reaches of Zion Creek, and scores of other ponds constructed throughout the watershed. The still water environments available in lakes and ponds are supplemented by marshy and low-lying areas, the largest found adjacent to the Lake's tributaries (see Map 2.8). Approximately 1,360 acres of defined wetlands are found in the Pewaukee Lake watershed.[31] Collectively, these smaller water bodies and wetlands can store appreciable volumes of floodwater, and can therefore help reduce runoff intensity.

Viewed from above, the network of water channels forming a river system typically displays a branch-like pattern as shown in Figure 2.4. A stream that flows into a larger stream or river is considered a tributary to the larger waterbody. The entire area drained by a single river system is termed a drainage basin or watershed. Streams normally increase in size in the downstream direction. In the stream order classification system, lower order streams correspond to the smaller headwater tributaries. The first visible traces of streams are labelled first-order streams. Second-order streams are formed where two first order streams converge, third order streams are formed where two second order streams converge, and so on. As water travels from headwater streams toward the mouth of larger rivers, streams gradually increase width and depth as well as the amount of water they discharge.

The Pewaukee Lake system is somewhat unusual in that six mapped tributaries converge within Pewaukee Lake. The named tributaries are the third-order Coco and Meadowbrook Creeks, second-order Zion Creek, and first-order Audley Creek. Two additional first-order streams are unnamed. One unnamed stream enters the west basin near West Lakeside Drive and another enters the east basin just south of the railroad. The physical characteristics and predicted biological community of these streams is summarized in Table 2.4. These streams contribute a significant amount of the water reaching Pewaukee Lake (see Figure 2.5), with the amount of water contributed by each mapped stream summarized in Table 2.5.

The Pewaukee River itself is a significant tributary of the upper Fox River of Southeastern Wisconsin. In fact, where the Pewaukee and Fox Rivers join, both are fourth order streams, and the Pewaukee River drains nearly a third of the combined fifth order river's watershed and contributes about a third of the combined flow. Pewaukee Lake and its headwaters comprise about two-thirds of the Pewaukee River's total watershed, and contributes up to three-quarters of its overall flow. [32]

Although dry for much of the time, floodplains are very important to water body function and health. During intense runoff periods (e.g., heavy or sustained rainfall or snowmelt), water elevations rise. Floodplains help convey, detain, and treat runoff and can help promote groundwater recharge. Mapped floodplains in the Pewaukee Lake watershed are located on Map 2.9. Approximately 797 acres of floodplain are found in the Lake's watershed.[33]

Groundwater Resources

General Principles and Importance

Groundwater includes water that has percolated into the earth and has reached areas of saturation below the Earth's surface. The free-water elevation of the shallowest saturated subsurface water-bearing media is commonly referred to as the "water table". Groundwater is not visible to casual observation except where it discharges to surface water (e.g., springs and seeps). Water in unsaturated soil above the water table can either return to the atmosphere via evapotranspiration or may move to aquifers if soil moisture increases through additional percolation from the surface.

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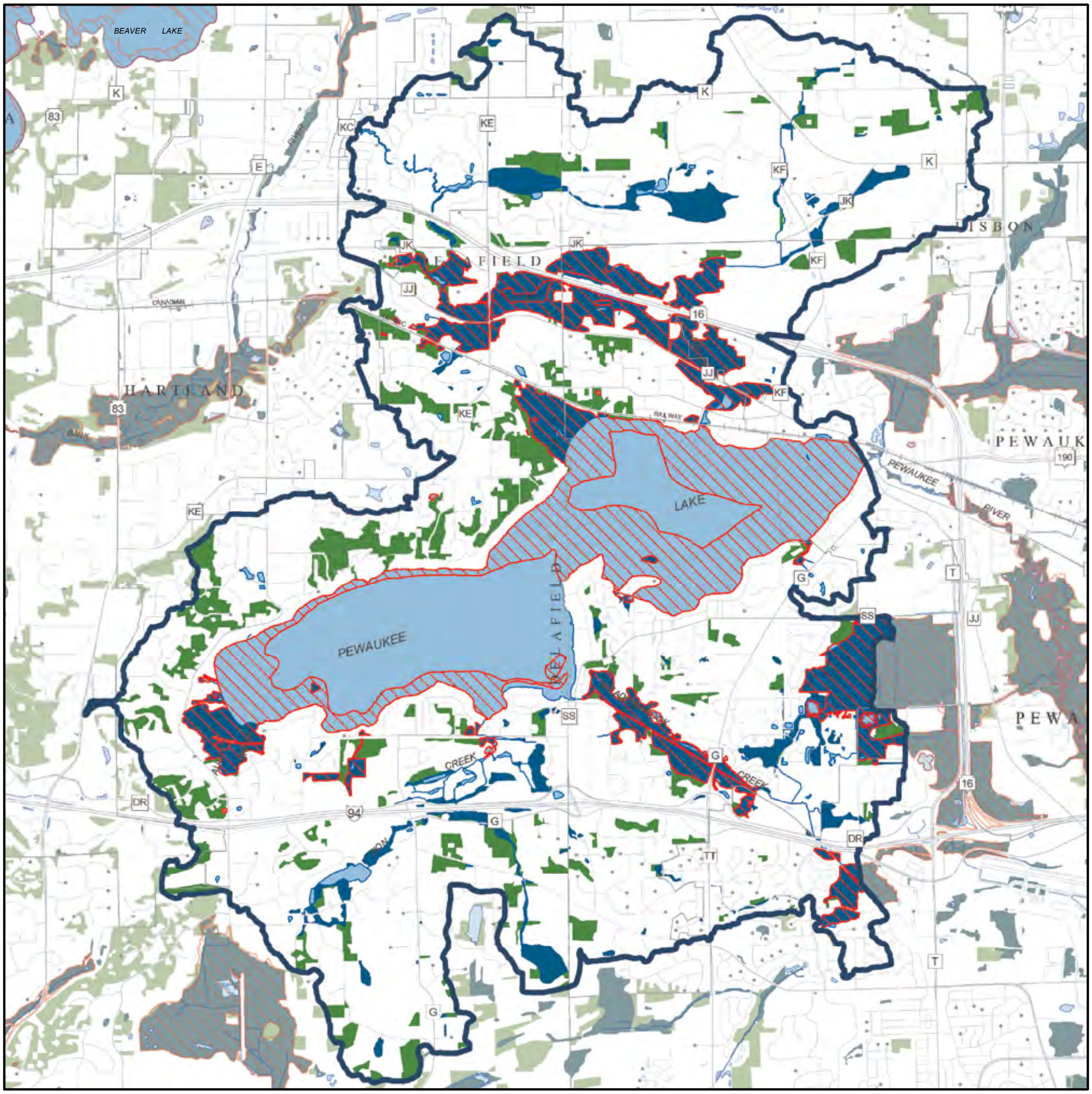
[31] *Wetlands are discussed in greater detail in the land use section of this report (see "Natural Resource Elements" in Section 2.3, "Human Use and Occupation").*

[32] *Derived from Presto-Lite Watershed Delineation Reports available through WDNR's Watershed Restoration Viewer website: dnr.wi.gov/topic/SurfaceWater/restorationviewer.*

[33] *Floodplains are discussed in greater detail in the land use section of this report (see "Natural Resource Elements" in Section 2.3, "Human Use and Occupation").*

Map 2.8
Wetlands, Woodlands and ADID Wetlands Within the Pewaukee Lake Watershed



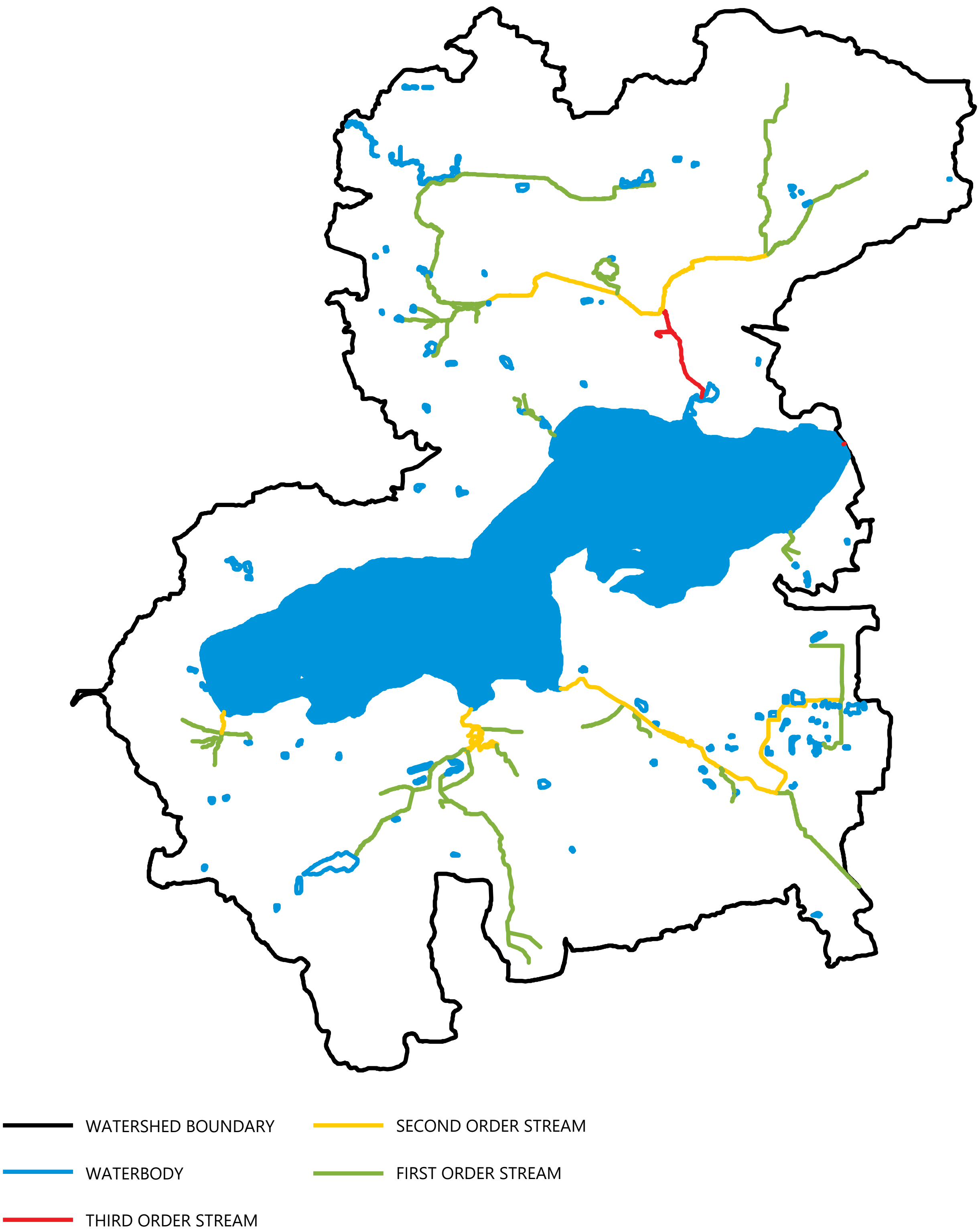
WETLANDS (2015)
WOODLANDS (2015)
ADID WETLANDS (2005)
SURFACE WATER
STREAM
WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Figure 2.4
Pewaukee Lake Tributary Network



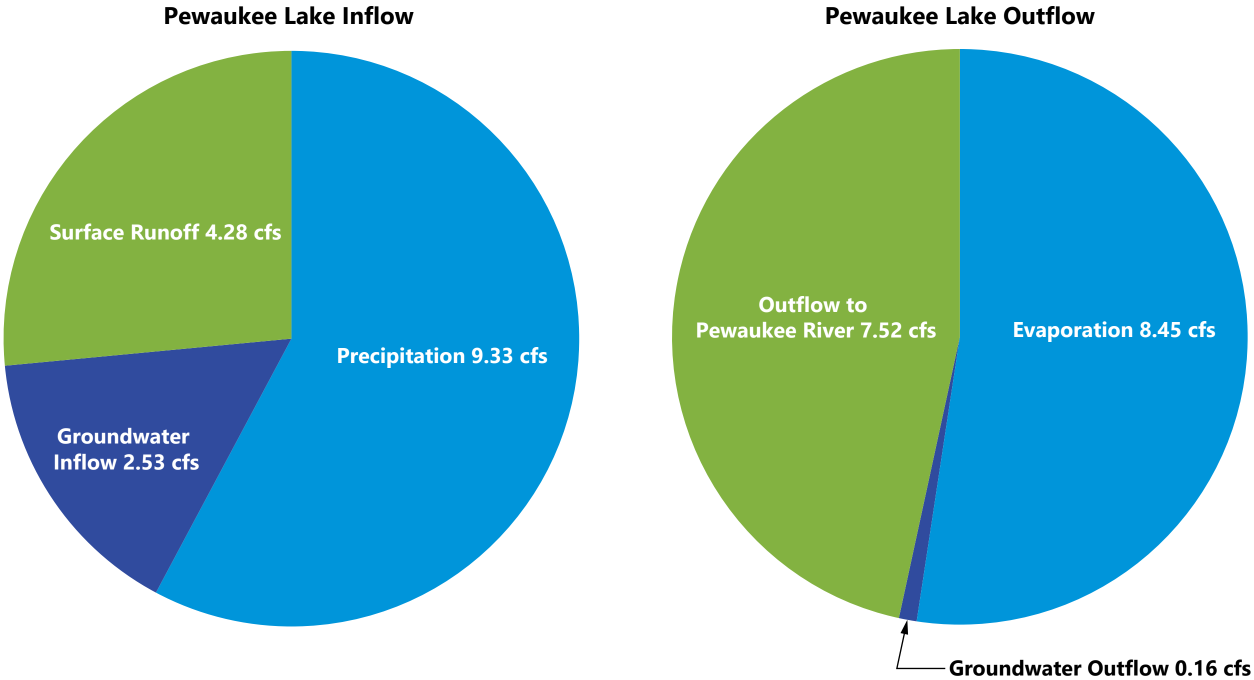
Source: SEWRPC

Table 2.4
Pewaukee Lake Tributary Characteristics and Predicted Habitat Types

			Predicted Stream Habitat Type and Channel Length (feet/percent of total stream length)				
Mapped Stream Name	**Stream Order at Mouth**	**Watershed Area (square miles)**	Coldwater	Cold Headwater	Cool-Cold Headwater	Warm Headwater	Macroinvertebrates
Audley Creek	First	0.56	1,166/100	--	--	--	--
Coco Creek	Third	8.31	3,032/16	2,277/12	9,963/54	--	3,294/18
Meadowbrook Creek	Second	5.75	--	8,222/53	--	2,400/16	4,785/31
Zion Creek	First	3.49	197/3	--	6,491/85	--	953/12
Unnamed – West Lakeside Drive	First	0.27	994/100	--	--	--	--
Unnamed – Railroad	First	0.40	--	--	236/47	--	271/53

Source: SEWRPC

Figure 2.5
Pewaukee Lake Water Budget



Note: Values devired from groundwater simulation model.

Source: U.S. Geological Survey and SEWRPC

In Southeastern Wisconsin, local precipitation is the source of most groundwater and essentially all groundwater is stored and moves in the natural pore spaces and fractures found in unconsolidated sediment and bedrock.[34] Sediment and rock units with significant porosity or fracturing are able to supply useable amounts of water over prolonged periods, and are referred to as "aquifers." Three aquifers underlie the Pewaukee Lake watershed, as summarized below in order of increasing depth from the land surface.

- **Sand and gravel aquifer**. This aquifer is primarily found in porous, coarse-grained sand and gravel deposited by glacial action. Much of the water feeding this aquifer infiltrates the land surface in the local area. Its thickness and properties vary widely, but it is an important water supply under many portions of Waukesha County. It is commonly highly vulnerable to contamination and over exploitation. Water quality and quantity can be significantly influenced by local land use change. The sand and gravel aquifer is commonly in good hydraulic communication with the underlying Niagara dolomite aquifer.

- **Niagara dolomite aquifer**. Water in this aquifer is stored and moves primarily in fractures. Much of the water found in this aquifer is derived from local stormwater infiltration. Although its water-bearing characteristics and thickness vary widely, it is a very important water supply aquifer. When located under a relatively thick layer of unconsolidated sediment, it is somewhat less vulnerable to contamination and overexploitation.

- **Sandstone aquifer.** The sandstone aquifer is commonly deeply buried and is found at depths well below the sand and gravel and Niagara dolomite aquifers. Water is stored and moves through fractures and the rock's innate porosity. This aquifer is very thick, but the water bearing characteristics vary widely with depth. A layer of low permeability Maquoketa shale which overlies the sandstone aquifer extends over the entire Pewaukee Lake watershed, thus, water recharging

[34] *A common local myth suggests that water flows in underground rivers from the far north (e.g., Lake Superior). Although a few small caves are found in Southeastern Wisconsin, they are not significant contributors to overall groundwater flow and do not extend appreciable distances.*

Table 2.5
Pewaukee Lake Tributary Flow Ranges

Mapped Stream Name	Probability of Exceeding Flow (cubic feet per second)		
	95 Percent (extremely dry weather)	50 Percent (average weather)	5 Percent (extremely wet weather)
Audley Creek	0.09	0.16	0.50
Coco Creek	0.88	2.13	12.90
Meadowbrook Creek	0.42	1.36	12.50
Zion Creek	0.58	1.16	4.18
Unnamed – West Lakeside Drive	0.03	0.06	0.25
Unnamed – Railroad	0.04	0.08	0.46
Total	2.04	4.95	30.79

Source: Wisconsin Department of Natural Resources and SEWRPC

the sandstone aquifer infiltrates through the shallow sand and gravel and dolomite aquifer to the west of the Pewaukee Lake watershed. Therefore, the sandstone aquifer is less vulnerable to local pollution sources in the watershed. The sandstone aquifer is an important public and industrial water supply, but because of the cost of establishing deep wells, is not commonly used for residential water supplies in the immediate area.

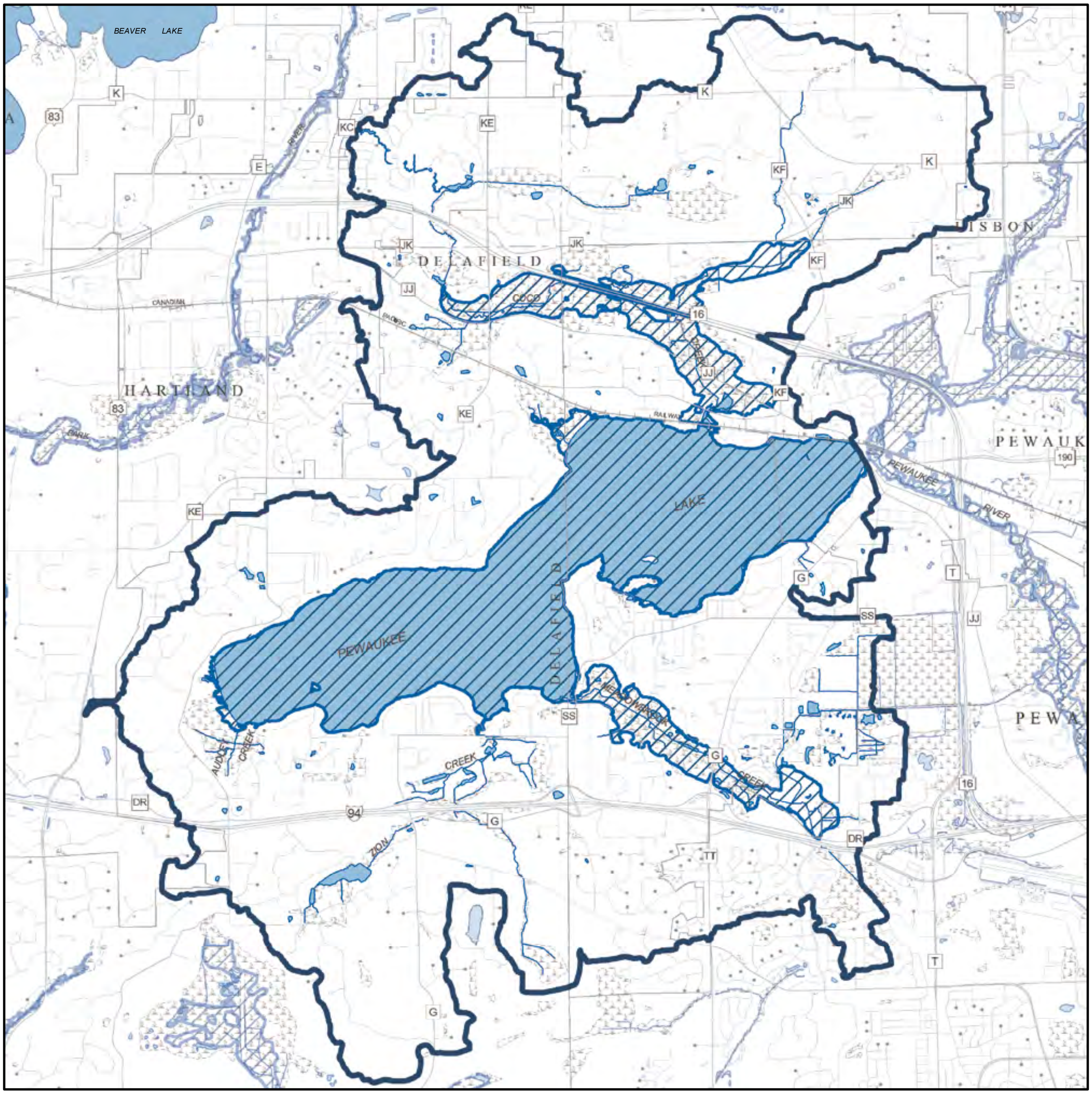
The amount, recharge, movement, and discharge of groundwater are controlled by several factors including precipitation, topography, soil permeability and structure, land use, and the lithology and water-bearing properties of rock units.

All residential, municipal, and industrial water supplies in the Pewaukee Lake watershed depend upon groundwater, making it a natural resource critical to human habitation. In general, groundwater supplies in the Region are adequate to support a growing population, agricultural demands, commerce, and viable and diverse industrial uses. However, overexploitation and attendant water shortages could occur in areas of concentrated development, nonconductive geology, and/or intensive water demand. In addition to supplying human needs, groundwater is important to the health, vitality, and overall ecology of natural systems. Groundwater sustains water levels and flow in lakes, wetlands, and perennial streams during dry weather. Groundwater systems also modulate flood flows by detaining water during wet weather. Groundwater that reaches surface waterbodies is commonly referred to as "baseflow". Baseflow can either directly enter large waterbodies, or it can enter small streams, ponds, and seeps tributary to larger waterbodies. Growing population and industry while maintaining vitality of valuable natural resource elements necessitates wisely developing and managing groundwater resources.

Baseflow sustains dry-weather Lake elevation and the flow of the perennial tributary streams. Groundwater typically contains little to no sediment or phosphorus, has a more stable temperature regimen, and commonly contains a lower overall pollutant load when compared to surface water runoff—all of which are favorable to aquatic life and the ecology of waterbodies. Groundwater-derived baseflow sustains water elevations and/or flow in many lakes, wetlands, and streams during drier weather periods. Reliable water elevations and flow regimens enables groundwater-fed waterbodies to maintain a diverse assemblage of plants and animals. Groundwater is critical to these waterbodies' ability to provide unique ecological functions. An outstanding example is the presence of trout in Coco Creek—groundwater discharging to the stream provides the cold water needed for trout to survive. Consequently, it is important to maintain baseflow from the aquifers that supply the Lake and the streams and wetlands that drain to the Lake.

Groundwater supplies are generally replenished by precipitation soaking into the ground and entering aquifers. Water that infiltrates the land surface and enters aquifers is often referred to as "groundwater recharge." Precipitation is the source of essentially all groundwater recharge, but recharge does not necessarily occur uniformly throughout the landscape, at the point where precipitation initially strikes the Earth, or uniformly throughout the year. Relatively flat undeveloped areas underlain by thick layers of granular permeable mineral soil are generally able to contribute more water to groundwater recharge, and are identified as having high or very high groundwater recharge potential. On the other hand, hilly areas underlain with low permeability (e.g., clay) soils and drained by storm sewers would likely be classified as

Map 2.9
Mapped Floodplains Within the Pewaukee Lake Watershed: 2014



ONE-PERCENT-ANNUAL-PROBABILITY (100-YEAR RECURRENCE INTERVAL) FLOODPLAIN (FEMA FIS, NOVEMBER 2014)

SURFACE WATER

WETLAND

STREAM

WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

0 1,250 2,500 5,000 Feet

Source: Federal Emergency Management Agency and SEWRPC having low recharge potential. However, it must be remembered that water running off from areas less conducive to groundwater recharge can still flow to areas more conducive to groundwater recharge and infiltrate there, becoming a component of groundwater flow. Most groundwater recharge occurs during periods of low natural water demand (i.e., when plants are dormant) and/or abundant precipitation or runoff. Little groundwater recharge occurs from small summer rains, even on the best sites, because plants and higher evaporation rates associated with higher temperatures consume the incident precipitation, returning it to the atmosphere. Evaluating groundwater recharge potential helps identify areas most important to sustainable groundwater supplies. The Commission evaluated groundwater recharge potential for all of Southeastern Wisconsin.[35] Such data can help planners decide which areas should not be covered with impervious surfaces and/or where infiltration basins would be most effective.

In most instances, the elevation of the water table is a subdued reflection of surface topography. The Commission has estimated water table elevation throughout the Region.[36] Topographically higher areas are commonly recharge areas, while lakes, wetlands, and streams are commonly groundwater discharge areas. Groundwater recharge/discharge systems occur on many spatial scales: long regional recharge/discharge relationships and short localized flow paths, both of which can be important contributors to a water body's overall water budget. While localized groundwater flow systems are commonly confined within a lake's surface watershed, regional groundwater flow paths may trace directions and distances out of phase with surface water feeding a lake. Therefore, some groundwater feeding a lake may originate in areas distant from the lake and/or outside the lake's surface watershed boundary. The relationship between short- and long-distance flow paths is illustrated in Figure 2.6.

Smaller-scale local groundwater flow paths commonly approximate surface water flow paths. However, to estimate the direction of more regionally extensive flow systems, groundwater elevation contours derived from measurements collected in water supply or monitoring wells need to be consulted. Since water normally moves perpendicular to elevation contours, groundwater flow directions can be predicted. When performing such analyses, it is necessary to consider the locations and elevations of streams, ponds, and lakes. This relationship can be used to predict if a surface water body is fed by groundwater, recharges groundwater, or has little interaction with groundwater. By combining these data, maps can be prepared identifying those land areas that likely contribute recharge and are, therefore, sources of baseflow to a surface water feature and those areas that convey groundwater directly to a lake.

As illustrated in Figure 2.6, groundwater and surface water systems are connected. Water sources include:

- **Precipitation** falling directly upon a water body. While this can be a significant water source to expansive features such as lakes and wetlands, it typically is not a significant contributor to a stream or river's total water budget

- **Surface runoff** (or overland flow) that travels over the land surface to a waterbody. Surface runoff is the primary source of wet-weather flow to most watersheds.

- **Hyporheic flow** (stream flow occurring in stream bed materials paralleling the general direction of stream flow). This is only important in streams and rivers. Hyporheic flow commonly persists even when visible stream flow ceases. Hyporheic flow initiates and sustains a large number of important geochemical and biological processes that support stream health.

- **Groundwater** is the primary source of water to most waterbodies during dry weather. In some instances, waterbodies lose water to the groundwater flow system.

Surface runoff and interflow are important during storm events, and their contributions typically are combined into a single term called the direct runoff component of streamflow. Groundwater, on the other hand, is most important for sustaining waterbodies during periods between storms and during dry times of the year and is often a substantial component of the total annual flow through a waterbody.

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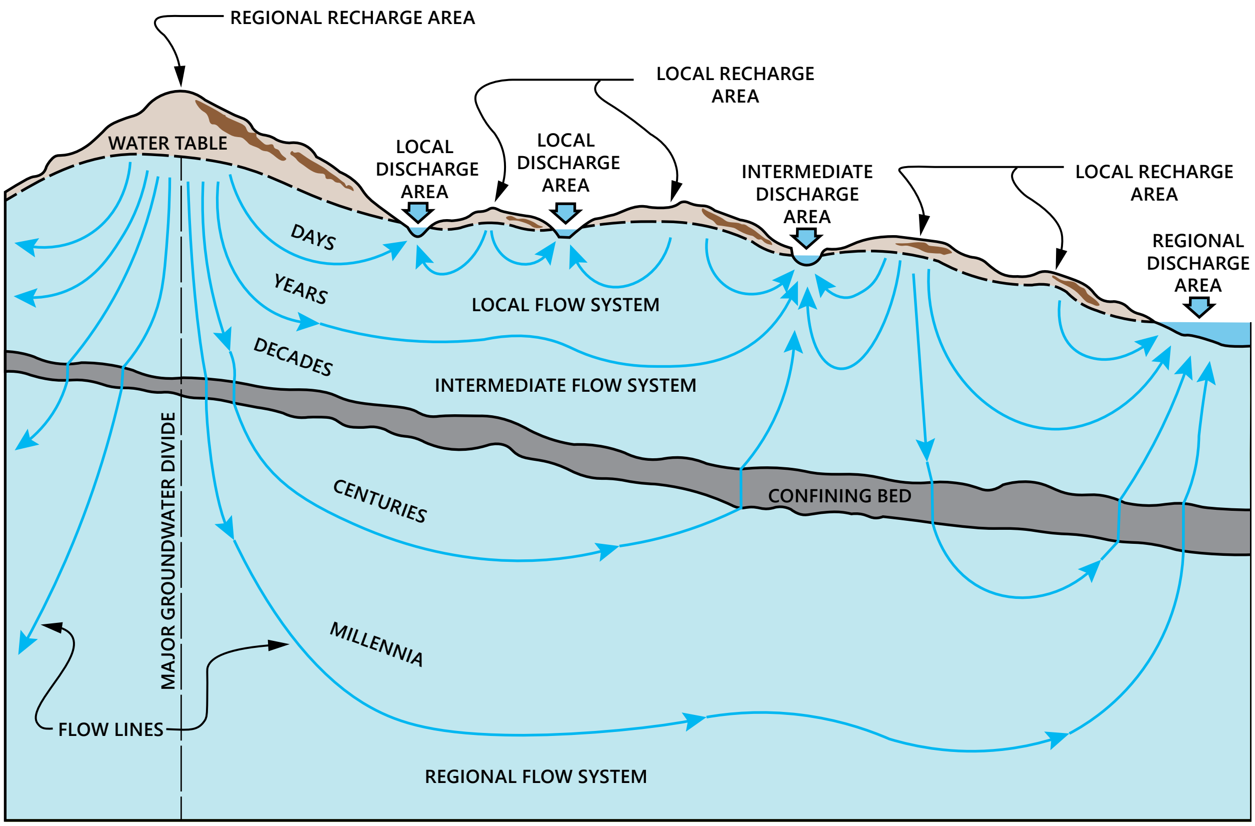
[35] *SEWRPC Technical Report No. 47,* Groundwater Recharge in Southeastern Wisconsin Estimated by a GIS-Based Water-Balance Method, *July 2008.*

[36] *SEWRPC Technical Report No. 37,* Groundwater Resources of Southeastern Wisconsin*, June 2002.*

Figure 2.6
Cross Section Depicting Local Versus Regional Goundwater Flow Paths



Source: Modified from A. Zaporozec in SEWRPC Technical Report No. 37, Groundwater Resources of Southeastern Wisconsin, *2002*

As shown in Figure 2.7, a waterbody gains water when groundwater elevations are higher than the adjacent waterbody (see Figure 2.7, "Gaining Stream"). Conversely, a perennial waterbody loses water wherever water table elevation is lower than the waterbody's elevation. In such instances, water seeps into the underlying groundwater system (see Figure 2.7, "Losing Stream"). In some instances (e.g., ephemeral streams) the water table may not be in contact with the surface water feature. Stream reaches that receive groundwater discharge are called gaining reaches and those that lose water to the underlying aquifer are called losing reaches. The rate at which water flows between a stream and its adjoining aquifer depends on the hydraulic gradient between the two waterbodies and also on the hydraulic conductivity of geologic materials that may be located at the groundwater/surface-water interface. For example, a clayey streambed will reduce the rate of flow between a stream and aquifer compared to a sandy or gravelly streambed. In the absence of surface-water contributions, streamflow volume increases along gaining reaches and decreases along losing reaches. Streams can have both gaining and losing reaches and the extent of these reaches may change based upon prevailing conditions. Since precipitation rates, evapotranspiration, water table elevations, and human-induced hydrologic stressors vary with time, a particular stream reach can switch from a gaining to a losing condition or from a losing to a gaining condition from one period of time to the next.

Groundwater is a dynamic, vital, yet often poorly understood resource. Water discharging to water bodies is replaced with water received from infiltrating precipitation, much of it in the local area. By combining data regarding groundwater recharge potential, groundwater flow direction, and the elevation of water bodies, a broad understanding of the interconnected nature of surface water and groundwater resources can be surmised. Maps can be prepared identifying land areas that more likely contribute to recharge and are, therefore, sources of baseflow to a waterbody. Such maps also can help illustrate the routes groundwater takes in the subsurface and whether a waterbody gains or loses water to the groundwater flow system. Such information helps resource managers plan where work should be focused. For example, this information can help resource managers identify parcels where action should be taken to maintain or enhance the landscape's ability to provide groundwater recharge or where features purposely designed to detain and infiltrate stormwater should be located.

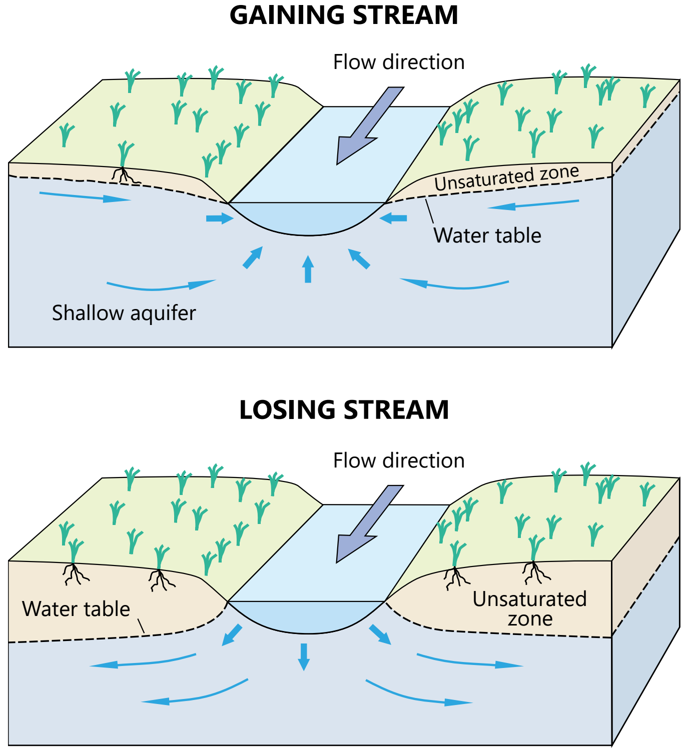
Human Influence

Humans deplete groundwater in two primary ways: 1) actively pumping water from aquifers, which reduces, or in extreme cases eliminates, natural groundwater discharge through springs and seeps, and 2) reducing groundwater recharge through land use changes that increase impervious cover and/or hasten runoff.

Development's Effects on Groundwater

Land use can profoundly alter the ability for an area to absorb water and contribute to groundwater recharge. Urban development decreases groundwater recharge potential. Most areas developed greater than 30 years ago route stormwater runoff directly to surface waters, discouraging groundwater recharge. Despite requirements of Chapter NR 151, "Runoff Management," of the *Wisconsin Administrative Code* calling to detain/infiltrate runoff from new developments, where practicable, such developments still have the cumulative effect of reducing groundwater recharge compared to pre-development conditions. In addition to reducing groundwater recharge, urban development places additional demand on groundwater supplies as water is extracted for various uses. Removing water from natural groundwater flowpaths reduces groundwater elevations and the volume of natural groundwater discharge to surface waterbodies.

Figure 2.7
Surface-Water/Groundwater Interaction



Source: Modified from T.C. Winter, J.W. Harvey, O.L. Franke, and W.M. Alley, Ground Water and Surface Water: A Single Resource, *U.S. Geological Survey Circular 1139, p. 9, 1998, and SEWRPC*

Depletion through artificial groundwater abstraction most commonly occurs when high-capacity wells, numerous smaller wells, or dewatering systems are operated without considering the effect pumping may have on naturally occurring groundwater discharge areas. Wells developed in the shallow aquifers often provide sufficient yield, but can negatively impact nearby surface water resources, and are generally more vulnerable to contamination than deeper bedrock wells. Communities tapping the shallow aquifer also face choices between using individual low-capacity household wells or developing a municipal water system with homeowners connecting to high-capacity municipal wells. In some cases, these communities have an overall negative groundwater balance because wastewater treatment plant effluent is pumped to discharge points outside of the watershed. In cases where development of high capacity wells in the shallow aquifer could negatively affect surface water resources, the Commission's regional water supply plan recommends conducting studies to evaluate the potential negative effects.[37] The plan also calls for installing systems to enhance infiltration in areas where such studies indicate a potential significant reduction in baseflow to surface waters.

Groundwater recharge can be reduced in many ways. Examples include hastening stormwater runoff, eliminating native vegetative cover and reducing soil's ability to absorb water (e.g., compaction, disrupted structure), ditching, tiling and otherwise draining wet areas, disconnecting floodplains from streams, and increasing the amount of impervious land cover all contribute to reduced stormwater infiltration, increased runoff, and reduced groundwater recharge. Similarly, if sanitary sewers are installed in areas now served by private onsite wastewater treatment systems, much of the water that currently re-enters the shallow aquifer is often conveyed to downstream discharge points outside of the watershed, a condition that could reduce

[37] *SEWRPC Planning Report No. 52,* A Regional Water Supply Plan for Southeastern Wisconsin*, December 2010.*

the volume of groundwater entering a lake or stream. Development and land management activities need to consider groundwater recharge, and actions to protect and enhance recharge should be a priority. Some communities have passed groundwater ordinances to protect precious resource elements and help assure groundwater supplies are sustainable in the long term.[38]

Waterbody Depletion

Although groundwater generally provides a safe and reliable source of potable water, groundwater extraction can seriously and adversely affect desirable, life-cycle critical, aquatic habitat. One of the most visible effects is reduced dry-weather flow and water levels in hydraulically connected lakes and streams—a process called depletion. Depletion stems from reduced discharge to springs and seeps feeding these waterbodies and has the potential to impact lakes, ponds, streams, rivers, and wetlands. The complex interconnection and interaction between surface and groundwater makes managing depletion challenging, particularly because significant delays may occur from the time when extraction begins to the time when the effects of that extraction are discerned in affected waterbodies. Other complicating factors may confound analysis and influence the timing, rate, and location of depletion. Nonetheless, managers should keep in mind several important factors when studying the relationship between surface-water features and groundwater pumping, including the following:

- Individual wells may not produce noticeable change. However, well clusters and/or unfavorable aquifer properties can combine to significantly decrease groundwater discharge to surface-water features.

- Basin-wide groundwater development typically occurs over a period of several decades. Therefore, resulting cumulative depletion effects may not manifest themselves for decades.

- Depletion may persist for extended periods of time after groundwater withdrawal ends. Aquifers take time to recover from long-term extraction stress. In some aquifers, maximum depletion may occur long after pumping stops, and full recovery of the groundwater system may take decades to centuries.

- Depletion can affect water quality in surface-water features and/or the aquifer. For example, in many streams, groundwater discharge sustains year-round habitat for fish and other aquatic organisms, by moderating seasonal temperature fluctuations, cooling stream temperatures in summer and warming stream temperatures in winter. Reduced groundwater discharge can degrade these moderating influences.

- Major factors affecting depletion timing and intensity are distance from a well to the stream and aquifer properties.

- Decreased discharge may be more isolated to certain waterbodies or waterbody segments or may be pervasive throughout the watershed.

Sustainable groundwater utilization does not solely depend on the rates at which groundwater systems are naturally replenished (recharged). Instead, sustainable pumping rates must consider myriad factors including aquifer properties, groundwater elevations, surface-water features, biologically acceptable minimum stream flows, and the wishes of the general public and regulatory agencies. These considerations underscore the need to employ an interdisciplinary approach that simultaneously considers both surface-water features and groundwater supplies.

An example of unsustainable groundwater use is extraction from the deep sandstone aquifer. Water levels in the deep sandstone aquifer were once above the ground surface, meaning that water rose to above the ground without pumping. The quality and abundance of this resource made it a prime target for large volume wells. On account of heavy withdrawals throughout the region, this aquifer's water levels have

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[38] *The Village of Richfield in Washington County passed a groundwater protection ordinance over 10 years ago and uses the ordinance as a tool to regulate development that is consistent with long-term sustainability. More information about Richfield's groundwater ordinance can be found at the following website: www.richfieldwi.gov/index.aspx?NID=300.*

declined hundreds of feet since the 1800s, as shown in Figure 2.8, "Figure A." In much of the Region, including the Pewaukee Lake watershed, water movement from the shallow sand and gravel and dolomite aquifer into the deep sandstone aquifer is limited by the low permeability Maquoketa shale aquitard, a rock layer which forms a relatively impermeable barrier between the two aquifers and direct surface recharge. As a result, the rates of local groundwater recharge to the deep aquifer are much less than the rates that water is being extracted by pumping. The drawdowns of the deep aquifer are indicative of a water budget deficit and are the combined result of pumping primarily in Southeastern Wisconsin and Northeastern Illinois. In contrast, drawdowns in the shallow aquifer throughout the Region are much smaller (see Figure 2.8, "Figure B") despite the fact that nearly twice the amount of water is being extracted from it compared to the deep aquifer. The reason for the lower drawdowns is that the shallow aquifer is unconfined in most places. It receives direct recharge from precipitation and is also linked directly to surface waterbodies.

Management Tools – Plans and Models

The Commission developed a water supply system plan for the Southeastern Wisconsin Region.[39] This plan considers existing water demands, future development, sustainability, and protection of natural resource features. This plan is the third component of the Commission's regional water supply planning program. The other two elements were a groundwater resource inventory and a regional groundwater model.[40,41] The regional aquifer simulation model allows water levels in the deep and shallow aquifers under historical, current, and planned conditions to be predicted and allows the effects of different groundwater management alternatives on surface water resources to be simulated. Additionally, the model provides a framework within which more-detailed "inset" models may be developed to investigate site-specific groundwater-related questions, including the possible effects of high capacity wells on surface water resources. In summary, the model provides the capability of addressing the following questions:

- What is the sustainable capacity of an aquifer to supply human needs?
- How much have humans altered the groundwater system?
- What effect does human groundwater system alteration have on surface waters?

It is important to note that while the resolution of the regional groundwater models was considered sufficient and valid to compare differences in alternative plans, it may not be sufficiently fine to predict site-specific impacts, or may not be able to resolve differences in impacts between surface water or groundwater features that are in close proximity to one another.[42] Simulating conditions over a relatively small area such as the Pewaukee Lake watershed would require a refined model that includes more detailed site-specific hydrogeological data and smaller model cell size. As noted previously, in cases where development of high capacity wells in the shallow aquifer could negatively affect surface water resources, the Commission regional water supply plan recommends conducting detailed site-specific studies to evaluate potential negative effects and installing enhanced rainfall infiltration systems in areas where such studies indicate a potential significant reduction in baseflow to surface waters.

One of the most accessible and effective tools developed as part of the water supply planning effort is the groundwater recharge potential map derived from a soil-water balance recharge model developed for the Southeastern Wisconsin Region. Understanding groundwater recharge potential and its distribution on the landscape are key to making informed land use decisions that jointly consider human and environmental groundwater needs. Unlike the regional model discussed above, groundwater recharge potential maps are plotted at a significantly smaller grid size (about 100 feet on a side) and can therefore be directly employed for local level groundwater planning purposes. Therefore, these groundwater recharge potential

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[39] *Ibid.*

[40] *SEWRPC No. 37, June 2002,* op. cit.

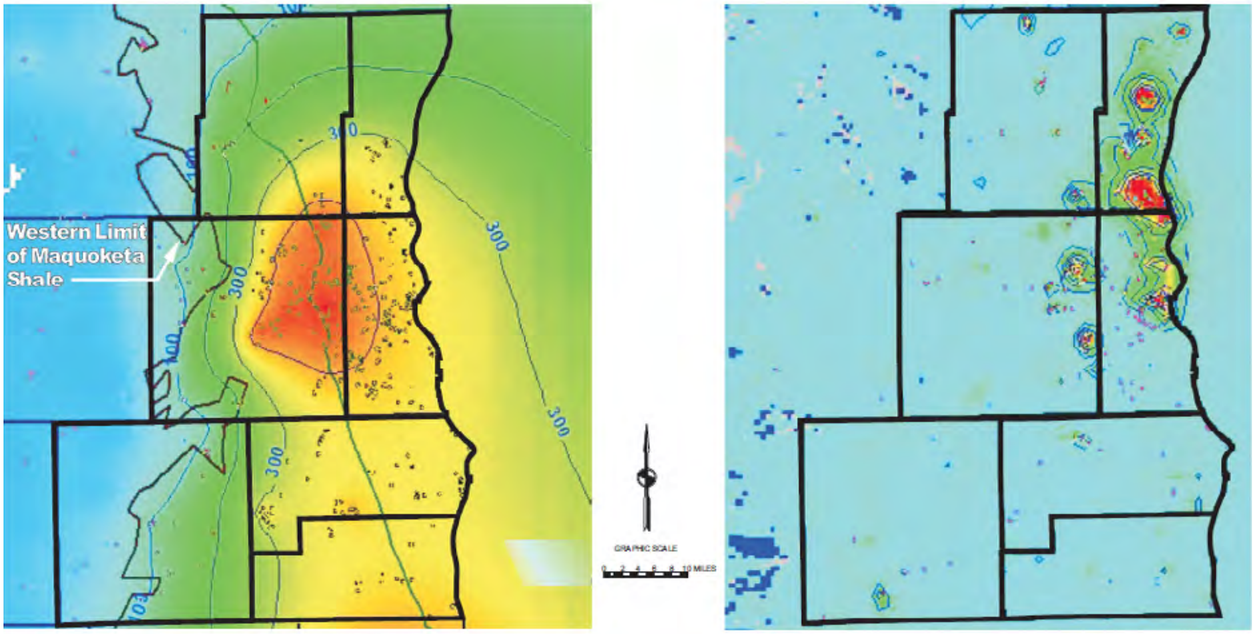
[41] *SEWRPC Technical Report No. 41,* A Regional Aquifer Simulation Model for Southeastern Wisconsin*, June 2005.*

[42] *Since the average grid cell size of the groundwater simulation model is over one-quarter square mile (about 2,500 feet on a side), the results from this regional modeling effort are not sufficiently detailed to estimate the impact of groundwater withdrawal on a site-specific basis. In other words, this regional model cannot specifically be used for local level groundwater supply planning purposes for the Pewaukee Lake watershed, because this area is too small.*

Figure 2.8
Simulated Groundwater Drawdowns for the Region

Figure A: Deep Aquifer – the red zones shows areas where pumping has depressed natural groundwater pressure head by more than 400 feet. In many areas, the deep aquifer naturally had pressure sufficient to produce artesian conditions.

Figure B: Shallow Aquifer – the red zones are areas where pumping has depressed the water table by more than 50 feet.



Source: U.S. Geological Survey, Wisconsin Geological and Natural History Survey, and SEWRPC Technical Report No. 46, Groundwater Budget Indices and Their Use in Assessing Water Supply Plans for Southeastern Wisconsin, *February 2010*

maps are generally applicable to the Pewaukee Lake watershed for identifying and protecting recharge areas that contribute most to baseflow of the lakes, streams, springs, and wetlands in the watershed, which is important to the goals of sustainable groundwater use and a healthy natural environment.

In summary, sustainable groundwater supplies provide reliable, high-quality water that supports both short-term and long-term needs and desires. Reliable water supplies support existing and new development, avoid undue influence on existing wells and natural groundwater discharge areas, and avoid reduced groundwater discharge or adulterated quality that could affect treasured and sensitive natural resource features.

<u>Groundwater Conditions in the Pewaukee Lake Watershed</u>

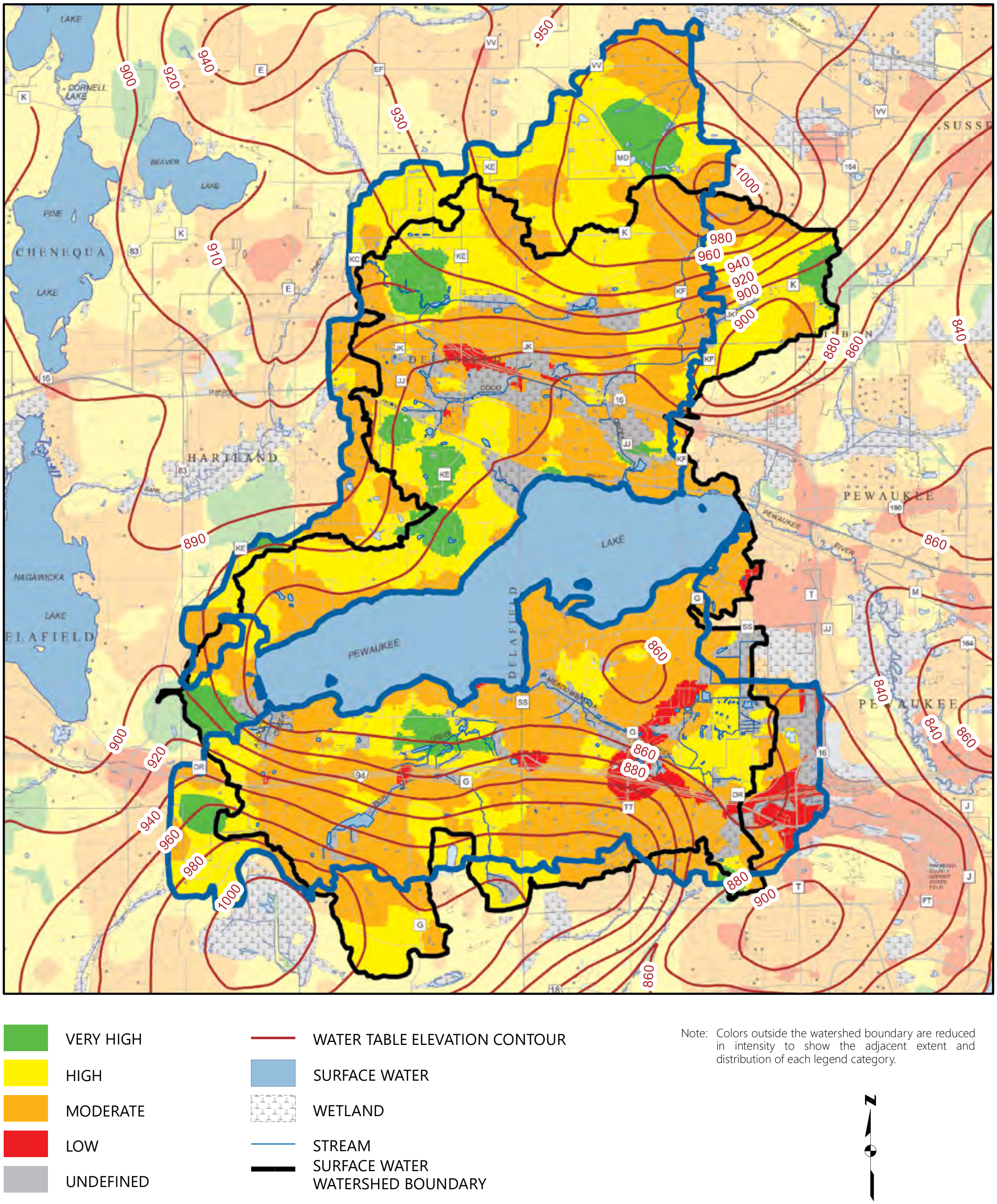
To help determine *where* management efforts could best protect groundwater recharge to aquifers feeding Pewaukee Lake, Commission staff analyzed groundwater elevation contours and groundwater recharge potential in the areas surrounding the Lake.[43] This inventory was not confined to the surface watershed (as was the case for the other inventories completed in this report) because the groundwater flow paths may extend outside of the surface-water watershed. The results of these inventories are described below.

Shallow groundwater elevation contours for the Pewaukee Lake area are shown in Map 2.10. Depth to groundwater varies considerably across the landscape. In and near waterbodies and wetlands, groundwater is found near the land surface, whereas it can be 150 feet or more below the land's surface in upland areas.[44] Pewaukee Lake lies in a prominent embayment in local water table contours, meaning that the Lake is a significant groundwater discharge area. Groundwater monitoring wells installed as part of an earlier study

[43] *SEWRPC Planning Report No. 52, December 2010,* op. cit.

[44] *The depth to groundwater for a particular area can be estimated by subtracting groundwater elevation values from surface topography values.*

Map 2.10
Groundwater Elevation Contours and Recharge Potential Within the Pewaukee Lake Groundwatershed



Source: Wisconsin Geological and Natural History Survey and SEWRPC confirmed that groundwater discharged to the Lake in all areas except near the eastern end of the lake.[45] Based upon groundwater contour lines, springs and seeps are likely especially prevalent along the north, west, and southwest portions of the Lake.

The groundwatershed depicted on Map 2.10 is based upon the USGS MODFLOW model. The Commission recently completed research regarding the groundwater flow direction in the Bark River watershed upstream of Nagawicka Lake.[46] Groundwater contours examined as part of this study strongly suggest that the Pewaukee Lake groundwatershed extends slightly farther west in the Hartland area than suggested by the USGS groundwater model. Of most interest to the Pewaukee Lake study is the strong implication that the Bark River loses surface water to the groundwater flow system under parts of the Village of Hartland. Some of this Bark River sourced water appears to contribute to springs and seeps emerging along Pewaukee Lake's northwest shoreline and the headwaters of Coco Creek, both of which are noted as strong groundwater discharge areas. This suggests that stormwater infiltration practices implemented by the Village of Hartland in the southeast portion of their community could increase the volume of groundwater discharging to Pewaukee Lake and Coco Creek. Another example of the potentially larger groundwatershed is the narrow area directly to the west of Pewaukee Lake that has not been included in the groundwatershed by the USGS MODFLOW model. Instead, the model suggests that Pewaukee Lake water seeps into the Lake bottom and is contributed to the Nagawicka Lake watershed in this area. Given the groundwater elevation contours in the area, this scenario is unlikely.

A water balance study completed during the late 1970s concluded that groundwater contributes roughly 2000 acre-feet of water directly to the Lake each year. Furthermore, about 600 acre-feet of Lake water infiltrate into the Lake bottom near the Lake's outlet each year.[47] The USGS completed a groundwater flow model of the entire area.[48] The model suggests that groundwater contributes 1800 acre-feet of water to Pewaukee Lake each year, a value that agrees well with the 1970s water balance study.

The Lake's tributary streams also receive a large percentage of their flow from groundwater, and therefore indirectly contribute large volumes of groundwater to the Lake. Water balance studies suggest that tributary streams indirectly contribute almost 6,000 acre-feet of water to the lake each year. Based upon hydrographs and flow statistics compiled at the nearby USGS gage on the Bark River, roughly half (i.e., 3,000 acre-feet per year) of the water entering the Lake through tributary streams is likely groundwater. Therefore, on an overall basis, groundwater likely provides roughly 5,000 acre-feet of water to the Lake during a typical year.

Evaluating groundwater recharge potential helps identify areas most important to sustainable groundwater supplies. The Commission evaluated groundwater recharge potential for all of Southeastern Wisconsin.[49] The distribution of various groundwater recharge potential categories for the entire Pewaukee Lake watershed is illustrated in Map 2.10. Such data can help planners decide which areas should not be covered with impervious surfaces and/or where infiltration basins would be most effective. The Upper Fox River Basin model is calibrated to observed watershed conditions, and incorporates recharge rates ranging from 2.6 to 3.9 inches per year for the Pewaukee River watershed, which is consistent with previous studies for this part of Waukesha County.[50,51] These long-term average recharge rates are estimates, not associated with data collected any given year, and thus can greatly vary between seasons and years.

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[45] *SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* A Lake Management Plan for Pewaukee Lake, Waukesha County, Wisconsin*, May 2003.*

[46] *SEWRPC Community Assistance Planning Report No. 262, 2nd Edition,* A Lake Management Plan for Nagawicka Lake, Waukesha County*,* Wisconsin*, in press.*

[47] *Ibid.*

[48] *Feinstein et al., 2012,* op. cit.

[49] *SEWRPC Technical Report No. 47,* op. cit.

[50] *SEWRPC Technical Report No. 48,* Shallow Groundwater Quantity Sustainability Analysis Demonstration For The Southeastern Wisconsin Region*, November 2009.*

[51] *It is important to note that Pewaukee Lake was assigned a recharge rate of zero, because it is considered a groundwater discharge area and is therefore not a source for groundwater recharge.*

Notwithstanding controversy regarding the extent of the groundwatershed, the groundwater recharge area to the north of the Lake is not only the largest area, it is the also the area underlain by the highest percentage of high and very high recharge potential soils and is the area with the most undeveloped land. This area is critical to sustaining the recharge supplying groundwater to Coco Creek. Coco Creek's existing and regionally uncommon trout population is highly dependent on abundant groundwater discharge to the Creek. In addition to supporting groundwater dependent and unique natural resource elements, groundwater recharge areas supply potable water to all wells in the watershed. Without sufficient recharge, groundwater elevations fall, a situation that can compromise the utility of existing pumps and wells. This is especially important to the relatively shallow wells commonly used for household water supply.

Preserving and enhancing recharge potential within the groundwatershed, especially in the areas identified as having high and very high recharge potential, is essential to protecting the groundwater feeding the Lake and its tributaries. High and very high recharge potential sites should remain substantially open and may provide ideal sites to position stormwater infrastructure designed to infiltrate detained stormwater.[52] Infiltrating stormwater helps reduce peak flows and increases cool, high quality baseflow to waterbodies during dry periods, conditions that generally improve waterbody health.

Numerous wells are found throughout the watershed, with clusters centering on highly developed areas such as within the Cities of Pewaukee and Hartland and the Village of Pewaukee. All wells, as well as other human-induced groundwater abstraction such as quarry dewatering, diverts groundwater from natural discharge points, can reduce the flow of springs, seeps, and streams. Therefore, human demands placed on groundwater supplies should be considered as part of lake management planning.

To comprehend the potential impact of wells on groundwater supplies, consider that the Village of Hartland pumped an average of nearly 1,000,000 gallons per day during 2018 (roughly equal to 1.5 cubic feet per second). At that time, the Village pumped water from five wells, four located within or near the Pewaukee Lake groundwatershed and all drawing from sand and gravel layers less than 100 feet below the ground surface, the same aquifer that supplies water to Pewaukee Lake and its tributaries. Most water provided by the Village of Hartland ultimately is discharged to sanitary sewers that export water from the Pewaukee Lake watershed. The volume of exported water (roughly 1. 5 cubic feet per second) is significant when compared to the average water discharged from the Pewaukee Lake outlet (7.5 to 20.6 cubic feet per second), and is especially significant during periods of drought when average outlet flows can decline to less than four cubic feet per second. The Village of Hartland is not the sole operator of high capacity wells in the Pewaukee Lake groundwatershed. High capacity wells also extract groundwater for public and private water supplies. Furthermore, based upon the reported proportions of groundwater withdrawal in Waukesha County, it is likely that private domestic wells located within the Pewaukee River watershed can account for at least 25 percent of the total local groundwater supply from the shallow aquifers.[53] Modeling assumed that the majority of domestic pumping is returned to the shallow aquifer via mound and/or septic system infiltration, which is not likely to be the case in much of the Pewaukee Lake watershed. Therefore, depletion modeling may underestimate total demand.

Quarry dewatering can also influence water table elevations over large areas. For example the quarry operations near Sussex create pronounced cones of depression, and likely redirect a portion of the flow that would otherwise discharge to Coco Creek. As such, the quarry operations may affect groundwater discharge to the northeastern branch of Coco Creek.

Most of the Pewaukee Lake watershed is either served or is planned to be served by public sewers (see Map 2.11). All wastewater discharged to public sanitary sewers is exported from the watershed. Since the water discharged to sanitary sewers originates as groundwater drawn from within the watershed, human water use in areas served by public wastewater collection systems represents a significant net artificial demand placed upon the groundwater flow system feeding waterbodies in the Pewaukee Lake watershed. This decreases the volume of groundwater discharges to the watershed's waterbodies.

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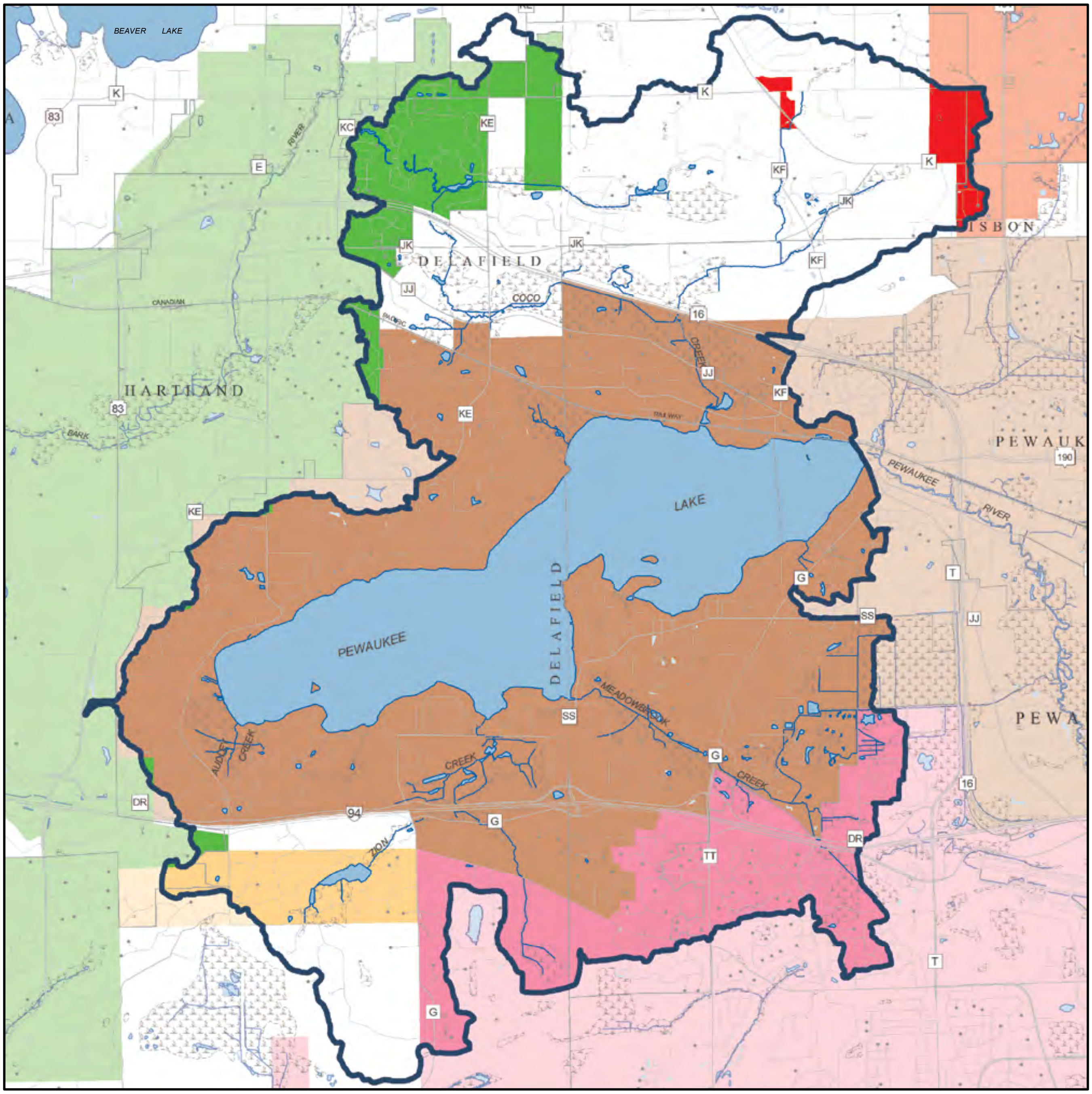
[52] *Care needs to be taken to infiltrate water that does not degrade the quality of groundwater resources. More information regarding stormwater infiltration is available from many sources, including the following website: learningstore.uwex.edu/assets/pdfs/g3691-3.pdf.*

[53] *Feinstein et al., 2012,* op. cit.

Map 2.11
Adopted Sanitary Sewer Service Areas Within the Pewaukee Lake Watershed: 2019



CITY OF WAUKESHA

CITY OF WAUKESHA OR FOX RIVER WATER POLLUTION CONTROL COMMISSION

FOX RIVER WATER POLLUTION CONTROL COMMISSION

DELAFIELD-HARTLAND WATER POLLUTION CONTROL COMMISSION

VILLAGE OF SUSSEX

SURFACE WATER

WETLAND

STREAM

WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Since the Lake's water surface elevation is reportedly remaining within a desirable ranges during dry weather, groundwater pumping and impervious surfaces apparently have not yet unduly reduced baseflow to the Lake. Nevertheless, since groundwater flow systems react only slowly to change, decreases in baseflow may only be noticeable with time, and vigilance is warranted. Consequently, to maintain groundwater baseflow to the Lake and its tributary waterbodies, it is necessary to identify both high priority groundwater recharge areas for protection and watershed-wide practices that enhance recharge in all areas.

Groundwater is the water supply for all of the residences, agriculture, and industry within the Pewaukee Lake watershed. Additionally, it is a critical source of cool, clean water to the Lake and its tributaries; maintaining surface water elevations and stream baseflow during dry periods. However, human activities can imperil groundwater resources, particularly by depleting groundwater through increased demand and constructing impervious surfaces on high groundwater recharge areas. The loss of high recharge areas with increased urban development in the area will continue to place greater stress on groundwater supply within the watershed. Discussion of these problems and associated management recommendations are provided in Section 3.2, "Hydrology/Water Quantity."

2.3 HUMAN USE AND OCCUPATION

The health of a lake or stream is usually a direct reflection of the use and management of the lands surrounding the lake (i.e., the lake's watershed). This section should be used to better understand conditions within the watershed in order to identify potential sources of pollution and determine target areas for watershed management efforts. It can also provide context for understanding water quality data within the Lake.

Watershed land use and population density are important considerations for water quality management. Environmental stressors, such as soil erosion and water pollution, are often the result of human activities within a Lake's watershed. These environmental stressors become especially significant in areas that are in close proximity to lakes, wetlands, and streams where user conflicts can occur.

Cultural History

Humans first occupied Southeastern Wisconsin a few thousand years after glaciers retreated from the area. Several American Indian cultures rose and declined over the millennia. While some Indian cultures were subsistence hunter-gatherer cultures and modified the natural landscape to a very limited degree, others practiced agriculture and modified the native vegetation using fire to promote agricultural and favorable game conditions. Native Americans frequented the lakes of Waukesha County for thousands of years before European settlement. The meaning of the name "Pewaukee" is uncertain, with sources suggesting a meaning of "swampy" in the Ojibwa language,[54] a potential allusion to the extensive wetland that once occupied the Lake's east basin. However, other sources suggest that "Pewaukee" means "lake of shells" in Potawatomi or "place of flint" in Menominee.[55]

Although a few European adventurers, missionaries, trappers and traders had frequented the area since the 1600s, the 1800s witnessed the first great influx of European settlers to the Pewaukee Lake area. These settlers brought sweeping changes to the natural environment. The first Europeans settled in the vicinity of Pewaukee Lake during the 1830s.

As native forests and prairies were converted for agricultural use, and as more people settled in the area, public infrastructure was developed. A plank road along the north shore of Pewaukee Lake was proposed in 1844 and constructed in 1848 (see Figure 2.9) at a cost of $2000 per mile. It was at this time (1848) that Wisconsin became a State and the Village of Pewaukee was incorporated. As the area around Pewaukee Lake was settled and word of the Lake's natural beauty and commercial potential became more widely known, development pressure increased. A railroad was completed in 1855 (Figure 2.10) which resulted in an influx of settlers and visitors. By 1873, the first large passenger boat on the Lake, the sidewheeler "Lady of the Lake" (Figure 2.11), was brought to the Lake by Colonel N.P. Iglehardt and began steaming the waters of the Lake under the direction of Captain Henry Davy.

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[54] *V.J. Vogel,* Indian Names on Wisconsin's Map*, The University of Wisconsin Press, 1991.*

[55] *E. Callary,* Place Names of Wisconsin*, The University of Wisconsin Press*, *2016*.

Increased commercial activity included establishment of robust ice harvesting businesses.[56] In 1878, the first icehouse (owned by Best Brewery of Milwaukee) was constructed on the north shore of Pewaukee Lake. Ice harvesters cut ice from the Lake and shipped it by rail to Milwaukee for use by the brewing and meat packing industries. The rail station used for loading Pewaukee ice onto trains was jokingly dubbed "Alaska." The Lake was known for its high quality "contact grade" ice. Contact grade refers to high clarity and purity such that it could be in direct contact with food or beverages, and is a testament to the water quality of the Lake during this period of time. As evidence of the enormity of the ice business on Pewaukee Lake at that time, the Wisconsin Lakes Ice and Coal Company put 500 ice cutters and handlers to work on Pewaukee Lake to harvest the winter ice with expectations of storing at least 250,000 tons of ice for Milwaukee consumption. By the early 1920s, the large scale commercial ice industry came to an end as mechanical refrigeration became widespread.

In 1888, Christopher Starke conducted the first dredging activities in Pewaukee Lake, using a steam dredge to create a peninsula of land (Starke's Peninsula – see Figure 2.12) for a housing development on the Lake's south shore. By 1890, most shoreline areas along the Lake's western end had been developed for residential use, although agriculture remained the dominant land use in the Lake's watershed. Also in 1890, portions of Meadowbrook Creek were straightened to accommodate construction of an electric rail line. In 1894, the Waukesha Beach amusement park opened on the southern shore of the Lake and Milwaukee Electric began operating electric rail service to and from Milwaukee, a service that continued until 1948 (Figure 2.13). Significant urban development in the Pewaukee Lake watershed began around 1900 and continued with a burst of development from 1920 through 1940. The Waukesha Beach amusement park closed in 1949.

Around this time, Lake users and residents recognized that water quality was deteriorating, which inspired formation of Lake resident organizations, such as the Pewaukee Lake Advancement Association. In 1943, an organizational meeting was held to consider creation of the LPSD to more formally address

[56] *L.E. Lawrence, "The Wisconsin Ice Trade,"* Wisconsin Magazine of History*, 48(4), Summer 1965.*

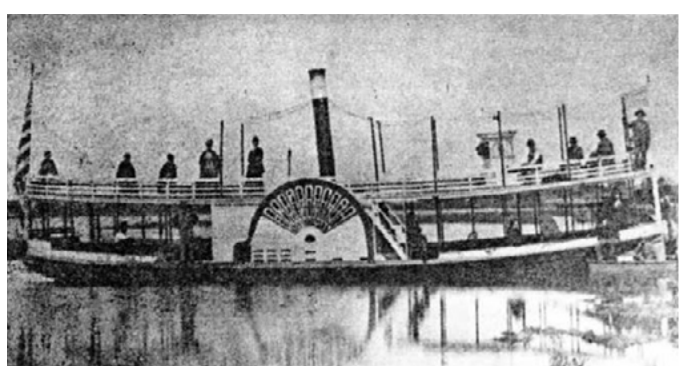
Figure 2.9
Artist Conception of Building the Plank Road

Source: Lake Pewaukee Sanitary District and SEWRPC

Figure 2.10
The Railroad Comes to Pewaukee Lake: 1855

Source: Lake Pewaukee Sanitary District and SEWRPC

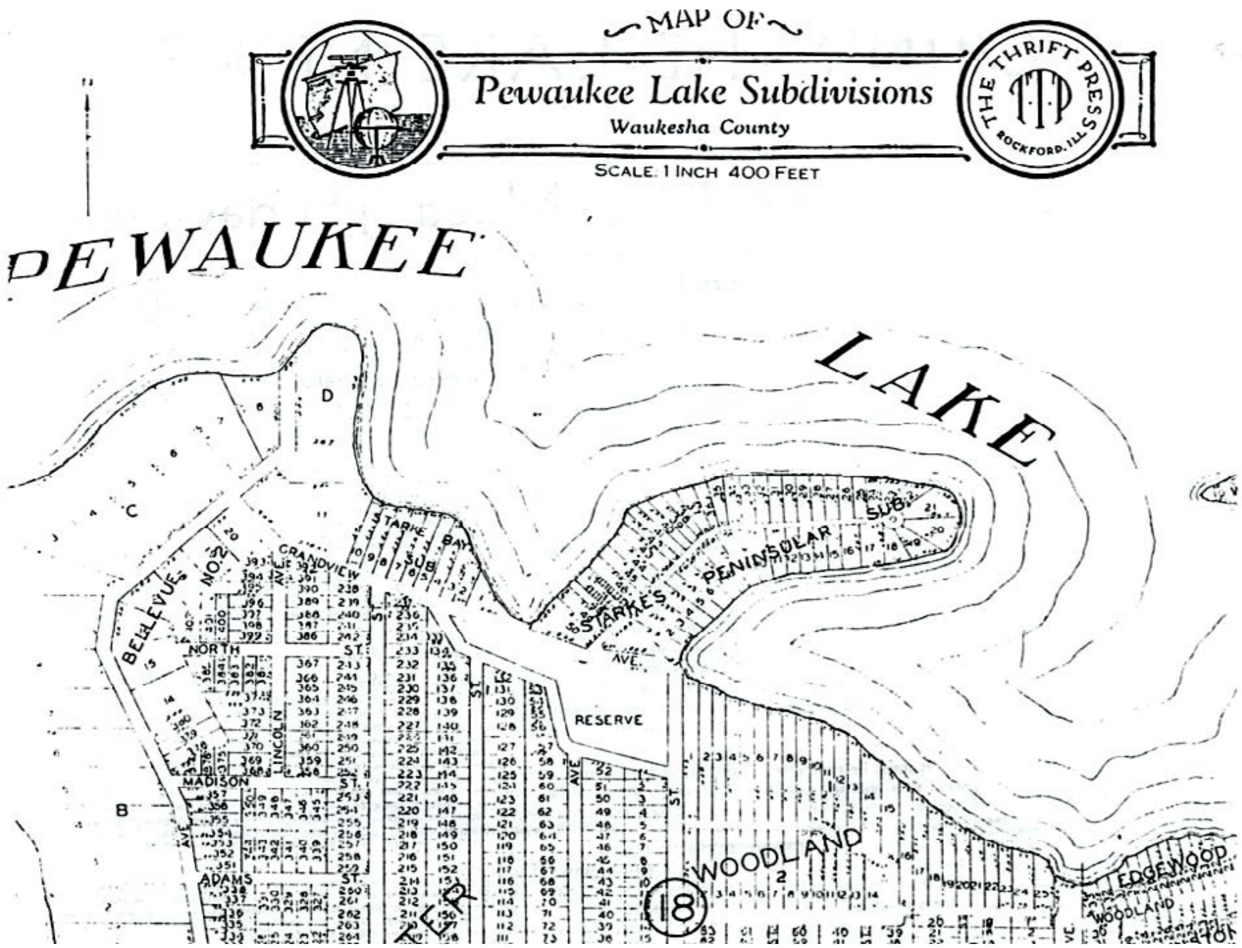
Figure 2.11
"Lady of the Lake" Sidewheeler: Circa 1873



The Lady of the Lake, a side-wheeler, was the first large passenger boat on Pewaukee Lake. Brought here in 1873 by Col. N.P. Iglegardt, it was operated by Capt. Henry Davy

Source: Lake Pewaukee Sanitary District and SEWRPC

Figure 2.12
Creation of the Artificial Peninsula "Starke's Peninsular Subdivision": Circa 1888



Source: Lake Pewaukee Sanitary District and SEWRPC

water quality and sanitation issues confronting Pewaukee Lake. In 1944, the LPSD was officially formed and a sanitary systems inspector was hired. The LPSD had three main objectives:

- Inspect sanitary disposal systems (suspected to be a major source of pollution of the Lake)
- Collect garbage
- Control nuisance aquatic plants

As a result of the LPSD formation, regular garbage collection at individual home sites began and septic system inspections were initiated during 1945.

Pewaukee Lake's bathymetry was first mapped in 1955. The resultant water-depth contour map was revised in 1966 (see Figure 2.14). In 1963, the WDNR completed a land use survey of the Lake's watershed and followed up in 1967 with a housing survey. Also in 1967, hydrology and bathymetry data were compiled and became part of the first WDNR Lake Use Report on Pewaukee Lake[57]. By 1976, public sanitary sewers began to be installed around the Lake as below average rainfall that year prompted a temporary closing of the dam gates at the east end of the Lake. In 1978, the Wisconsin legislature mandated an inventory of Wisconsin wetlands; the inventory was completed in 1982 for the counties of Southeastern Wisconsin and included the Pewaukee Lake watershed.

[57] *Wisconsin Department of Natural Resources Lake Use Report No. FX-2,* Pewaukee Lake, Waukesha County, Fox River Watershed, *1970*.

Historical Land Use

Prior to European settlement in the mid-1800s, the landscape within the Pewaukee Lake watershed consisted largely of oak savanna (oak opening): a transitional habitat between forest and grassland containing prairie grasses and forbs beneath widely spaced trees, primarily Bur oaks. Other natural habitats in the watershed included oak forest, open wetlands, and lowland hardwoods. The extent of these natural habitat types in the Pewaukee River watershed, derived from the original land survey records, is shown on Map 2.6.

Following European settlement, large portions of the landscape were converted to agricultural use. Natural vegetation was cleared to make way for crops. Efforts were made to open up wetlands to cultivation through ditching and draining of wet soils. Steeply sloped, non-arable lands were often grazed by livestock. This land conversion had significant consequences for water quality, water quantity, and wildlife habitat. For example, water quality has been compromised through increases in erosion leading to siltation of surface waters. In addition, natural waterways have been dredged and straightened to facilitate rapid runoff, bypassing natural functions of adjacent wetlands such as the absorption of flood waters. By 1940, agriculture was the most dominant land use and comprised over 70 percent of the total watershed area, based on the historical urban growth data and aerial photographs.

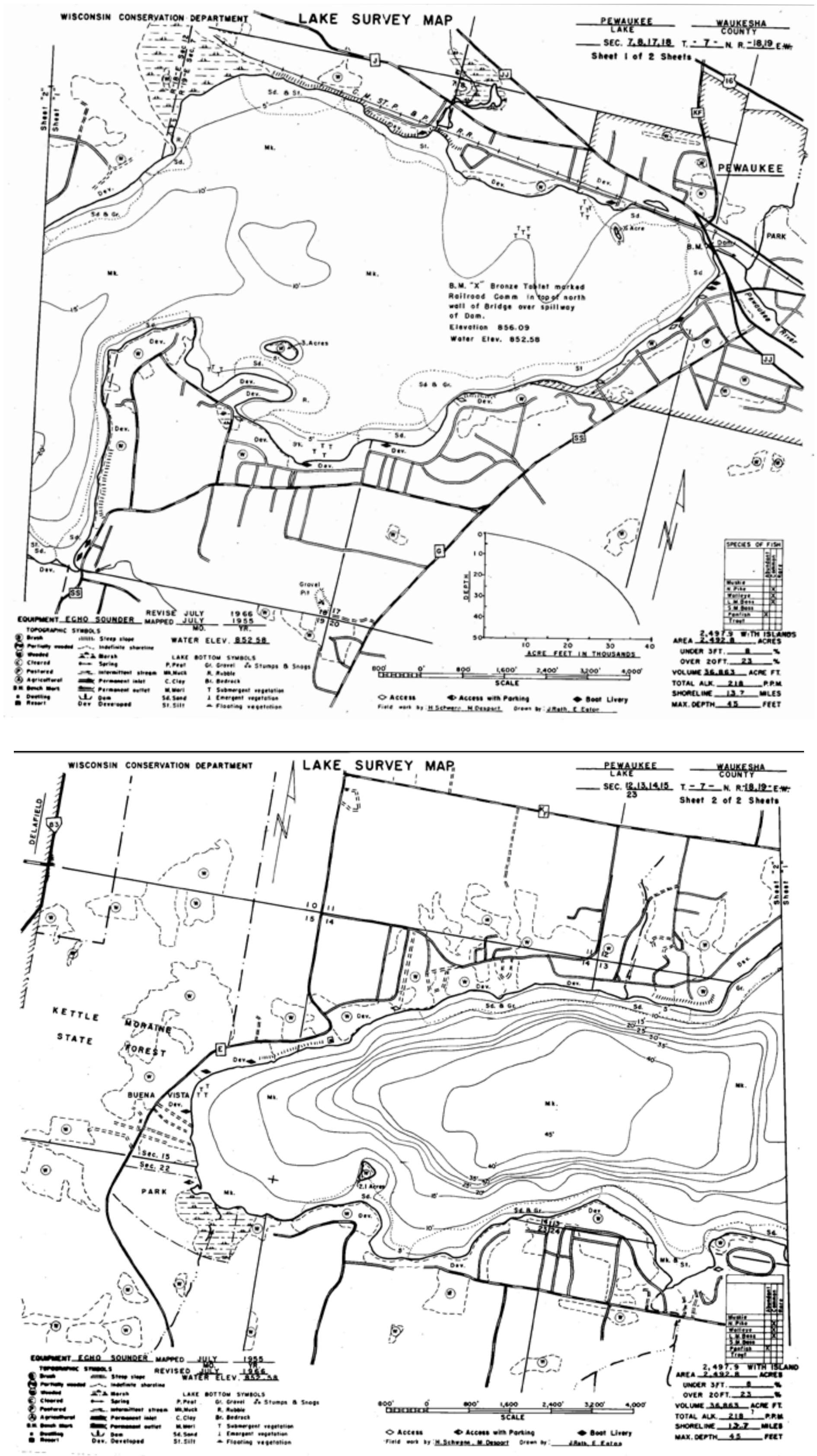
Agriculture remains a dominant land use, but has decreased in area by nearly 7,400 acres since the 1940s. This formerly agricultural land has been converted into residential and transportation land uses. The construction of Interstate Highway 94 and of State Highway 16 by 1950 subsequently contributed to the development of residential land use in the watershed. This second major phase of land conversion has led to other water quality and quantity-related issues, such as altering infiltration rates through an increase in impervious surfaces (paving, concrete walkways and roads, roof tops, etc.). However, some areas used for agriculture in the 1940s have reverted back to woodland and wetland, particularly along riverine corridors. This expansion of woods and wetlands have reduced the fragmentation of current environmental corridors, highlighting the capacity to shift the landscape from a "disturbed" to a more "natural" condition.

Figure 2.13
Pewaukee Lake Amusement Park and Electric Railway

Source: Lake Pewaukee Sanitary District and SEWRPC

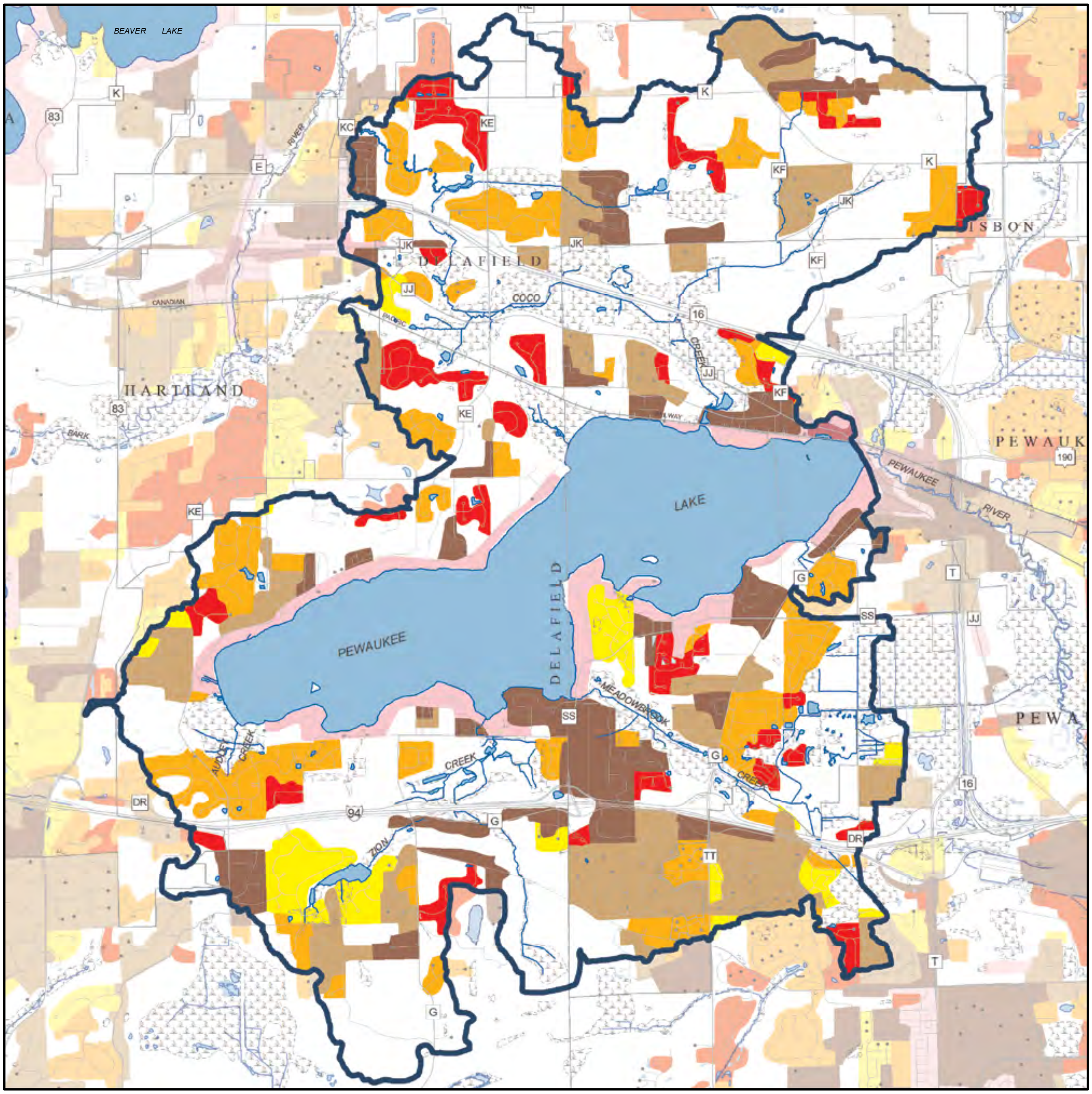
Historical records of urban growth and development can help inform the history of land use within a watershed. Urban growth within the Pewaukee Lake watershed is summarized on Map 2.12 and Table 2.6. As indicated on the map, much of the pre-1900 growth in the watershed centered on the Village of Pewaukee downtown

Figure 2.14
Pewaukee Lake Bathymetric Map: 1955 and Revised 1966



Source: Wisconsin Department of Natural Resources and SEWRPC

Map 2.12
Historical Urban Growth Within the Pewaukee Lake Watershed: 1850-2010



	BEFORE 1900		1991-2000
	1901-1950		2001-2010
	1951-1970		SURFACE WATER
	1971-1980		WETLAND
	1981-1990		STREAM
			WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: SEWRPC

area.[58] As shown in Table 2.7 and in Figure 2.15, there were three 10-year time periods during which significant amounts of land were converted into urban use: 1950 to 1960, 1970 to 1980, and 1990 to 2000. From the 1950s to 1980, a post-war housing boom occurred throughout the entire watershed, probably spurred on by the construction of Interstate Highway 94 and State Highway 16. A lull in urban development occurred from 1980 to 1990, where urban growth dropped from about 1,500 acres in the preceding decade to less than third of that, or about 484 acres. After that slow period, urban growth increased from 1990 to 2000 to the highest recorded, or nearly 1,531 acres, which is consistent with the population and housing trends discussed below. Despite these fluctuations, urban growth in the watershed has shown two distinct patterns. First, the earliest growth that began around the perimeter of Pewaukee Lake continues to emanate from the Lake and expand outward. Second, growth is expanding around the perimeter of the watershed boundary from the outlying cities, towns, and villages.

Table 2.7 and Figure 2.16 show the growth of the population and the number of households in the Pewaukee Lake watershed between 1960 and 2010. Those periods of greatest urban growth shown in Figure 2.15 are reflected in similar increases in population and households: population increased 42 percent from 1970 to 1980 with a 54 percent increase in the number of households, while population increased 33 percent from 1990 to 2000 with a 45 percent increase in households.

Table 2.6
Historical Urban Growth Within the Pewaukee Lake Watershed

Year	Land Converted to Urban Use During Time Period (acres)
Before 1850	0.6
1851-1880	9.6
1881-1920	179.7
1921-1950	424.0
1951-1963	644.9
1964-1970	551.7
1971-1975	812.6
1976-1980	703.6
1981-1985	157.1
1986-1990	326.5
1991-1995	704.9
1996-2000	826.0
2001-2010	1,824.0
2011-2015	124.2
Total	7,289.4

Year	Total Urban Land Use	
	Acres	Percent of Contributing Watershed Area[a]
1850	0.6	0.0
1880	10	0.1
1920	190	1.4
1950	614	4.6
1963	1,259	9.4
1970	1,811	13.5
1975	2,623	19.5
1980	3,327	24.8
1985	3,484	25.9
1990	3,810	28.4
1995	4,515	33.6
2000	5,341	39.8
2010	7,156	53.3
2015	7,289	54.3

[a] *This watershed area does not include the 2,446 acres of Pewaukee Lake.*

Source: SEWRPC

Current and Planned Land Use

The Commission periodically quantifies the ways humans use land in Southeastern Wisconsin and projects how land use will change over the near term. Existing land uses in the Pewaukee Lake watershed were last evaluated in 2015. As shown in Table 2.8 and Map 2.13, as of 2015, a little less than half (45 percent) of the area tributary to Pewaukee Lake is used for various urban purposes. Residential use is the single largest land use in any category—rural or urban—occupying 4,569 acres (29.3 percent) of the land draining to the Lake. Almost 2,000 acres of the rural land use areas identified during 2015 are forecast to be converted to urban uses (mainly residential, along with increases in commercial, industrial, and transportation) based on local government comprehensive plans (see Map 2.14). Changing land use is likely to affect Pewaukee Lake in a number of ways, an example of which includes the mass of various pollutant types entering the Lake. For example, primary pollutants from rural/agricultural are sediment and nutrients (from fertilization) while pollutants from urban/residential uses are more likely to include metals (e.g., copper and zinc).

Political Jurisdictions

The Pewaukee Lake watershed lies entirely within Waukesha County (see Map 1.1). Pewaukee Lake open water area is shared by three communities: the City of Pewaukee, the Town of Delafield, and the Village of Pewaukee (see Table 2.9). Just over half of the total shoreline length is in the Town of Delafield, while

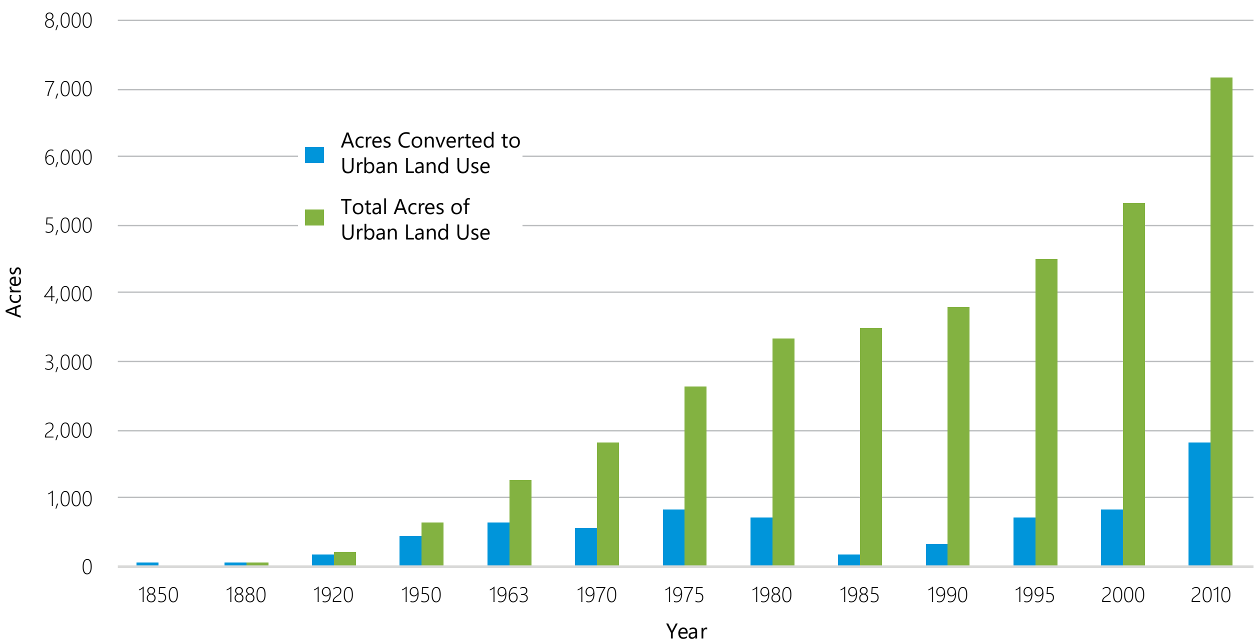
[58] *Information and resources on the history of Pewaukee is provided on the Pewaukee Areas Historical Society website at www.pewaukeehistory.org.*

Table 2.7
Populations and Households Within the Pewaukee Lake Watershed: 1960-2010

	Population			Households		
		Change from Previous Reference Period			Change from Previous Reference Period	
Year	Total	Number	Percent	Total	Number	Percent
1960	7,258	--	--	1,884	--	--
1970	8,109	851	11.8	2,321	437	23.2
1980	11,514	3,409	41.9	3,579	1,258	54.2
1990	12,795	1,281	11.1	4,356	777	21.8
2000	17,016	4,221	32.9	6,307	1,951	44.7
2010	19,775	2,759	16.2	7,648	1,341	21.3

Source: U.S. Bureau of Census and SEWRPC

Figure 2.15
Land Devoted to Urban Land Use Within the Pewaukee Lake Watershed: 1850-2015



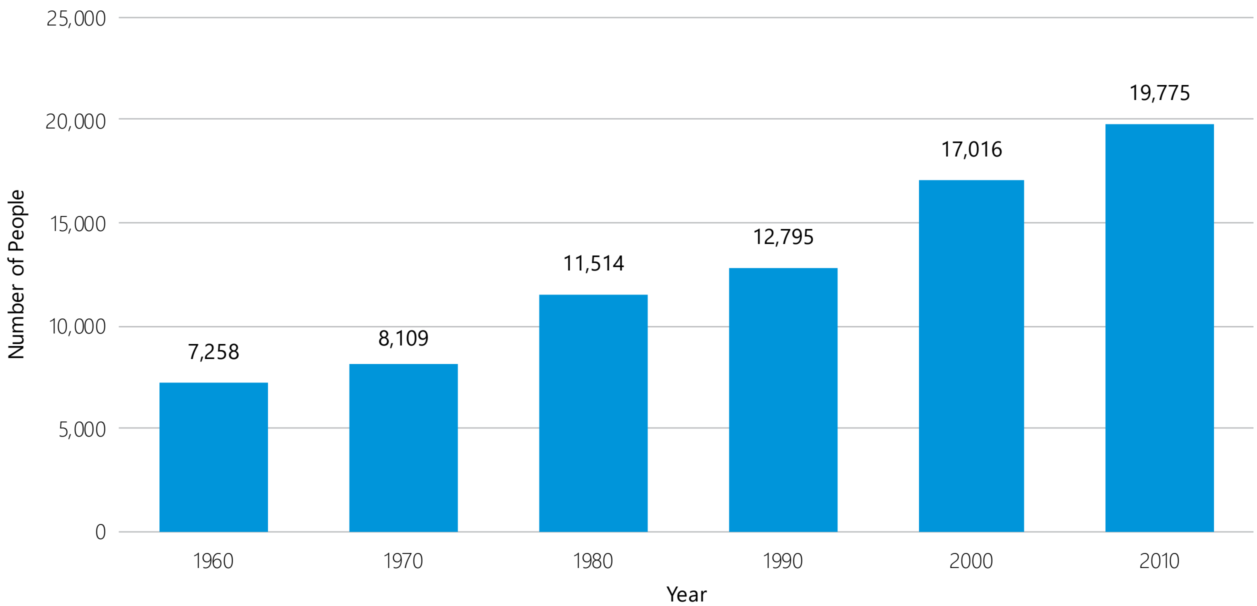
Source: SEWRPC

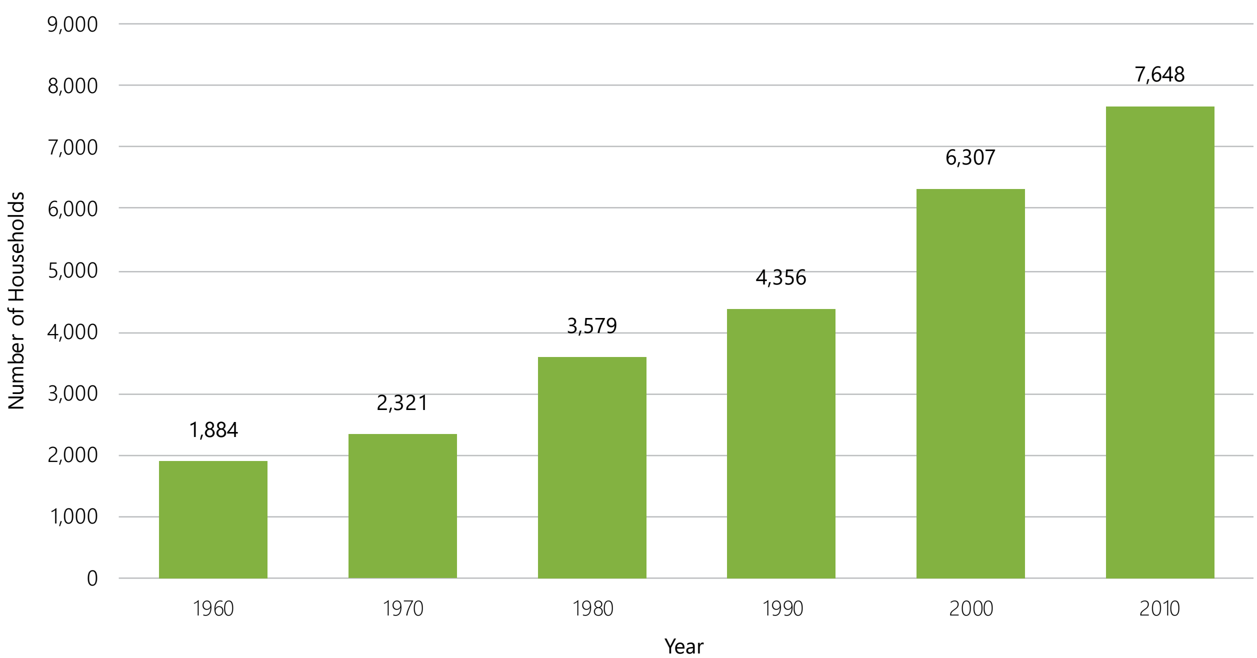
38 percent of the Lake's shoreline is in the City of Pewaukee and 12 percent in the Village of Pewaukee (see Table 2.10). The Lake is the ultimate discharge point for portions of the Cities of Delafield, Pewaukee, and Waukesha; the Towns of Delafield, Lisbon, and Merton; and the Villages of Hartland, Pewaukee, and Sussex (see Map 2.15 and Table 2.11). The Lake and its watershed are within easy driving to downtown Milwaukee. As the largest lake in Waukesha County, Pewaukee Lake is one the Milwaukee Metropolitan Area's premier water-based recreation lakes. These factors increase development and overall lake-use demand, which contributes to heavy pressure on the watershed's natural resource assets.

Sewer Service Area

Adopted sanitary sewer service areas are shown on Map 2.11. These sewer service areas have been delineated through a local sewer service area planning process. As part of this process, communities, assisted by the Commission, define a public sewer service area boundary that is consistent with local land use plans and development objectives. Sewer service area plans include detailed maps of environmentally significant areas within the sewer service area. Following plan adoption by the designated management agency for the wastewater treatment plant, the Commission considers local sewer service area plans for adoption. Once adopted by the Commission, the plans become a formal amendment to the regional water quality management plan and the Commission forwards the plans to the WDNR for approval.

Figure 2.16
Population and Households Within the Pewaukee Lake Watershed





Note: Watershed areas approximated by whole U.S. Public Land Survey quarter sections.

Source: U.S. Bureau of Census and SEWRPC

There are no wastewater treatment plants within the Pewaukee Lake watershed. Instead, sewage is pumped to a station in the Village of Pewaukee and then transported to the Fox River Pollution Control Center in the City of Brookfield for treatment and discharge to the Fox River. Sewer service areas have been adopted for most of the watershed except for parts of the Towns of Delafield, Lisbon and Merton and a portion of the City of Pewaukee.

Natural Resource Elements

Natural resources elements are features that remain integral parts of the Southeastern Wisconsin landscape that provision many human needs and desires and are vital to continued environmental health. Since environmental provisioning of human needs and desires and ecology are built on a network of abiotic and

Table 2.8
Land Use Within the Pewaukee Lake Watershed: 2015-Planned

Land Use Categories[a,b]	2015 Acres	2015 Percent of Total Tributary Drainage Area	Planned[c] Acres	Planned[c] Percent of Total Tributary Drainage Area	Change: 2015-Planned Acres	Change: 2015-Planned Percent (2015 base)
Urban						
Residential	4,733	29.8	5,657	35.6	+924	+19.5
Commercial	46	0.3	264	1.7	+218	+473.9
Industrial	21	0.1	138	0.9	+117	+557.1
Governmental and Institutional	110	0.7	270	1.7	+160	+147.7
Transportation, Communication, and Utilities	1,744	11.0	1,641	10.3	-103	-5.9
Recreational	636	4.0	747	4.7	+111	+17.4
Urban Subtotal	7,290	45.9	8,717	54.9	+1,427	+19.6
Rural						
Agricultural and Open Lands	3,559	22.4	2,132	13.4	-1,427	-40.1
Wetlands	1,358	8.6	1,358	8.6	0	0.0
Woodlands	1,125	7.1	1,125	7.1	0	0.0
Water	2,547	16.0	2,547	16.0	0	0.0
Rural Subtotal	8,589	54.1	7,162	45.1	-1,427	-16.6
Total	15,878	100.0	15,878	100.0	0	0.0

[a] *As approximated by whole U.S. Public Land Survey one-quarter sections.*

[b] *Off-street parking of more than 10 spaces are included with the associated land use.*

[c] *Planned land use is based on comprehensive plans adopted by local governments located within the Pewaukee Lake watershed.*

Source: SEWRPC

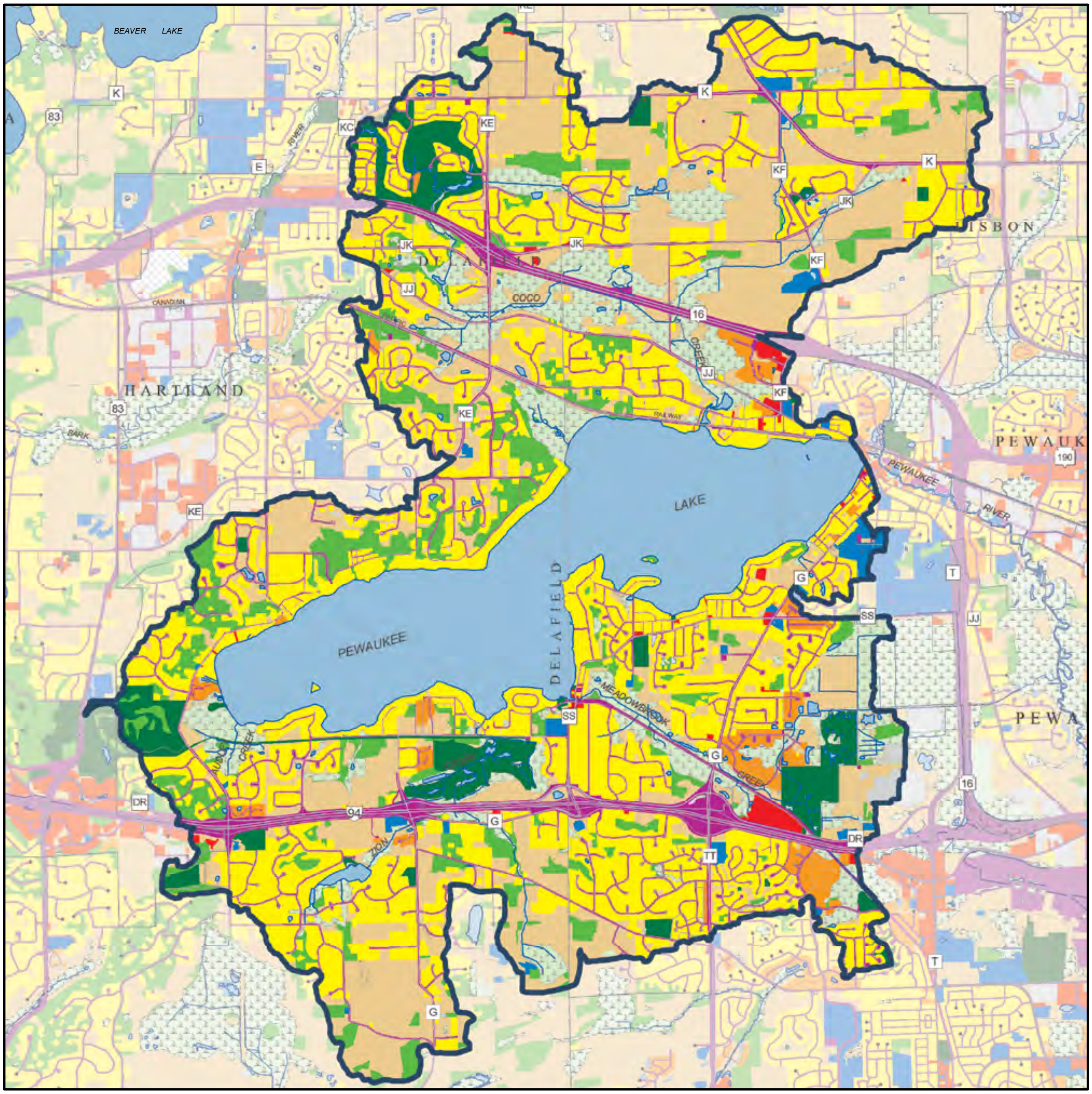
biotic relationships, deterioration or removal of one important relationship may cause damage throughout the entire network. For example, draining a wetland can eliminate the area's ability to supply important fish reproduction, nursery, and refuge functions, may compromise upland wildlife habitat value, can interrupt important groundwater recharge/discharge relationships, and can inhibit natural runoff filtration and floodwater storage. This loss in ecosystem function may further affect groundwater supply for domestic, municipal, and industrial use or its contribution to low flows in streams and rivers. Preserving natural resource elements not only improves local environmental quality but can also sustain and possibly enhance aquatic, avian, and terrestrial wildlife populations across the Region.

Floodplains

Section 87.30 of the *Wisconsin Statutes* requires that counties, cities, and villages adopt floodplain zoning to preserve floodwater conveyance and storage capacity and prevent new flood-damage-prone development in flood hazard areas. The minimum standards that such ordinances must meet are set forth in Chapter NR 116, "Wisconsin's Floodplain Management Program," of the *Wisconsin Administrative Code*. The required regulations govern filling and development within a regulatory floodplain, which is defined as the area that has a 1 percent annual probability of being inundated. The one-percent-annual-probability (100-year recurrence interval) floodplains within the Pewaukee Lake watershed are shown on Map 2.9. As required under Chapter NR 116, local floodland zoning regulations must prohibit nearly all development within the floodway, which is that portion of the floodplain with actively flowing water conveying the one-percent-annual-probability peak flood flow. Local regulations must also restrict filling and development within the flood fringe, which is that portion of the floodplain located beyond the floodway that is inundated during the one-percent-annual-probability flood, detaining floodwater for later release. Filling within the flood fringe reduces floodwater storage capacity and may increase downstream flood flows and flood depths/elevations. Approximately 797 acres of floodplain are present within the Pewaukee Lake watershed.

Ordinances related to floodplain zoning recognize existing uses and structures and regulate them in accordance with sound floodplain management practices. These ordinances are intended to: 1) regulate and diminish proliferation of nonconforming structures and uses in floodplain areas; 2) regulate reconstruction, remodeling, conversion and repair of such nonconforming structures—with the overall intent of lessening

Map 2.13
Generalized Land Use Within the Pewaukee Lake Watershed: 2015



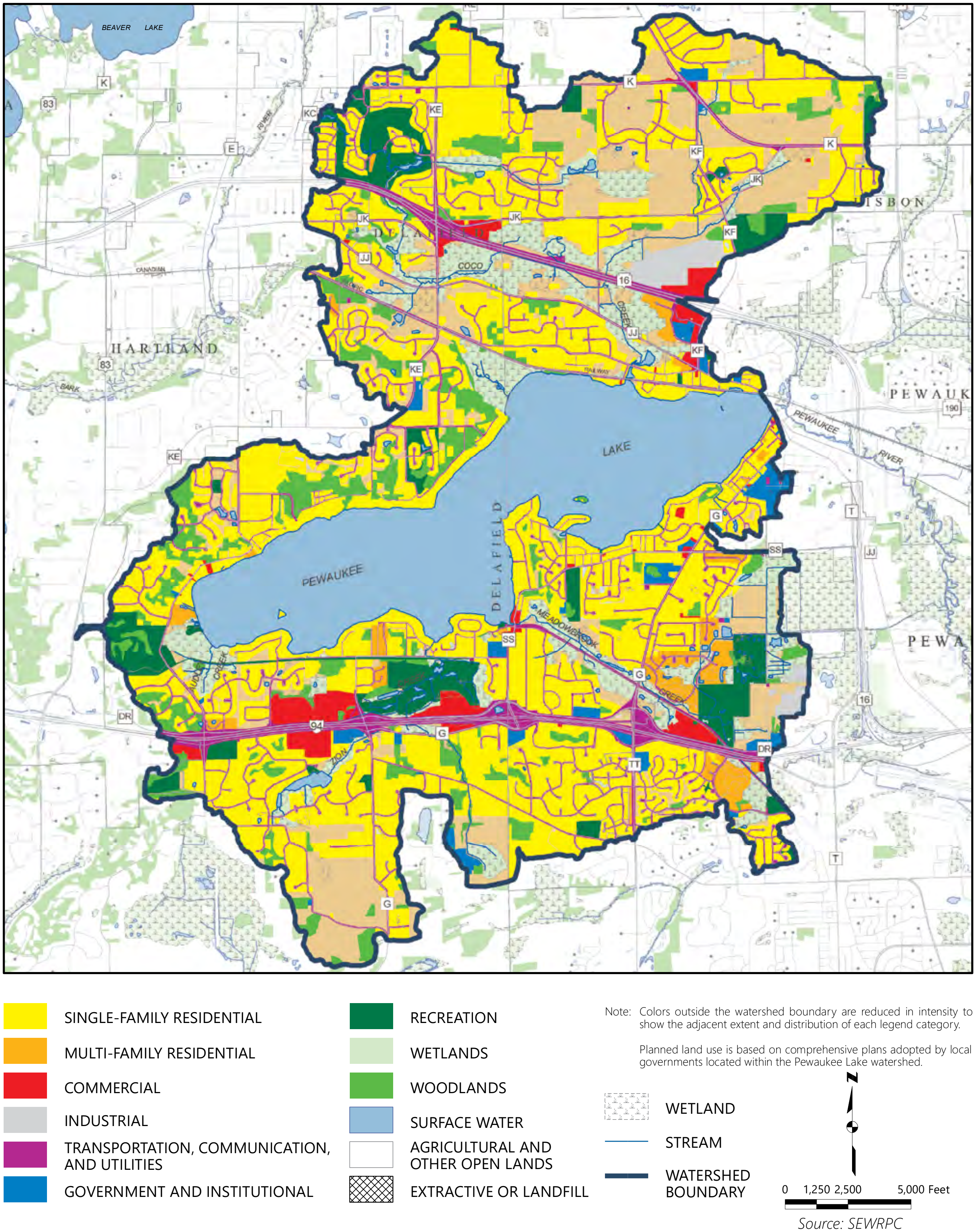
SINGLE-FAMILY RESIDENTIAL	RECREATION	WETLAND	
MULTI-FAMILY RESIDENTIAL	WETLANDS	STREAM	
COMMERCIAL	WOODLANDS	WATERSHED BOUNDARY	
INDUSTRIAL	SURFACE WATER		
TRANSPORTATION, COMMUNICATION, AND UTILITIES	AGRICULTURAL AND OTHER OPEN LANDS		
GOVERNMENT AND INSTITUTIONAL	EXTRACTIVE OR LANDFILL		

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Map 2.14
Pewaukee Lake Watershed Planned Land Use



Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

Planned land use is based on comprehensive plans adopted by local governments located within the Pewaukee Lake watershed.

Source: SEWRPC

Table 2.9
Pewaukee Lake Open-Water Jurisdiction

Depth Category (feet)	Town of Delafield (acres/percent)	City of Pewaukee (acres/percent)	Village of Pewaukee (acres/percent)
0-5	147/37	193/49	57/14
5-10	220/22	633/64	134/14
10-15	252/90	29/10	--
15-20	157/100	--	--
20-25	79/100	--	--
25-30	57/100	--	--
30-35	90/100	--	--
35-40	150/100	--	--
40-45	149/100	--	--
Total	1,301/55	855/36	191/8

Note: The total percentage does not equal 100 percent due to rounding.

Source: SEWRPC

Table 2.10
Pewaukee Shoreline Length by Municipality

Municipality	Shoreline Length (feet)	Percent of Total Shoreline
Town of Delafield	35,081	50
City of Pewaukee	26,264	38
Village of Pewaukee	8,349	12
Total	69,694	100

Note: Shoreline lengths do not include islands on Pewaukee Lake.

Source: SEWRPC

public responsibilities generated by continued and expanded development of land and structures inherently incompatible with natural floodplains; and 3) lessen potential danger to life, safety, health, and welfare of persons whose lands are subject to the hazards of floods.

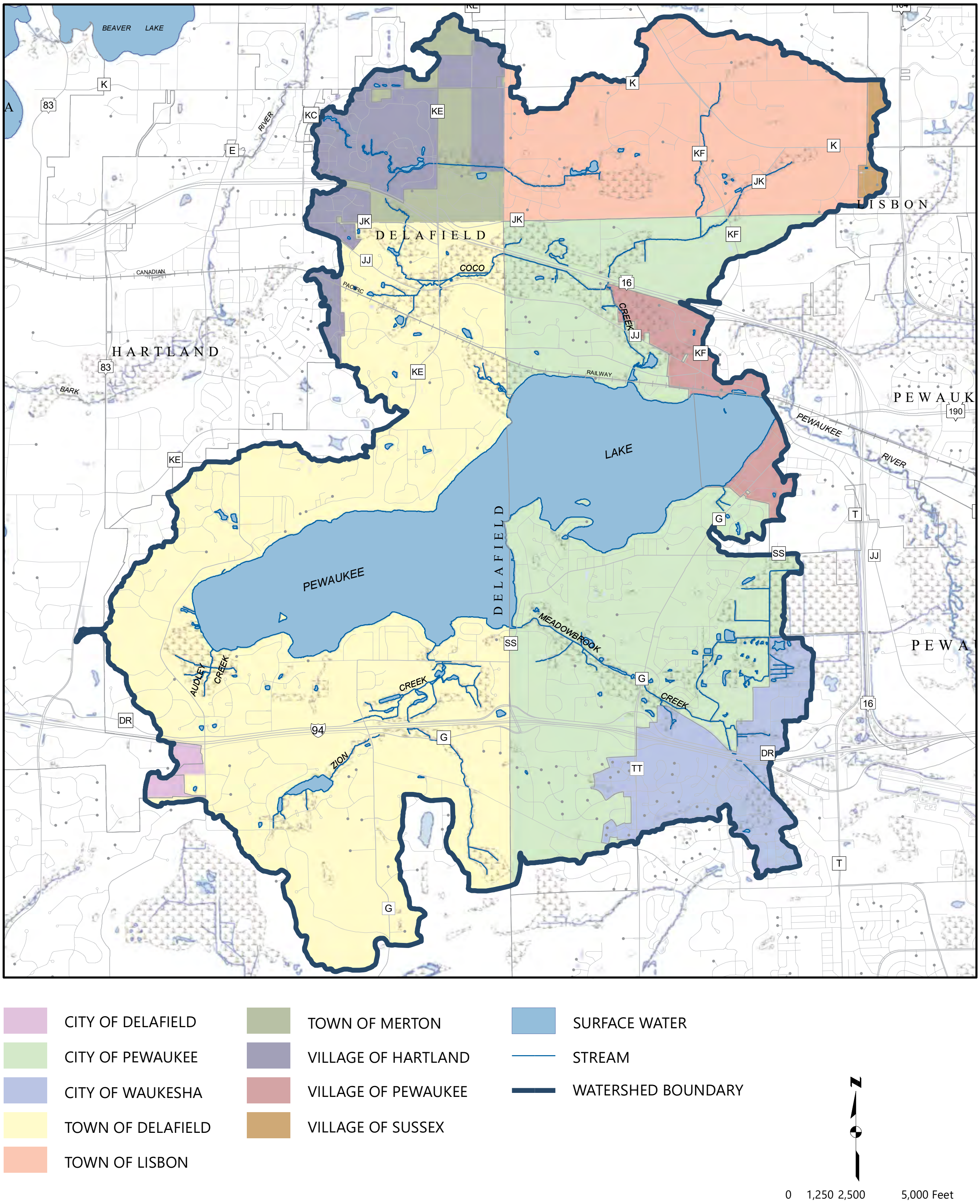
Wetlands

Historically, wetlands were largely viewed as wastelands, presenting obstacles to agricultural production and development. Private interests as well as governmental institutions supported the transformation of wetlands through large-scale draining and filling. Dramatic removal of wetland habitat occurred until scientific research revealed their value as incredibly productive and biologically diverse ecosystems.[59] Wetlands are most known for their variety of plant life, with communities composed of a mixture of submergent pondweeds, floating-leaf plants, emergent cattails, bulrush, and woody tamaracks, as just a few examples. Wildlife species that have been found to rely on, or are associated with, wetlands for at least part of their lives include: crustaceans, mollusks, and other aquatic insect larvae and adults; fishes, including forage fish and important gamefish species like trout, northern pike, and largemouth bass; amphibians; reptiles; mammals including deer; resident bird species like turkey as well as migrants like sandhill or whooping cranes. Thus, wetlands help maintain biologically diverse communities of ecological and economic value.

In addition to maintaining biodiversity, wetlands also store floodwaters, filter pollutants, improve water quality, protect groundwater aquifers, serve as sinks, sources, or transformers of materials, and provide recreation sites for boating and fishing. Recognition of the value and importance of wetlands has led to the creation of rules and regulations to protect wetlands globally, nationally (i.e., the Federal Clean Water Act of 1972), statewide, and locally. Most recently, the US Army Corp of Engineers and USEPA, in coordination with the U.S. Fish and Wildlife Service, WDNR, and the Commission have updated the delineation of wetlands in areas of special natural resource interest for the entire regional area to protect these areas and their

[59] *J.A. Cherry, "Ecology of Wetland Ecosystems: Water, Substrate, and Life,"* Nature Education Knowledge, *3(10): 16, 2012, www.nature.com/scitable/knowledge/library/ecology-of-wetland-ecosystems-water-substrate-and-17059765.*

Map 2.15
Pewaukee Lake Watershed Civil Divisions: 2019



Source: SEWRPC

associated critical species habitats (Advanced Delineation and Identification – ADID – lands; see Map 2.8).[60] These efforts are designed to protect or conserve wetlands and the ecosystem services they provide.

The term "ecosystem services" refers to any of the benefits that ecosystems—both natural and semi-natural—provide to humans.[61] In other words, ecosystem functions are classified by their abilities to provide goods and services that satisfy human needs,[62] either directly or indirectly. Examples of ecosystem services provided by wetland ecosystems are illustrated in Figure 2.17. The economic value of the ecosystem services provided by wetlands exceeds those provided by lakes, streams, forests, and grasslands and is second only to the value provided by coastal estuaries.[63] Society gains a great deal from wetland conservation. Therefore, it is essential to incorporate wetland conservation and restoration targets as part of this plan to guide management and policy decisions regarding the use and preservation of such ecosystems.

Table 2.11
Civil Divisions Within Pewaukee Lake's Watershed

Municipality	Acres of Watershed[a]	Percent of Watershed
Cities		
Delafield	59	0.4
Pewaukee	4,566	28.8
Waukesha	800	5.0
Towns		
Delafield	6,687	42.1
Lisbon	2,020	12.7
Merton	486	3.1
Villages		
Hartland	656	4.1
Pewaukee	545	3.4
Sussex	60	0.4

[a] *This watershed acreage includes 2,446 acre Pewaukee Lake.*

Source: SEWRPC

Wetlands are transitional areas, often possessing characteristics of both aquatic and terrestrial ecosystems while at the same time possessing features unique unto themselves. For regulatory purposes, the State of Wisconsin defines wetlands as areas where water is at, near, or above the land surface long enough to be capable of supporting aquatic or hydrophytic vegetation and which has soils indicative of wet conditions Three specific characteristics of wetlands are evaluated when a wetland determination is made including:

- Hydrology that results in wet or flooded soils
- Soils that are dominated by anaerobic (without oxygen) processes
- Rooted vascular plants that are adapted to life in flooded, anaerobic environments

These characteristics pose severe limitations for urban development, as wetlands have high water tables as well as high soil compressibility, instability, shrink-swell potential, and low bearing capacity. Thus, development in wetlands may result in flooding, wet basements, unstable foundations, failing pavements, and failing sanitary sewer and water lines. There are significant and costly onsite preparation and maintenance costs associated with the development of wetland soils, particularly in connection with roads, foundations, and public utilities.

[60] *Pursuant to Section NR 103.04(4) of the Wisconsin Administrative Code, wetlands in areas of special natural resources interest include those wetlands both within the boundary of designated areas of special natural resource interest and those wetlands that are in proximity to or have a direct hydrologic connection to such designated areas, which include Advanced Delineation and Identification study (ADID) areas. See SEWRPC Planning Report No 42,* Amendment to the Natural Areas and Critical Species Habitat Protection and Management Plan for the Southeastern Wisconsin Region*, December 2010. www.sewrpc.org/SEWRPCFiles/Publications/pr/pr-042-natural-areas-crit-species-habitat-amendment.pdf.*

[61] *Millennium Ecosystem Assessment,* Ecosystem Services and Human Well-Being: Wetlands and Water, *Synthesis. Report to the Ramsar Convention. Washington, DC: World Resources Institute. 2005.* millenniumassessment.org/en/Global.html.

[62] *R.D.S. de Groot, M.A. Wilson, and R.A.M. Bauman, "A Typology for the Classification, Description and Valuation of Ecosystem Functions, Goods and Services,"* Ecological Economics*, 41: 393-408, 2000, www.sciencedirect.com/science/article/pii/S0921800902000897.*

[63] *R.W. Costanza, R. d'Arge, R. de Groot, et al., "The Value of the World's Ecosystem Services and Natural Capital,"* Nature, *387(6630): 253–260, 1997.*

Figure 2.17
Natural and Created Wetland Ecosystem Services

Service	Examples of Goods and Services Derived	Estimated value (1994 US $/$ac^{-1}$ yr^{-1})[a]
REGULATION SERVICES		
Water quality		
Erosion control and sediment retention	Sediment filtration and storage capabilities that prevent downstream migration of sediment and improve downstream water quality.	NA
Waste treatment	Reduction of excess nutrient, organic, and metal loadings reduced through microbial degradation and/or sorption to improve water quality. Reduction of runoff temperature via shading and water's heat capacity.	1,690
Nutrient cycling	Reduction of nitrogen and phosphorus concentrations through denitrification and biological uptake.	NA
Hydrologic regulation	Moderation of the rate, volume, and frequency of surface runoff to provide flood and storm surge protection.	1,860
Climate regulation		
Greenhouse gas regulation	Maintenance of air quality and CO_2/CH_4 balance (through C sequestration); regulation of gases also influences climate effects.	54
Microclimate regulation	Maintenance of a favorable climate (such as temperature, precipitation) for human habitation, health, and cultivation.	NA
Soil formation	Building of land surface through the accumulation of organic material in wetlands.	NA
HABITAT SERVICES		
Refugia	Maintenance of biological and genetic diversity through provision of suitable habitat for resident or migratory plant and animal species. Includes the maintenance of populations of commercially harvested species and biological pest control services. This diversity forms the basis of many other ecosystem services.	123
PRODUCTION SERVICES		
Food production	Production of fish, game, fruits for small-scale hunting/gathering or aquaculture.	104
Raw materials	Production of trees, peat, and other biomass appropriate for lumber, fuel, or fodder.	43
INFORMATION SERVICES		
Recreation	Provision of opportunities for hunting, bird-watching, hiking, or other recreational uses.	232
Cultural	Provision of opportunities for noncommercial uses, including the use of wetlands for school excursions/education and for scientific research. Aesthetic, artistic, and spiritual values are also included.	357

[1]Adapted from Costanza et al., 1997, and de Groot, 2006)

[2]Value estimates for each service taken from Costanza et al. (1997). A listing of NA for individual services indicates that a formal valuation of this service had not yet been conducted.

Ecosystem services are products of the structure (for example, plant and animal community composition) and processes (such as nutrient cycling and decomposition) that characterize an ecosystem such as a wetland. These services also include food and raw material provision, air and water purification, biodiversity maintenance, and aesthetic and other cultural benefits to humans. These services can be attributed economic, social, and ecological values. Ideally, the inherent value of these services will guide management and policy decisions regarding the use and preservation of ecosystems.

Source: T.L. Moore and W.F. Hunt III, Urban Waterways: Stormwater Wetlands and Ecosystem Services, *North Carolina Cooperative Extension, 2011; Adapted from R.S. de Groot, M.A. Wilson, and R.M. Boumans, "A Typology for the Classification, Description, and Valuation of Ecosystem Functions, Goods, and Services,"* Ecological Economics, *41: 393-408, 2002*

Within the Pewaukee Lake watershed, wetlands total approximately 1,360 acres, or about 8.6 percent of the total watershed area, as illustrated on Map 2.16. The wetlands vary by community type, including aquatic beds, emergent/wet meadows, scrub/shrub, and forested, and in their floristic quality, from fair to excellent.[64]

[64] *For a greater description of the wetland community types and their floristic quality, see SEWRPC Community Assistance Planning Report No. 313,* op. cit.

As part of an effort to protect Pewaukee Lake's water quality, wildlife habitat, and areas of groundwater recharge, the LPSD, under direction of the citizen advisory committee, created the Wetland Conservancy Fund and began purchasing wetland areas in the Pewaukee Lake watershed. With the original goal of purchasing 350 acres of the most critical wetlands, the LPSD has purchased several wetland parcels, including: 46-acres in the Taylors Bay area, 75 acres along Coco Creek, 38 acres along Meadowbrook Creek, and 75 acres of previously converted farmland located on the upper reaches of Coco Creek (the Department of Transportation completed a wetland restoration project on 34 acres of this parcel). In addition, the LPSD has purchased additional parcels ranging in size from 32 to 56 acres, the majority of which is wetland habitat.

Uplands

Upland/woodland habitat is comprised of non-wetland natural areas. These areas are usually higher in elevation and farther from open water than wetlands, and thus are generally not as moist. However, there are many exceptions in this broad generalization of uplands, as can be seen within the Pewaukee Lake watershed. Upland habitat can sometimes be very difficult to distinguish from wetland, because these features form broad and complex mosaics or combinations across the landscape. It is precisely this combination and the linkages between these unique community types that provides the critical habitats to sustain healthy and diverse aquatic and terrestrial wildlife.

The upland habitat in the Pewaukee Lake watershed, shown in Map 2.16, is dominated by deciduous woodlands, with substantial areas of brush and grassland.[65] As most of this land was agricultural in the 1940s, these deciduous woodlands are an indication of the regrowth of forested lands within the watershed. The grassland areas may be under active management as pasture land or enrolled in a soil conservation program. There are also small portions of conifer and mixed (combinations of some or all of the others) upland communities.

Like wetlands ecosystems as described above, upland habitats also provide a variety of ecosystem services. Although the economic value of their ecosystem services is not as large as wetland ecosystems, these areas do provide important services worth protecting.[66] Uplands provide production of food, livestock, and crops, groundwater recharge and water quality, flood risk prevention, air quality protection, soil conservation, wildlife management potential through provision of critical breeding, nesting, resting, and feeding grounds, as well as refuge from predators for many species of upland game and nongame species, recreation, tourism, and education opportunities.

Another important contrast between upland and wetland is that the upland soils generally pose fewer limitations for urban development. In general, uplands have a lower water table, lower compressibility and greater soil stability, greater bearing capacity, and lower shrink-swell potential than wetland soils. These conditions usually result in less flooding, dry basements, more stable foundations, more stable pavements, and less failure of sanitary sewer and water lines. Therefore, there are significantly lower costs associated with onsite preparation and maintenance with the development of upland soils, particularly in connection with roads, foundations, and public utilities, making these areas highly desirable for urban development. Therefore, it is important to incorporate upland conservation and restoration targets as part of this plan to guide management and policy decisions regarding the use and preservation of such ecosystems.

Natural Resource Planning Features

The Commission has studied the distribution of natural resource elements in Southeastern Wisconsin for decades. As part of this study, it has labelled, ranked, and mapped important natural resource elements.

<u>Primary Environmental Corridors</u>

Primary environmental corridors (PEC) include a wide variety of important resource and resource-related elements. By definition, they are at least 400 acres in size, two miles in length, and 200 feet in width.[67] PEC encompassed about 4,254 acres, or about 32 percent of the Pewaukee Lake watershed, in 2015 (see Map 2.17). These PECs represent a composite of the best remaining elements of the natural resource

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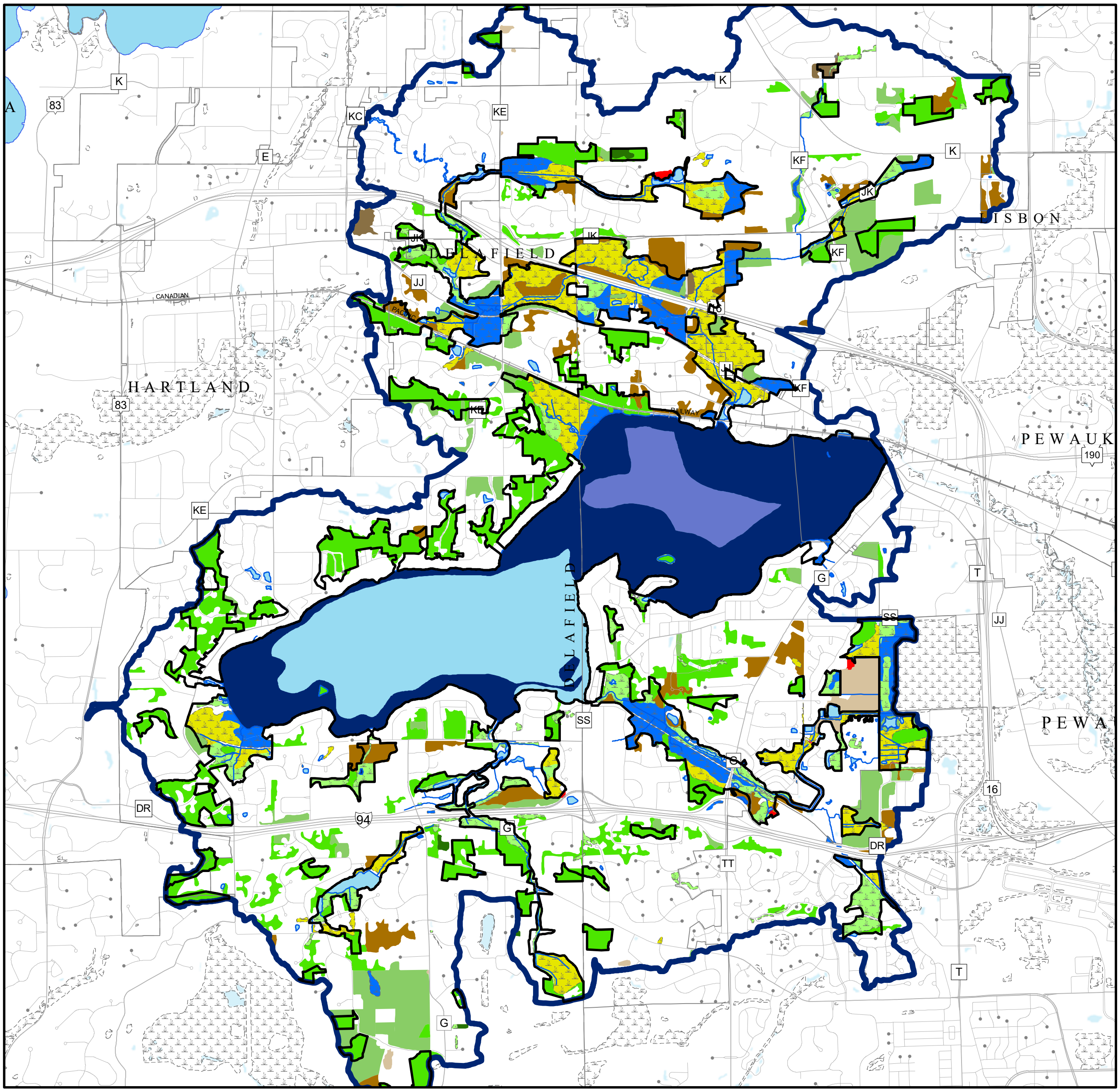
[65] *SEWRPC Planning Report No. 42,* op. cit.

[66] *R.W. Costanza et al., 1997,* op. cit.

[67] *SEWRPC Planning Report No. 42,* op. cit.

Map 2.16
Upland and Wetland Cover Types Within the Pewaukee Lake Watershed: 2010



UPLAND COVER TYPES

BRUSH
CONIFER
DECIDUOUS
GRASSLAND

WETLAND COVER TYPES

AQUATIC BED
DEEP WATER LAKE
EMERGENT/WET MEADOW
FILLED/DRAINED WETLAND
FORESTED
SCRUB/SHRUB

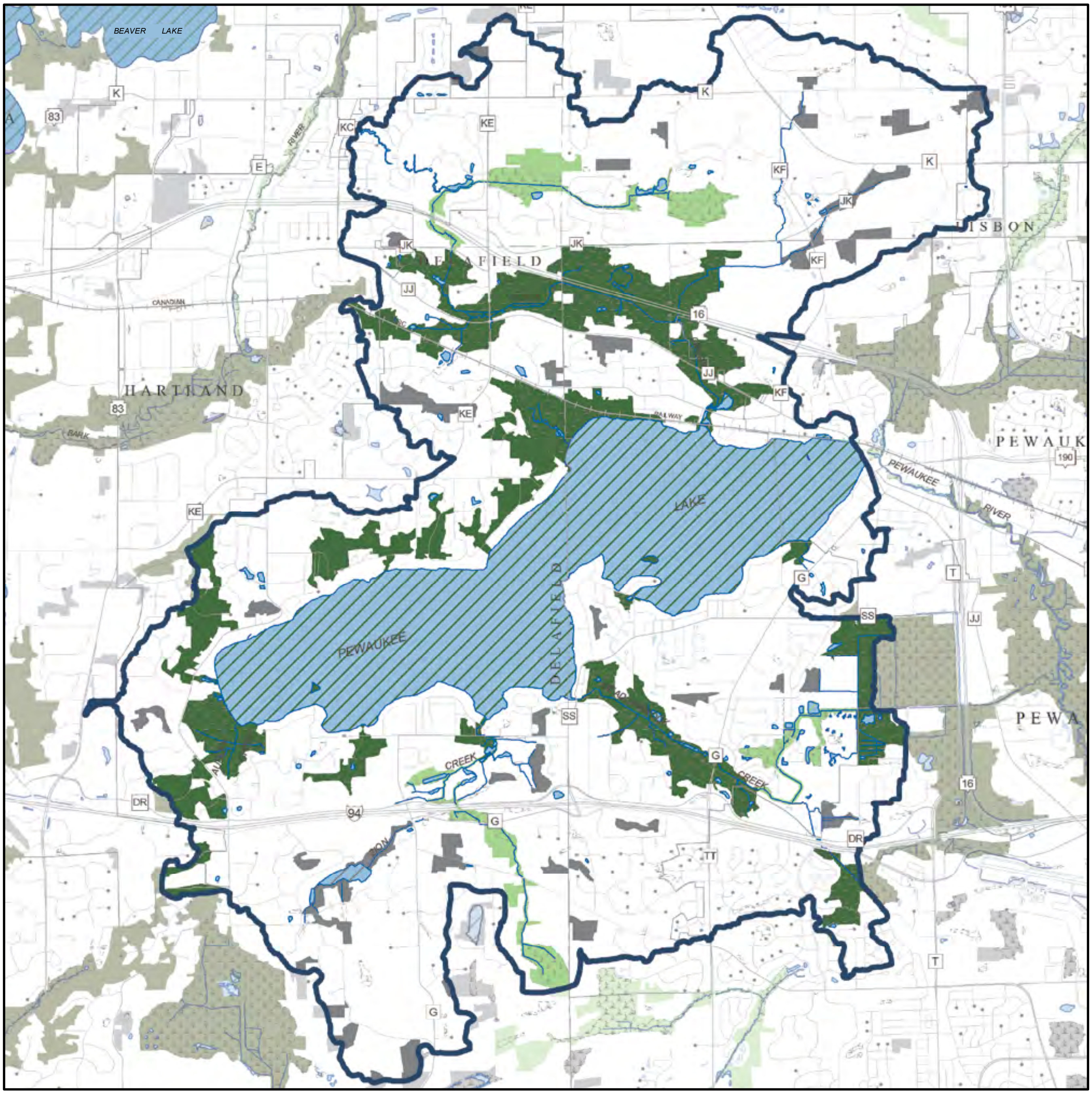
SURFACE WATER
STREAM
WATERSHED BOUNDARY
PRIMARY ENVIRONMENTAL CORRIDOR

N

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Map 2.17
Environmental Corridors and Isolated Natural Resources Areas Within the Pewaukee River Watershed: 2015



PRIMARY ENVRIRONMENTAL CORRIDOR

SECONDARY ENVIRONMENTAL CORRIDOR

ISOLATED NATURAL RESOURCE AREA

SURFACE WATER

WATERBODIES IN ENVIRONMENTAL CORRIDOR

WETLAND

STREAM

WATERSHED BOUNDARY

Note: Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

N

0 1,250 2,500 5,000 Feet

Source: SEWRPC

base, and contain almost all of the best remaining woodlands, wetlands, and wildlife habitat areas in the watershed. Although typically displayed as open water, lakes, rivers, streams, and associated shorelands are PECs for aquatic life. Thus, Pewaukee Lake and its associated shorelands are part of the highest quality natural resources within the Pewaukee Lake watershed, highlighting the importance of managing nearshore areas to protect their quality and integrity.

Secondary Environmental Corridors

Secondary environmental corridors (SEC) generally connect with the primary environmental corridors and are at least 100 acres in size and one-mile long. In 2015, secondary environmental corridors encompassed about 408 acres, or just over 3 percent of the watershed (see Map 2.17). Secondary environmental corridors are remnant resources that have been reduced in size compared to the larger PEC as described above, due to land development for intensive urban or agriculture purposes. However, secondary environmental corridors preserve ecosystem function by facilitating surface water drainage, maintaining pockets of natural resource features, as well as providing corridors for the movement of wildlife and dispersal of vegetation seeds.

Isolated Natural Resource Areas

Smaller concentrations of natural resource features that have been separated physically from the environmental corridors by intensive urban or agricultural land uses have also been identified. These natural resource areas, which are at least five acres in size, are referred to as isolated natural resource areas. Widely 4 percent, of the total study area in 2015, as shown in Map 2.17.

Natural Areas and Critical Species Habitat Sites

Natural areas, as defined by the Wisconsin Natural Areas Preservation Council, are tracts of land or water so little modified by human activity, or sufficiently recovered from the effects of such activity, that they contain intact native plant and animal communities believed to be representative of the pre-European settlement landscape (see Map 2.18). Natural areas are generally comprised of wetland or upland vegetation communities and/or complex combinations of both these fundamental ecosystem units. In fact, some of the highest quality natural areas within Southeastern Wisconsin are wetland complexes that have maintained adequate or undisturbed linkages (i.e., landscape connectivity) between the upland-wetland habitats, which is consistent with research findings in other areas of the Midwest.[68]

Natural areas have been identified for the seven-county Southeastern Wisconsin Region in SEWRPC Planning Report No. 42, "*A Regional Natural Areas and Critical Species Habitat Protection and Management Plan for Southeastern Wisconsin*," published in September 1997 and amended in 2008. This plan was developed to assist Federal, State, and local units and agencies of government, and nongovernmental organizations, in making environmentally sound land use decisions including acquisition of priority properties, management of public lands, and location of development in appropriate localities that will protect and preserve the natural resource base of the Region. Waukesha County uses this document to guide land use decisions. The identified natural areas were classified into the following three categories:

1. Natural area of statewide or greater significance (NA-1)

2. Natural area of countywide or regional significance (NA-2)

3. Natural area of local significance (NA-3).

Classification of an area into one of these three categories was based upon consideration of several factors, including the diversity of plant and animal species and community types present; the structure and integrity of the native plant or animal community; the extent of disturbance by human activity, such as logging, grazing, water level changes, and pollution; the frequency of occurrence within the Region of the plant and animal communities present; the occurrence of unique natural features within the area; the size of the area; and the educational value. The Pewaukee Lake watershed contains one natural area of countywide or regional significance (NA-2) and six natural areas of local significance (NA-3).

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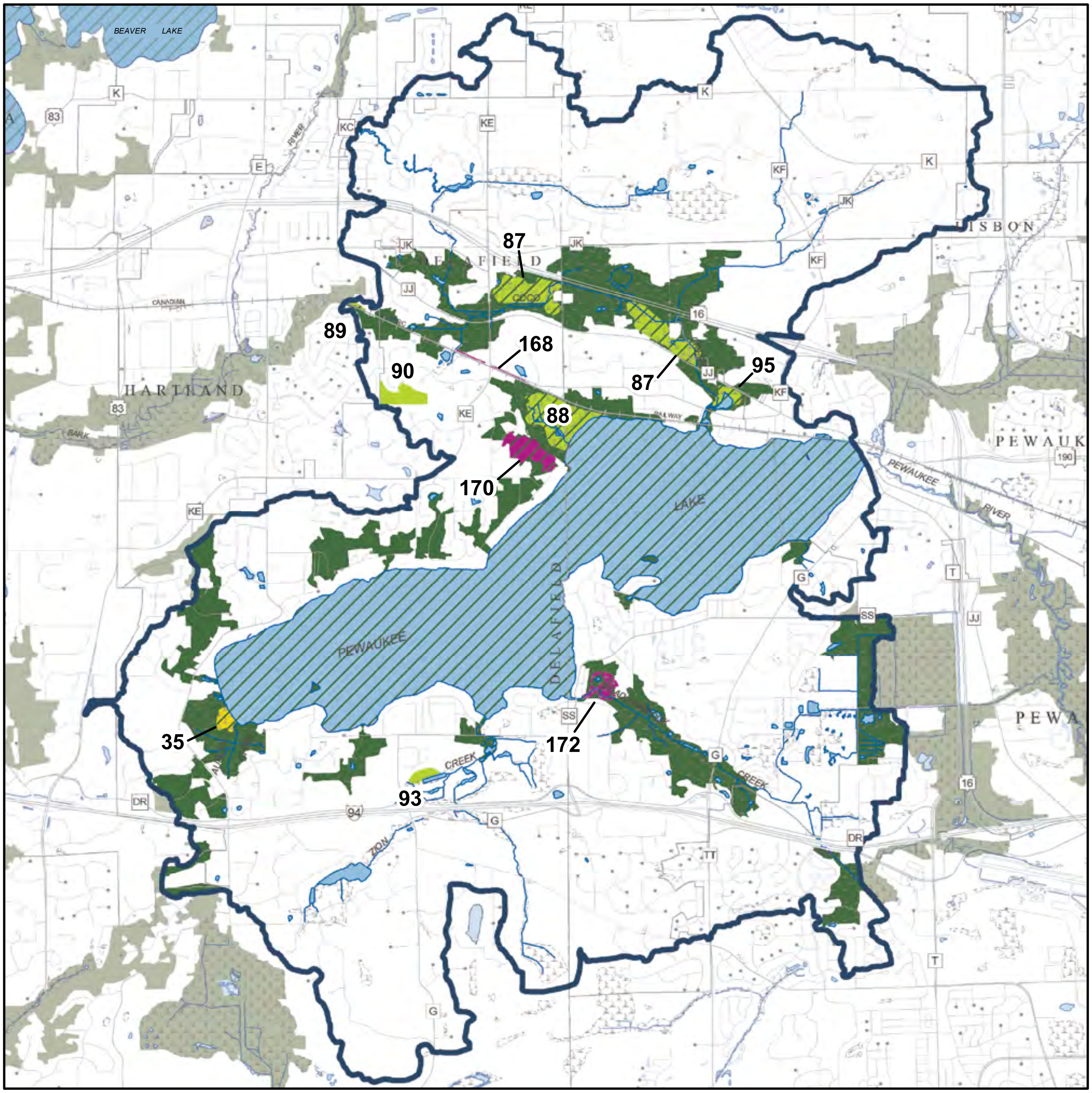
[68] *O. Attum, Y.M. Lee, J.H. Roe, and B.A. Kingsbury, "Wetland Complexes and Upland-Wetland Linkages: Landscape Effects on the Distribution of Rare and Common Wetland Reptiles,"* Journal of Zoology*, 275: 245-251, 2008.*

Map 2.18
Natural Areas and Critical Species Habitat Sites Within the Pewaukee Lake Watershed: 2010



NATURAL AREA OF COUNTYWIDE SIGNIFICANCE (NA-2)

NATURAL AREA OF LOCAL SIGNIFICANCE (NA-3)

CRITICAL SPECIES HABITAT SITE (CSH)

PRIMARY ENVIRONMENTAL CORRIDOR (2015)

SURFACE WATER

35 IDENTIFICATION NUMBER (SEE TABLE 2.13)

WETLAND

STREAM

WATERSHED BOUNDARY

Note: Any NA-2, NA-3, CSH or any water bodies that are included in primary environmental corridors are shown with a hatched pattern.

Colors outside the watershed boundary are reduced in intensity to show the adjacent extent and distribution of each legend category.

0 1,250 2,500 5,000 Feet

Source: SEWRPC

Within or immediately adjacent to bodies of water, the WDNR, pursuant to authority granted under Chapter 30 of the *Wisconsin State Statutes* and Chapter NR 170 of the *Wisconsin Administrative Code,* can designate environmentally sensitive areas on lakes that have special biological, geological, ecological, or archaeological significance, "offering critical or unique fish and wildlife habitat, including seasonal or life-stage requirements, or offering water quality or erosion control benefits of the body of water". Wisconsin law mandates special protections for these "sensitive areas", or "Critical Habitat Designation" areas, which are home to approximately 80 percent of the plants and animals on the state's endangered and threatened species list. A significant part of the critical habitat designation lies in the fact that it assists waterfront owners by identifying these areas so that they can design their waterfront projects to protect habitat and ensure the long-term health of the lake where they live. If a project is proposed in a designated Critical Habitat area, the permit process allows WDNR to ensure that proposed projects will not harm these sensitive resources. Those critical habitat areas in the Pewaukee Lake watershed are shown in Map 2.18 and described in Table 2.12. Of particular interest are the "Pewaukee Lake Access Fen" at the extreme western end of the Lake, and the "Pewaukee Lake Wetland" located on the northern shore of the Lake due to their close connection with the Lake itself. Not to be confused with Critical Habitat areas, the WDNR also designates Sensitive Areas on the Lake in which aquatic plant management is limited (see Section 3.5, "Aquatic Plants" more detail on Sensitive Areas).

Critical species are those plants, animals, or other organisms, considered by the Federal or State governments to be rare, threatened, or endangered, or of special concern. Twenty such species known to occur in the watershed are listed in Table 2.13 and include mussels, fish, reptiles, amphibians, birds, and plant species. Photos of each of these critical species and links to life history information are included in Figure 2.18.

2.4 LAKE LEVEL MANIPULATION AND MANAGEMENT CONCERNS

The Lake's outlet elevation was artificially raised about 180 years ago when a dam was built at the point where the Pewaukee River exits the Lake. Today's dam is not the same dam constructed in 1842. Several structures have been erected over the years, most of which relied primarily on a fixed weir elevation to pass water downstream. In such a structure, the amount of water passed by the dam increases as lake elevation increases. The relationship between lake elevation and flow over the recently replaced dam is shown in Figure 2.19. The current dam, built in 2010 and owned and operated by the Village of Pewaukee, uses subsurface gates to release water from the Lake. The outflow rate for the current dam depends upon both gate position and lake level elevation. The outlet dam raises the Lake's water elevation roughly eight feet.

The WDNR classified the lake outlet dam as a "high hazard" structure during 2005. Based on the high hazard rating, *Wisconsin Administrative Code* NR 333 required that the Pewaukee Dam's total spillway capacities be capable of passing the 1,000-year flood event without overtopping the engineered spillway, a finding requiring extensive changes to the dam. The Village of Pewaukee, the owner and operator of the dam, reconstructed the dam with bottomdraw gates and larger downstream concrete box culverts during 2010. The new dam became fully functional in 2011 (see Figure 2.20).

The 2011 dam's gates provide the capability to manipulate Pewaukee Lake's outflow and water elevation[69] and are designed to pass more water from the Lake. This allows the dam operator to draw down the water levels at will and at a much faster rate. However, these gates have changed the way water leaves the lake. Instead of passively passing over the top of the dam, the new structure draws water from under the water surface. Accommodating large increases in outlet flow to pass heavy precipitation and runoff now requires the dam operator to actively and physically alter dam gate positions. Similarly, to maintain Lake levels during extended periods of dry weather, the gates must be closed to a greater degree than wet weather.

The Wisconsin Department of Natural Resources (WDNR) ruled that the Lake's water elevation should be maintained between 852.20 and 852.80 feet (NGVD 1929). These water levels were based upon water levels made between 1920 and 1974. In general, higher water levels are meant to help to support summer recreation while lower levels help provide capacity to store early spring runoff and limit shoreland ice damage. The WDNR water level order stipulates that water levels should be gradually lowered to winter

[69] *A bottomdraw gate opens from the bottom up. The opening through which water leaves the lake is below the water surface and may not be visible.*

Table 2.12
Natural Areas and Critical Species Habitat Sites Within the Pewaukee Lake Watershed

Site Type	Number on Map 2.18	Name	Ownership	Size (acres)	Description
NA-2	35	Pewaukee Lake Access Fen	Waukesha County	10	Good quality calcareous fen on west side of Pewaukee Lake. Contains regionally uncommon plant species, including a good population of the State-designated threatened beaked spike-rush (*Eleocharis rostellata*). Site has improved with program of periodic burning.
NA-3	87	Capitol Drive Sedge Meadow and Wet Prairie	Lake Pewaukee Sanitary District, City of Pewaukee, and private	90	Moderate-quality sedge meadow, wet-mesic prairie, and shallow marsh. Disturbed by highway construction.
	88	Pewaukee Lake Wetland	Private	65	Moderate-quality wetland complex at northwest corner of Pewaukee Lake, consisting of shallow marsh, sedge meadow, and shrub-carr.
	89	Hartland Railroad Prairie	Private	4	Remnant mesic prairie, mostly on hill on north side of railway right-of-way. Characteristic species include big bluestem, rough blazing star, and prairie dock. Threatened by adjacent residential development.
	90	Prairie Wind Farm Woods	Private	22	Moderate-quality dry-mesic woods within residential development.
	93	Golf Cliff Ridge and Woods	Private	8	Small woodland containing limestone outcrops.
	95	Pewaukee Sedge Meadow	Private	13	Small, but good-quality sedge meadow, disturbed by ditching, highway construction, and residential development.
CSH	168	Jungbluth Road Railroad Prairie	Waukesha County and private	2	Small, narrow remnant of wet-mesic prairie between railway and highway.
	170	Taylor Road Woods	Private	30	Disturbed upland woods supports late coral-root orchid (*Corallorhiza odontorhiza*), a State-designated special concern species.
	172	Meadowbrook Prairie	Lake Pewaukee Sanitary District	16	Good population of small white lady's-slipper orchid (*Cypripedium candidum*), a State-designated threatened species, in managed wet-mesic prairie.

Note: The map numbers correspond to those presented in Amendment to SEWRPC Planning Report No. 42, *Amendment to the Natural Areas and Critical Species Habitat Protection and Management Plan for Southeastern Wisconsin*, December 2010.

Source: SEWRPC

levels between October 1st and 15th, gradually increased to summer levels between May 1st and May 15th, and held static during other periods to the extent practical.[70] Manipulating the gate changes the amount of water leaving the Lake, and can therefore influence water levels and help keep them within stipulated ranges.

Since lake elevation and outflow volume are both artificially controlled, and since water levels influence a wide variety of human desires and natural resource needs, water level management is an issue of significant interest. A few of the issues that relate to Lake water level management are briefly examined in this section.

Conditions Impeding Water Level Management

Pewaukee Lake's water levels have been artificially controlled for over 160 years to better serve a variety of human needs and desires. Water levels have been manipulated using flash boards and gates. All water level control structures require maintenance to operate reliably and are prone to operational challenges. As such,

[70] *Andrew Damon, Acting Administrator, Division of Enforcement, Wisconsin Department of Natural Resources, Order Associated with* Application of the Lake Pewaukee Sanitary District to Formally Establish the Existing Maximum Level and to Set a Minimum Level for Pewaukee Lake, Towns of Pewaukee and Delafield, Waukesha *County, 3-WR-1576, June 18, 1974.*

Table 2.13
Endangered and Threatened Species and Species of Special Concern Within the Pewaukee Lake Watershed: 2017

Common Name	Scientific Name	Status Under the U.S. Endangered Species Act	Wisconsin Status
Mussels			
Ellipse	*Venustaconcha ellipsiformis*	Not listed	Threatened
Fish			
Lake Chubsucker	*Erimyzon sucetta*	Not listed	Special concern
Pugnose Shiner	*Notropis anogenus*	Not listed	Threatened
Reptiles and Amphibians			
American Bullfrog	*Lithobates catesbeiana*	Not listed	Special concern
Blanchard's Cricket Frog	*Acris blanchardi*	Not listed	Endangered
Blanding's Turtle	*Emydoidea blandingii*	Not listed	Special concern
Butler's Garter Snake	*Thamnophis butleri*	Not listed	Special concern
Birds			
Black-Crowned Night-Heron	*Nycticorax nycticorax*	Not listed	Special concern/migrant[a]
Cerulean Warbler	*Dendroica cerulea*	Not listed	Threatened
Mammals			
Northern Long-Eared Bat	*Myotis septentrionalis*	Federally threatened	Endangered
Plants			
Autumn Coralroot	*Corallorhiza odontorhiza*	Not listed	Special concern
Beaked Spikerush	*Eleocharis rostellata*	Not listed	Threatened
Butternut	*Juglans cinerea*	Not listed	Special concern
Common Hoptree	*Ptelea trifoliata*	Not listed	Special concern
Hairy Beardtongue	*Penstemon hirsutus*	Not listed	Special concern
Hooker's Orchid	*Platanthera hookeri*	Not listed	Special concern
Kentucky Coffeetree	*Gymnocladus dioicus*	Not listed	Special concern
Prairie White-Fringed Orchid	*Platanthera leucophaea*	Federally threatened	Endangered
Small White Lady's Slipper	*Cypripedium candidum*	Not listed	Threatened

[a] *Migrant (i.e., fully protected by Federal and State laws under the Migratory Bird Act).*

Source: Wisconsin Department of Natural Resources, Wisconsin State Herbarium, United States Fish and Wildlife Service and SEWRPC

the Pewaukee Lake outlet experiences a variety of issues that require attention to allow water levels to be successfully manipulated. Examples of some of the more common and important concerns are discussed in this section.

Debris (e.g., leaves, uprooted and free floating aquatic plants, logs, floating ice) tends to be drawn to and accumulate just upstream of the Lake's outlet structure. Accumulating debris can reduce gate capacity and impede gate adjustment. To help clear debris, the gate has been opened more fully to allow debris to flush through the outlet works. However, during winter, ice can form in the outlet area and/or on gate components, locking the gate into a set position. In such circumstances, outflow from the lake cannot be adjusted until ice melts.[71] In anticipation of winter gate inoperability, the dam operator makes an intuitive assessment of how to position the gate to best achieve the desired winter season lake level.[72] However, this situation can lead to undesirable and uncontrollable fluctuation of the Lake's water elevation, particularly during heavy mid-winter rainfall or snowmelt events. Actions to promote safe and predictable dam operation are described in Chapter 3.

[71] *Personal communication, Daniel Naze, P. E., Village of Pewaukee Director of Public Works/Village Engineer, January 16, 2018.*

[72] *D.J. Naze, 2018,* op. cit.

Figure 2.18
Endangered, Threatened, and Special Concern Species Photos Within the Pewaukee Lake Watershed

MUSSELS	FISH

Ellipse

Lake Chubsucker

FISH (CONTINUED)	REPTILES AND AMPHIBIANS

Pugnose Shiner

American Bullfrog

REPTILES AND AMPHIBIANS (CONTINUED)

Blanchard's Cricket Frog

Blanding's Turtle

Figure 2.18 (continued)

REPTILES AND AMPHIBIANS (CONTINUED)

Butler's Garter Snake

Credit: Flickr User Todd Pierson

BIRDS

Black-Crowned Night Heron (juvenile)

Credit: Flickr User cuatrok77

BIRDS (CONTINUED)

Black-Crowned Night Heron (adult)

Credit: Wikimedia Commons User Dick Daniels

Cerulean Warbler

Credit: Wikimeda Commons User mdf

MAMMALS

Northern Long-Eared Bat

Credit: Flickr User USFWS Headquarters

PLANTS

Autumn Coralroot

Credit: Flickr User Judy Gallagher

Figure 2.18 (continued)

PLANTS (CONTINUED)

Beaked Spikerush

Butternut Tree

Common Hoptree

Hairy Beardtongue

Hooker's Orchid

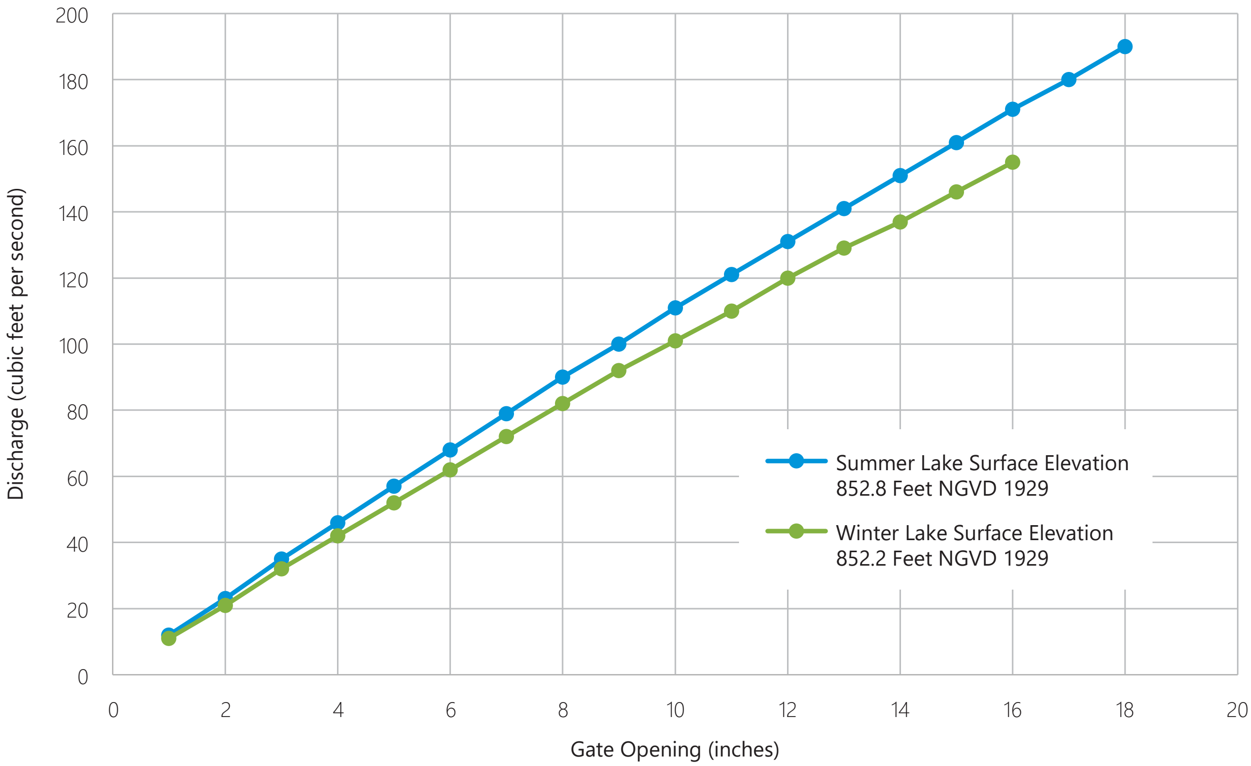
Kentucky Coffeetree

Prairie White-Fringed Orchid

Small White Lady's Slipper

Source: SEWRPC

Figure 2.19
Existing Pewaukee Lake Dam Discharge Capacity Nomogram



Source: David White, Engineer, Village of Pewaukee, and SEWRPC

Artificial Water Level/Flow Regimens

Pewaukee Lake and its dam influence and interrupt the physical, chemical, and biological continuity of the Pewaukee River watershed in many ways.[73] For example, the Lake modulates extreme tributary flows during all seasons. Furthermore, most sediment and nutrients carried by Lake tributaries remain in the Lake and are not passed downstream to the Pewaukee River, while the naturally cool water of the streams warms during summer as it passes through the Lake. Finally, the types of plants and animals living in still water are often quite different than those living in actively flowing water.

Similar to lakes, dams interrupt the normal upstream to downstream continuum of characteristics within a natural stream system.[74] An example of changes caused by Pewaukee Lake's outlet dam is its impact on the movement of fish and other aquatic organisms between the Lake, the Pewaukee River, and points further downstream. Fish from as far away as the Gulf of Mexico once migrated to Southeastern Wisconsin and certain migratory fish likely frequented Pewaukee Lake. The lake outlet dam and all other dams downstream of the Lake impede the ability of fish and other aquatic organisms to freely migrate. Fish may be able to move downstream but many cannot return to the Lake. Moreover, the installation of the bottom-draw gate on the dam has increased the potential for fish to be transported downstream to the Pewaukee River. Walleye abundance has anecdotally increased just below the dam since installing bottom-draw gate.

The artificial water level increase caused by the outlet dam not only inundated former wetland and upland habitat, but also influenced streams upstream of the dam. The lower portions of all stream tributaries to Pewaukee Lake were profoundly changed when the Lake was dammed and water levels rose. These formerly freely flowing stream segments were converted to quiescent water areas by the new reservoir,

[73] *J.V. Ward, and J.A. Stanford, The Serial Discontinuity Concept of Lotic Ecosystems, In* Dynamics of Lotic Ecosystems *(T.D. Fontaine and S.M. Bartell, editors), Ann Arbor Science Publishers, Ann Arbor, MI, pp. 29-42, 1983.*

[74] *R.L. Vannote, G.W. Minshall, K.W. Cummings, J.R. Sedell, and C.E. Cushing, "The River Continuum Concept,"* Canadian Journal of Fisheries and Aquatic Sciences, *37: 130-137, 1980.*

and the former channels likely filled with materials eroded from uplands converted to land uses that yielded much more sediment than long-standing natural conditions. Because of this, the lower portions of all streams feeding Pewaukee Lake do not contain naturally occurring cobbles or boulders and instead are underlain by thick deposits of silt, sand, and gravel.

Under natural conditions, a lake's water elevation normally rises in spring and declines during warm, dry summers. Certain plants and animal communities adapted to this rhythm and came to depend upon it. Humans tend to manage lake water levels out of phase with this natural rhythm, with water levels held highest during warm, dry summer weather (often artificially decreasing naturally low flows in outlet streams) and low during winter and early spring to lessen ice damage and detain floodwater. A growing body of scientific evidence suggests that water management practices based upon an arbitrary minimum flow or static lake elevation do not necessarily foster water body function and healthy ecosystems. However, most dam operation permits require essentially static water levels. Therefore, to protect freshwater biodiversity and maintain healthy waterbodies, it is desirable to attempt to mimic natural flow and water elevation variability to the extent practical. In streams, this includes mimicking flow volume, timing, duration, and rate of change. This can benefit rivers in many ways. For example, high flow events can flush accumulated sediment and flotsam, helping to maintain the stream channel's natural morphology, bed composition, and with its ability to pass flood water and provide suitable substrate for native organisms. Moreover, high flows can maintain the river's deep pools that provide sorely needed refuge areas during periods of low water. High flow events in early spring also are essential to migration and spawning of certain species of native fish (e.g., northern pike, suckers, and many prey species). Therefore, it is likely more beneficial to release large volumes of water for short periods of time in early spring as opposed to releasing small uniform quantities of water over long time frames. On a similar note, purposely managing lake water levels (to the extent possible within the operating order) may help promote the health of desirable plants and animals (e.g., bulrush).

Figure 2.20
Pewaukee Lake Dam Outlet Infrastructure Configuration

Pre-Construction

During-Construction: October 18, 2010

Post-Construction: August 15, 2011

Source: Charlie Shong and SEWRPC

Balancing Lake Water Elevations with Pewaukee River Flows

As opposed to a natural system or simple weir where lake water levels and outlet flows are essentially uncontrolled and vary only with lake elevation, Pewaukee Lake's gated dam allows the dam operator to exercise considerable discretion to modify outlet flow and thereby achieve various management objectives. Unfortunately, many of the management objectives may conflict with one another. For example, if water is held in the Lake to decrease flow in the Pewaukee River downstream of the dam, higher, longer term, or more serious flooding may occur around the Lake's shoreline. Therefore, maintaining desirable water elevations in the Lake and flow in the River requires balancing competing tradeoffs.

The water level order allows the dam operator to exercise prudence to achieve target lake elevations. The existing dam is designed to safely pass the enormous quantities of water associated with extreme precipitation events and may have to do so to maintain dam integrity. Passing large flows through the dam increases the stage of the Pewaukee River downstream of the Lake, a River stretch where the channel slope is relatively flat and flow is constrained by several bridges, artificially confined stream reaches, debris, and other obstructions. These conditions make the Pewaukee River downstream prone to substantial water level variation when large volumes of water are released from the Lake. In turn, this situation can flood downstream property, causing inconvenience and potential harm to those with properties abutting or influenced by the River. Although it is theoretically possible to temporarily modulate flows in the River with the Lake outlet dam to protect properties along the River, the Lake outlet dam was not designed to store floodwater to alleviate flooding, and holding back water during extreme events or on a regular basis could compromise the dam's long-term integrity. Additionally, the Federal Emergency Management Agency (FEMA) does not currently consider the dam a flood control structure. Therefore, while attempts are made to be sensitive to downstream flooding, the dam operator also must consider the ramifications of increasing or maintaining high water levels in the Lake.

Excessive and/or extreme Lake water elevation fluctuation is a great concern to the LPSD, resource managers, and residents of the Lake. Excessively low water elevations impedes Lake access and navigation and therefore may compromise recreational use, aquatic plant harvesting, and the ability of migrating fish to reach life-cycle critical habitat (e.g., spawning, nursery, feeding, and refuge areas). For example, northern pike spawning habitat is located in tributary streams and higher lake levels often promotes better fish passage into these tributaries. In contrast, excessively high lake water surface elevations can foster shoreline erosion, may promote decline of riparian and emergent vegetation, may help make shorelines more vulnerable to wave and ice damage, can flood buildings and infrastructure, and can allow clean water to enter sanitary sewers, which can force a sanitary sewer bypass event. To limit shoreline erosion, during periods of high water (defined as a water level of 853.4 feet above NVGD or greater), a local ordinance forbids operating boats at speeds faster than slownowake speed. When Lake elevations reach approximately 854.0 feet above NVGD, water is prone to enter low-lying buildings and sanitary sewer manholes, a condition that can damage property and overwhelm the sanitary sewer system's capacity. Even higher water levels begin to encroach on Wisconsin Avenue at the east end of the Lake. Water elevation thresholds are compared to recent Lake water elevations in Figure 2.21.

A substantial portion of the Pewaukee River's flow originates at the Lake outlet dam. During dry weather, the Lake acts as a reservoir, sustaining critical dry-weather flow. However, according to lake stage records, water levels in the Lake commonly fell below the former weir-type dam's control elevation, meaning that surface-water flow from the Lake to the River ceased during drought periods (see Figure 2.21). The current dam can draw water from several feet deeper than the old dam and can therefore contribute flow to the River during more intense drought. To protect aquatic organisms, the WDNR desires that some minimum level of flow (e.g., one cubic foot per second) be released from the Lake to the River, even if this means decreasing the Lake's water elevation below 852.2 feet above NVGD, the minimum water surface elevation goal.[75] Although there is no mandatory provision to maintain a minimum baseflow discharge at the Lake outlet to sustain the Pewaukee River's ecosystem, the Village generally opens the gate at least one full turn of the control mechanism to maintain a flow of about 0.5 cubic feet per second in the River immediately downstream of the dam.[76,77] This flow is similar to that measured by the Water Action Volunteers program downstream of the dam during drought periods. The River just downstream of the dam does receive additional dry weather flow through incidental leakage at the dam site, indirectly from the Lake via groundwater discharge, and from the North Branch of the Pewaukee River.

While the River's low flow can be maintained with few management problems, operating the dam's gates in a substantially open position can potentially flood low-lying downstream areas. The length and intensity of the flooding are related to outlet dam gate position and lake elevation. For a given volume of water, higher release rates will cause deeper flooding, but the flooding will persist for a shorter period of time, and

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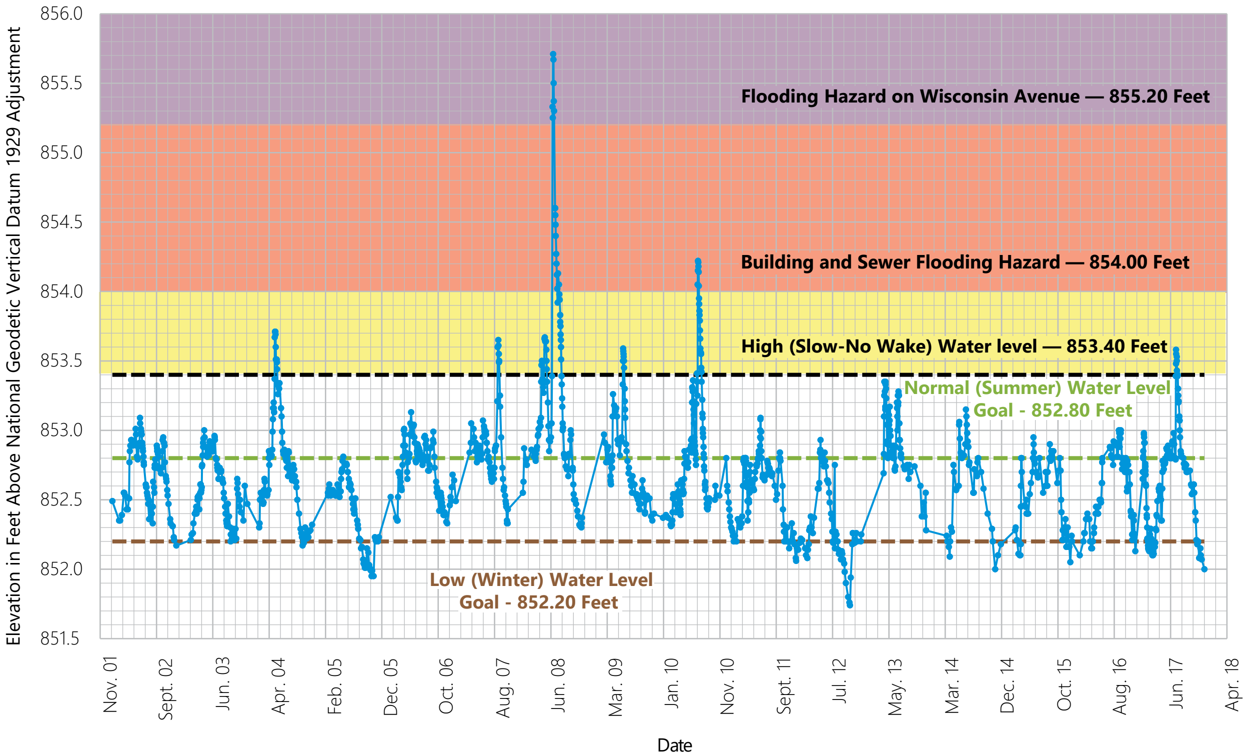
[75] *Personal communication with Michelle Hase, P. E., Water Regulations and Zoning Engineer, Wisconsin Department of Natural Resources.*

[76] *Personal Communication, David White, Engineer, Village of Pewaukee, August 2013.*

[77] *D.J. Naze, 2018,* op. cit.

Figure 2.21
Lake Water Surface Elevations and Their Influence on Lake Use and Infrastructures



Note: Floor of dam outlet elevation is 849.00 feet.

Source: Pewaukee Lake Sanitary District, Village of Pewaukee, and SEWRPC

may help maintain a clear stream channel and desirable habitat features. Conversely, slower release rates will limit the maximum depth of flooding, but the flooding will continue for longer periods of time, and the stream's ability to maintain desirable channel form and habitat conditions may be impaired. The depth and duration of flooding must be managed to minimize riparian damage and inconvenience, normalize Lake elevation over reasonably short periods of time, and promote desirable stream channel form and ecological health. Achieving this balance will require studying the conveyance capacity of the downstream channel and establishing reference point elevations to judge the effect of different gate positions.

The channel downstream of the dam is artificially constricted at several locations, a situation creating flood-prone areas. Examples include several undersized road/stream crossings that backwater floodwater and human-manipulated channels (e.g., filled floodplains, encroaching retaining walls) that compromise the River's conveyance and floodwater detention capacity. Although a comprehensive examination and description of these features is well beyond the scope of the this study, identifying features that accentuate flooding is a first step to improving the ability of the dam to pass flow volumes better in sync with the downstream river channel's capacity. A brief examination of FEMA flood profile for the Pewaukee River downstream of the dam reveals that floodwater backwaters at Wisconsin Avenue and at a point just upstream of State Highway 16. In addition to backwatering, flood elevations may be increased by human floodplain encroachment. As a starting point, it is highly advisable to investigate this reach, rectify conveyance capacity concerns, and thereby reduce flooding associated with normal dam operation.

Dam operation also has important implications for aquatic habitat. Lakes and streams typically reach their lowest levels in late summer. Frogs, turtles, and other herptiles burrow into bottom sediments in early fall to hibernate over the winter. Early lake draw down can mimic late season low water, assuring that herptiles hibernate in areas that remain submerged during winter water level drawdown. Natural lakes occasionally experience long periods of lower than normal water levels during extended periods of dry weather, a condition vital to regeneration of several desirable emergent aquatic plant species. Holding water elevations static year after year can favor undesirable changes in the aquatic plant community. In summary, a dynamic water management policy, to the extent practicable with the operating order of the dam, protects river channel form and function, ecological health, biodiversity and helps maintain the benefits that both Pewaukee Lake and the Pewaukee River provide.

Fitting the dam with a bottom-draw gate in 2010 has helped reduce the frequency of high surface water elevations on the Lake. Lake surface water elevations were monitored from 2001 to 2017 in cooperation with the Village of Pewaukee and the LPSD (see Figure 2.21). However, significant gaps in this data set occur during winter (e.g., winter of 2012) when data was not recorded as ice locked the gate into a set position. Casual correlation of 2003 – 2017 Lake surface elevation with larger rainfall events suggests that Lake elevations can rise approximately six inches for every 3.5 inches of rainfall within 24 hours (see Figure 2.22). This underscores the need to actively change gate position to match actual or forecast weather conditions, especially in winter when gates could be frozen and runoff can be heavy on frozen ground. Examples of suggestions to improve dam operation are included in Chapter 3.

Fitting the dam with a bottom-draw gate influenced the dam's tendency to entrain Lake-bottom sediment. Formerly, active flow was at the water surface, away from sediment. Now, the highest velocity water with the greatest capacity to move sediment is located near the Lake bottom, a situation which has increased the capacity to remove imported beach sand and other sediment from the east end of the Lake and ultimately redeposit this material downstream. This transport may be related to the recent reports of channel aggradation (i.e., filling) downstream of the dam. Several attempts to recreate a more functional stream channel have been made by the Village of Pewaukee, the Pewaukee River Partnership, and LPSD staff. Continued operation of the dam can affect the stability and composition of habitats downstream and is an issue of concern. More details regarding enhancement and protection are included in Chapter 3.

A staff gage affixed to the dam is used to monitor Lake water surface elevation. While functional, closely tracking water levels can be time-consuming, particularly during periods of rapidly changing water level. In addition, residents cannot conveniently review lake surface elevation and elevation trends. Hence, many calls of concern are made to the Village of Pewaukee and LPSD regarding water level questions, particularly during heavy rainfall, a situation taxing staff time by diverting effort to answering questions and away from protecting threatened infrastructure and/or responding to emergencies. Suggestions that may enhance water level monitoring and reporting are presented in Chapter 3.

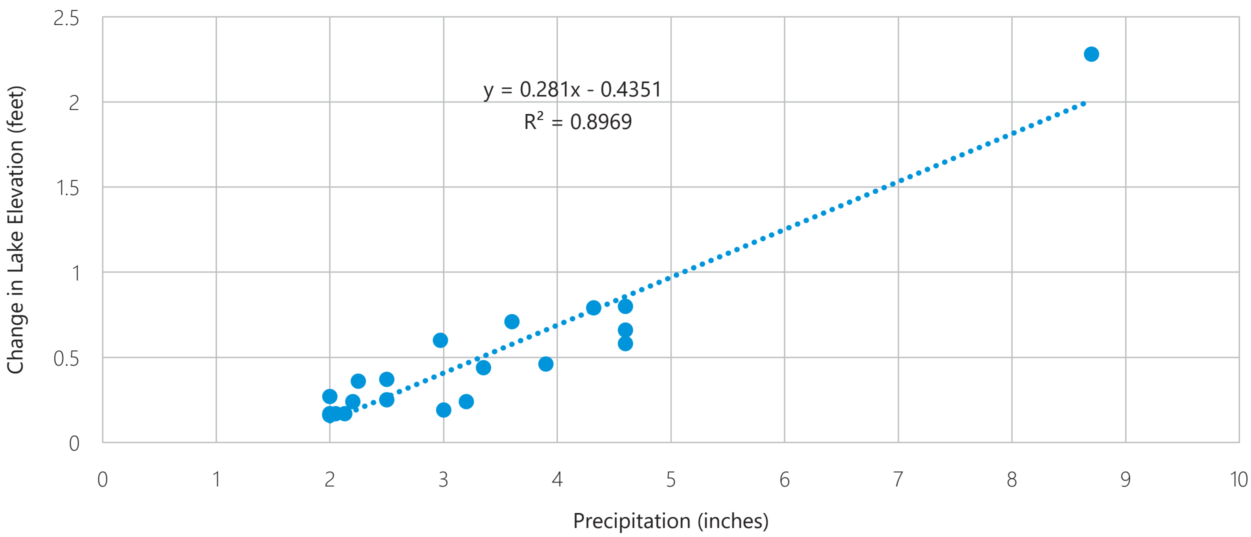
2.5 WATER QUALITY

Actual and perceived water quality are generally high priority concerns to lake and stream resource managers, residents, and Lake users. Concern is often expressed that pollutants entering the Lake from various sources have or could degrade water quality over time. The water quality information presented in this section can help interested parties better understand the current and historical conditions, trends, and dynamics of Pewaukee Lake and its major tributaries. By interpreting and applying this information, management strategies can target issues that have the highest likelihood of protecting the long-term health of these water bodies.

When discussing water quality, it is important to consider what "water quality" means, since individuals have varying perceptions, experiences, and levels of understanding. To the casual observer, water quality is commonly described using visual cues. For example, algae, cloudy water, and heavy growth of aquatic plants leads some to conclude a lake is "unclean." To judge if such a conclusion is merited and/or to quantify water quality, lake managers and residents must carefully examine specific chemical, physical, and biological parameters that influence or indicate water quality. Common metrics used to assess water quality include: water clarity, water temperature, and the concentrations of chloride, phosphorus, chlorophyll-*a*, and dissolved oxygen (DO) (see Table 2.14 for more information regarding the meaning and significance of these parameters).

Water quality metrics commonly respond in reaction to water quality changes. For example, nutrients from eroded topsoil and common fertilizers can cause a lake's phosphorus concentrations to increase. Increased phosphorus concentrations fuel algal growth. Increased algal abundance causes lake water to become cloudier, diminishing water clarity. Finally, chlorophyll-*a* concentrations (a measure of algae content) increase. In addition to water clarity, phosphorus, chlorophyll-*a*, and DO values, a number of other

Figure 2.22
Changes in Water Surface Elevation of Pewaukee Lake Caused by Precipitation Events Greater Than or Equal to Two Inches Within 24 Hours: 2003-2017



Note: These data are based upon daily readings of precipitation and lake level changes, except for three storm events that were a composite of total precipitation for the following dates; 6/7-6/8/2010, 6/22-6/24/2010, and 7/12-7/14/2017. The evaluation used the following gages for precipitation: Village of Pewaukee (5/11/2003-5/15/2018) and Pewaukee 3.8 WSW, USIWIWK0022, 3/3/2010-5/18/2018.

Source: Village of Pewaukee, NOAA, and SEWRPC

parameters can also help determine the "general health" of a lake. For example, the abundance of the bacteria *Escherichia coli*, commonly known as *E. coli*, is often measured as an indicator if lake water is safe for swimming while chloride concentrations are an indicator of overall human-induced pollution entering a lake.[78] Key water-quality indices must be regularly measured over long periods of time to develop a water quality maintenance and improvement program. This allows lake managers to establish baselines and identify trends.

Pewaukee Lake

To help quantify Pewaukee Lake's water quality, the Commission compiled available water quality data and analyzed these data in the context of relevant limnological factors. For example, by examining oxygen/temperature profiles, phosphorus concentrations, chlorophyll-*a* concentrations, and Secchi depth measurements, Pewaukee Lake is known to thermally stratify during summer, is prone to internal loading of phosphorus, and is meso-eutrophic.[79] These and other characteristics are examined and discussed in more detail in the following sections.

Lake Characteristics Influencing Water Quality

Water quality fluctuates over short- and long-term time periods. Therefore, thorough evaluation of lake water quality must rely on periodically monitoring various chemical and physical properties (ideally at the same depths and locations) over protracted time periods. Monitoring data are used to evaluate the level and nature of pollution within a lake, the risks associated with that pollution, the lake's ability to support various fish and recreational uses, and overall lake health. When examining water quality, it is

[78] *Chloride is used as an indicator of human-induced pollution because natural chloride concentrations are low in Southeastern Wisconsin. Chloride is a "conservative pollutant" meaning that it remains in the environment once released and is not attenuated by natural processes other than dilution. High chloride concentrations may result from road salt transported in runoff, fertilizer application, private onsite wastewater treatment systems that discharge to the groundwater that provides baseflow for streams and lakes, and a multitude of other sources.*

[79] *The trophic status of Pewaukee Lake was determined using the Wisconsin Trophic State Index value formula with Secchi disk measurements, total phosphorus levels, and chlorophyll-*a* levels.*

Table 2.14
Lake Water Quality Parameter Descriptions, Typical Values, and Regulatory Limits/Guidelines

Parameter	Description	Southeastern Wisconsin Values[a]		Regulatory Limit or Guideline	Pewaukee Lake Values	
		Median	Range		Median	Range
Chloride (mg/L)	Low concentrations (e.g., < 5 mg/L) naturally occur in lakes due to natural weathering of bedrock and soils. Human activities increase concentrations (e.g., road salts, wastewater, water softener regeneration) and can affect certain plants and animals. Chloride remains in solution once in the environment and **can serve as an excellent indicator of other pollutants.**	41	18-260	Acute toxicity[b,c] 757 Chronic toxicity[b,c] 395	60[d]	28-146
Chlorophyll-*a* (µg/L)	The major photosynthetic "green" pigment in algae. The amount of chlorophyll-*a* present in the water is an indicator of the biomass, or amount of algae, in the water. **Chlorophyll-*a* levels above 10 µg/L generally result in a green-colored water** that may be severe enough to impair recreational activities such as swimming or waterskiing and are commonly associated with eutrophic lake conditions.	9.9	1.8-706.1	2.6[e]	8.3[f]	0.94-36.1[f]
Dissolved Oxygen (mg/L)	Dissolved oxygen levels are one of the most critical factors affecting the living organisms of a lake ecosystem. Generally, dissolved oxygen levels are higher at the surface of a lake, where there is an interchange between the water and atmosphere, stirring by wind action, and production of oxygen by plant photosynthesis. Dissolved oxygen levels are usually lowest near the bottom of a lake where decomposer organisms and chemical oxidation processes deplete oxygen during the decay process. **A concentration of 5.0 mg/L is considered the minimum level below which many oxygen-consuming organisms, such as fish, become stressed**. Many species of fish are unlikely to survive when dissolved oxygen concentrations drop below 2.0 mg/L.	--	--	≥5.0[e]	7.8[g]	0.0-17.6
Growing Season Epilimnetic Total Phosphorus (µg/L)	Phosphorus enters a lake from natural and human-derived sources and is a fundamental building block for plant growth. Excessive phosphorus can lead to nuisance levels of plant growth, unsightly algal blooms, decreased water clarity, and oxygen depletion, all of which can stress or kill fish and other aquatic life**. A concentration of less than 30 µg/L is the concentration considered necessary in a drainage lake such as Pewaukee Lake** to limit algal and aquatic plant growth to levels consistent with recreational water use objectives. Phosphorus concentration exceeding 30 µg/L are considered to be indicative of eutrophic lake conditions.	30	8-720	30[e]	18.6[f]	10-160[f]

Table continued on next page.

Table 2.14 (Continued)

Parameter	Description	Southeastern Wisconsin Values[a]		Regulatory Limit or Guideline	Pewaukee Lake Values	
		Median	Range		Median	Range
Water Clarity (feet)	Measured with a Secchi disk (a ballasted black-and-white, eight-inch-diameter plate), which is lowered into the water until a depth is reached at which the disk is no longer visible. It can be affected by physical factors, such as suspended particles or water color, and by various biologic factors, including seasonal variations in planktonic algal populations living in a lake. **Measurements less than five feet are considered indicative of poor water clarity and eutrophic lake conditions**.	4.6	3-12	10.9[h]	5.9	0-17.4[f]
Water Temperature (°F)	Temperature increases above seasonal ranges are dangerous to fish and other aquatic life. Higher temperatures depress dissolved oxygen concentrations and often correlate with increases of other pollutants.	--	--	Ambient[e] 35-77 Sub-lethal[e] 49-80 Acute[e] 77-87	--[g]	32-83.5

[a] *Wisconsin Department of Natural Resources Technical Bulletin No. 138,* Limnological Characteristics of Wisconsin Lakes, *Richard A. Lillie and John W. Mason*, 1983.

[b] Wisconsin Administration Code *Chapter NR 105, Surface Water Quality Criteria and Secondary Values for Toxic Substances. July, 2010.*

[c] *Pollutants that will kill or adversely affect aquatic organisms after a short-term exposure are termed acutely toxic. Chronic toxicity relates to concentrations of pollutants that will kill or adversely affect aquatic organisms over long time periods (time periods that are a substantial portion of the natural life expectancy of an organism).*

[d] *1973-2018; Chloride concentrations have been consistently increasing across the region, and current chloride concentrations are likely higher.*

[e] Wisconsin Administrative Code *Chapter NR 102, Water Quality Standards for Wisconsin Surface Waters, November 2010.*

[f] *Values collected, during growing season (June 1 through August 31) 1972-2013 for Chlor-a, 1972-2016 for total phosphorus; for water clarity, values based on combined east and west basins annual average 1972-2016.*

[g] *Oxygen concentrations and temperatures vary with depth and season. Median values provide little insight to understand lake conditions.*

[h] *U.S. Environmental Protection Agency*, Ambient Water Quality Criteria Recommendations: Information Supporting the Development of State and Tribal Nutrient Criteria: Lakes and Reservoirs in Nutrient Ecoregion VII, *EPA 822-B-00-009, December 2000.*

Source: Wisconsin Department of Natural Resources, Wisconsin

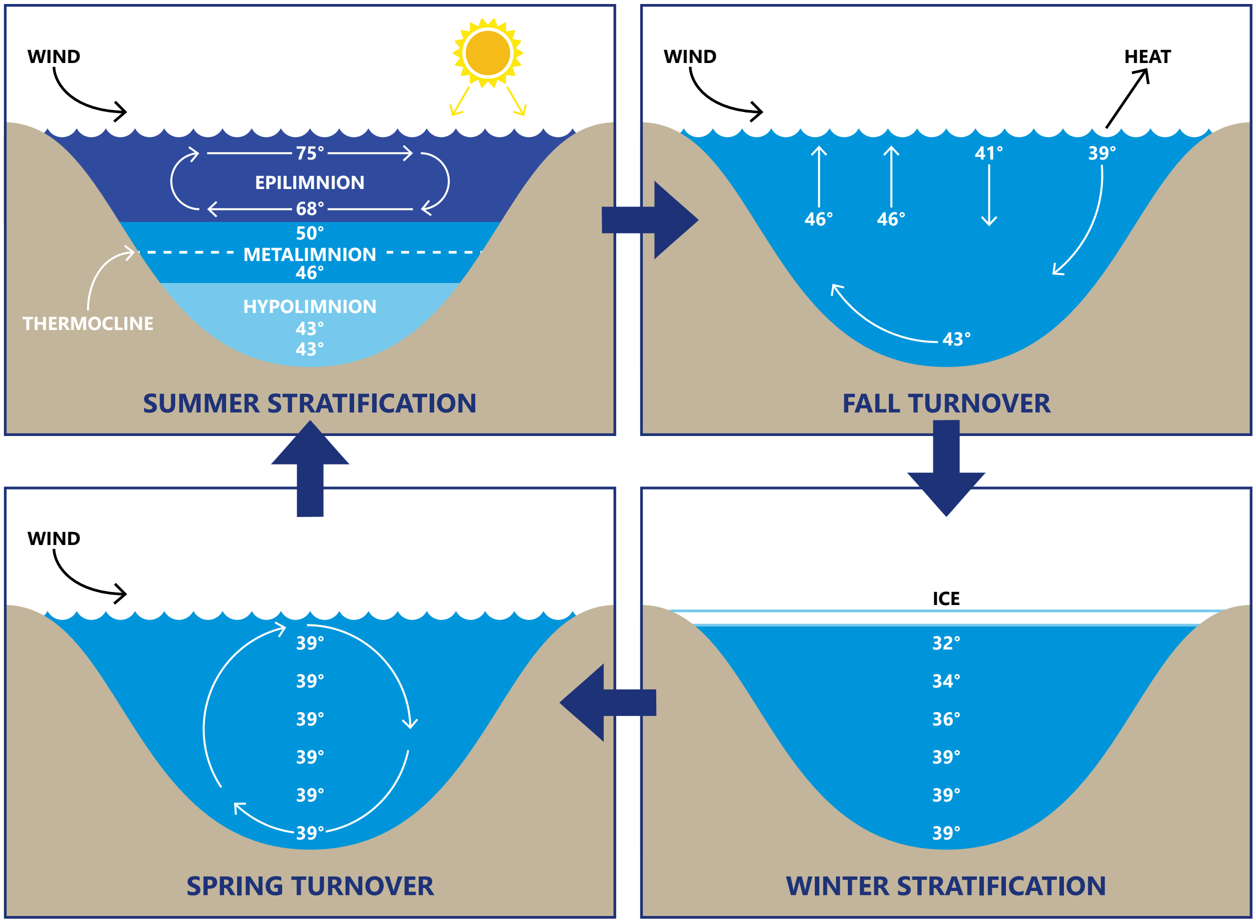
important to understand certain lake characteristics that provide context and meaning to the data. These lake characteristics include:

1. **A lake's residence time**—Residence time helps determine how quickly pollution problems can be resolved.

2. **Whether the lake stratifies and, if it does, when the lake mixes**—Stratification refers to a condition when the temperature difference (and associated density difference) between a lake's surface waters (the *epilimnion*) and the deep waters (the *hypolimnion*) is great enough to form thermal layers that can impede mixing of gases and dissolved substances between the two layers (see Figure 2.23).

3. **Whether internal loading is occurring**—*Internal loading* refers to release of phosphorus stored in a lake's bottom sediment under certain water quality conditions associated with stratification. Additional phosphorus loading can lead to increased plant and algal growth. If this is occurring, a water quality management plan may focus on in-lake phosphorus management efforts in addition to preventing polluted runoff from entering the lake.

Figure 2.23
Typical Seasonal Thermal Stratification Within Deeper Lakes



Source: Modified from B. Shaw, C. Mechenich, and L. Klessig, Understanding Lake Data, *University of Wisconsin-Extension, p. 3, 2004 and SEWRPC*

4. **The lake's current and past trophic status**—Lakes are commonly classified according to their degree of nutrient enrichment, or trophic status. The ability of lakes to support a variety of recreational activities and healthy fish and other aquatic life communities is often correlated with the lake's degree of nutrient enrichment. Three terms are generally used to describe the trophic status of a lake: oligotrophic (nutrient poor), mesotrophic (moderately fertile), and eutrophic (nutrient rich) (see Figure 2.24). Each of these states can happen naturally. Lakes tend to naturally shift to a more nutrient-rich state, a progression sometimes referred to as "aging" (see Figure 2.25). However, if a lake rapidly shifts to a more eutrophic state, human-induced pollution may be responsible for this change. An indicator of severe human pollution is when a lake displays "hyper-eutrophic" nutrient levels, a condition indicating highly enriched water (see Figure 2.26). Hyper-eutrophic conditions do not commonly occur under natural conditions, and are nearly always related to human pollutant sources.

5. **Lake tributary area/type**—Lakes with large tributary streams commonly receive larger sediment and nutrient loads than lakes that are fed primarily by precipitation or groundwater. The type of land use in the watershed greatly effects the pollutant loads carried by tributary streams. Lakes that are fed primarily by tributary streams are labeled drainage lakes.

Historical Data

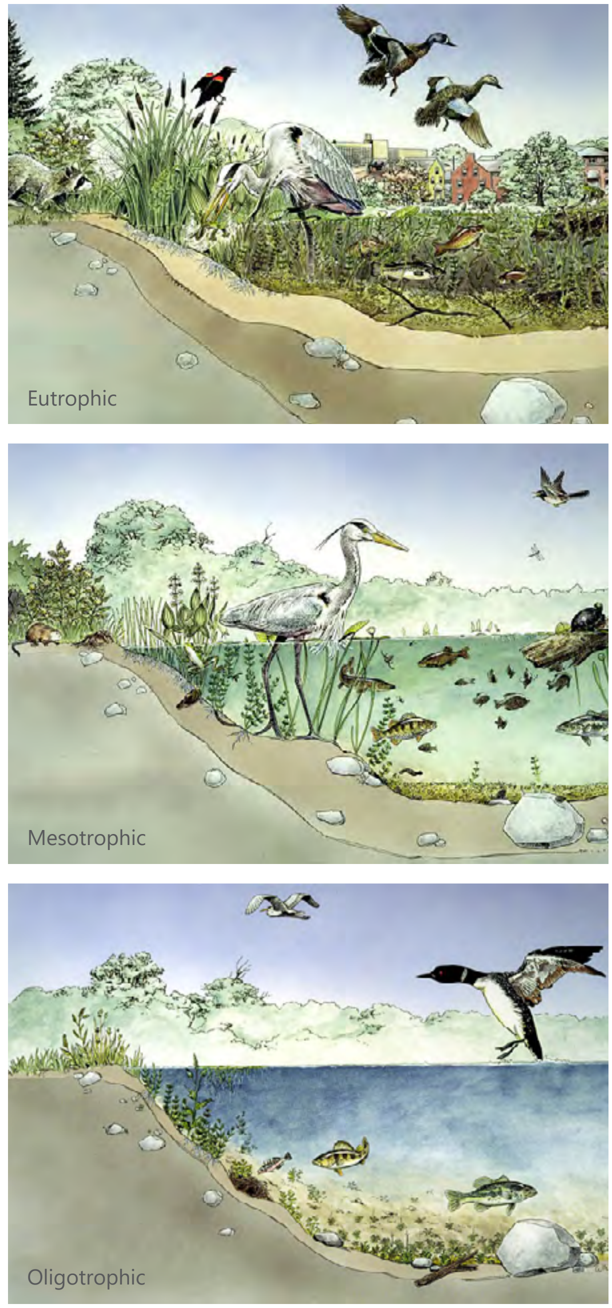
Pewaukee Lake has one of the longest running and most complete water quality records in Southeastern Wisconsin, dating from the turn of the previous century to the present day (i.e., over one hundred years). The earliest known water quality data for Pewaukee Lake dates back to the early 1900s, when Edward

Birge and Chancey Juday, widely-recognized pioneering lake researchers from the University of Wisconsin, collected basic information on the Lake.[80] The Wisconsin Conservation Department, now the Wisconsin Department of Natural Resources (WDNR), collected water chemistry data for Pewaukee Lake in 1944, 1946, and 1950, and between 1963 and 1966. Additional data were included in the 1963 WDNR Report, *Surface Water Resources of Waukesha County*,[81] and other data are included in miscellaneous WDNR file data and reports. The WDNR periodically monitored Pewaukee Lake's water quality between 1972 and 1981, and, under the auspices of their Long-Term Trend Monitoring Program, from 1986 to the present day.[82] During 1983, the WDNR published a compendium of water quality data for lakes in Wisconsin that allows the Lake's water quality to be contrasted to similar or nearby lakes.[83] Sediment core samples were collected by the WDNR from the lake bottom during 1994 that revealed increased sedimentation rates dating back to the 1920s.

State agencies are not the only organizations collecting water quality information at Pewaukee Lake. From 1986 through 1992, Pewaukee Lake residents participated in the WDNR Self-Help Lake Monitoring Program in which volunteers regularly collected and recorded basic water quality data and submitted their records to the WDNR for storage and compilation. The LPSD began monitoring water clarity with a Secchi disk in 1992. This monitoring effort has expanded over the years, and now includes biweekly temperature and oxygen profiles in both the east and west basins.

As illustrated in Map 2.19, water quality samples have been collected in Pewaukee Lake (east and west basins) and its three main tributaries: Coco Creek, Meadowbrook Creek, and Zion Creek. The primary sampling site for the Lake has historically been the "deep hole" in the west basin of the Lake. Water quality data from the shallow east basin of Pewaukee Lake are also included in this report to the extent such sampling has occurred.

Figure 2.24
Comparison of Lake Trophic Status



Source: UW-Extension Lakes Program and SEWRPC

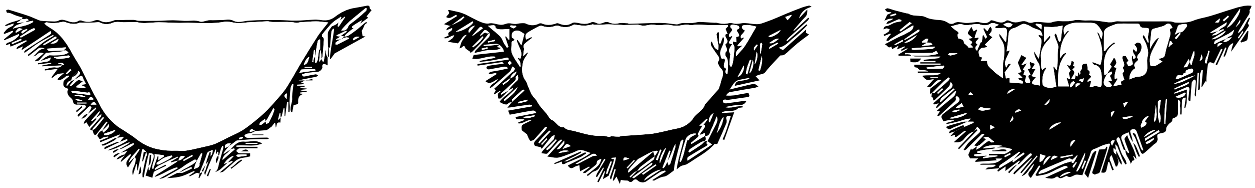
[80] *E.A. Birge and C. Juday,* The Inland Lakes of Wisconsin: The Dissolved Gases and their Biological Significance*, Wisconsin Geological and Natural History Survey Bulletin No. XXII, 1911.*

[81] *R.J. Poff and C.W. Threinen,* Surface Water Resources of Waukesha County, *Wisconsin Conservation Department, p. 69, 1963.*

[82] *Wisconsin Department of Natural Resources,* Pewaukee Lake, Waukesha County: Long-Term Trend Lake, 1986, *1986; Wisconsin Department of Natural Resources,* Pewaukee Lake, Waukesha County: Long-Term Trend Lake, 1987, *1987; E. R. Schumacher, Wisconsin Department of Natural Resources Fish Management Report No. 131,* Creel Survey on Pewaukee and Nagawicka Lakes, Waukesha County, Summer 1982, *February 1987; and Wisconsin Department of Natural Resources,* Pewaukee Lake Sensitive Area Study, *June 1994.*

[83] *Lillie and Mason, 1983, op. cit.*

Figure 2.25
Lake Aging's Effect on Trophic Status



OLIGOTROPHIC
- Clear water, low productivity
- Very desirable fishery of large game fish

MESOTROPHIC
- Increased production
- Accumulated organic matter
- Occasional algal bloom
- Good fishery

EUTROPHIC
- Very productive
- May experience oxygen depletion
- Rough fish common

Source: Modified from B. Shaw, C. Mechenich, and L. Klessig, Understanding Lake Data, *University of Wisconsin-Extension, p. 5, 2004 and SEWRPC*

At present, at least ten local government entities/non-profit organizations work to improve the water quality of the Lake. These include the following organizations and programs:

- Lake Pewaukee Sanitary District – aquatic plant harvesting, water quality monitoring, storm-water management, sensitive land preservation, sanitary services
- Town of Delafield – harvesting and wetlands programs
- City of Pewaukee – aquatic plant harvesting, wetland programs, and potentially stream restoration
- Village of Pewaukee – aquatic plant harvesting site share/pile pickup share, outlet dam operation
- Pewaukee River Partnership – stream monitoring, native plant sales
- Pewaukee Women's Club – prairie restoration and plantings
- Pewaukee Kiwanis – volunteers, student restoration work
- Pewaukee Waterski Club – donations to wetland/water resource funds/grants
- Pewaukee Chapter of Walleyes for Tomorrow – habitat and fisheries improvement efforts
- Waukesha County – MSA Education and Information Program

Temperature, Oxygen, and Stratification

During summer, many Wisconsin lakes (especially those with water depths greater than 20 feet) experience a layering of their waters known as "stratification" (see Figure 2.23, "summer stratification"). As summer progresses and surface waters warm, a difference in water temperature and density form a barrier between the shallow and deep waters. This barrier is comprised of a temperature gradient known as the *thermocline* (sometimes called the "metalimnion"), characterized by approximately 0.5°F of change per foot of water depth. The thermocline separates the warmer, less dense, upper layer of water (called the *epilimnion*) from the cooler, more dense, lower layer (called the *hypolimnion*). The thermocline is generally found somewhere between 10 and 30 feet below the surface, with the depth varying by lake, month, and year. As air temperatures go through seasonal warming and cooling cycles, lake waters experience resultant warming and cooling, leading to alternating periods of seasonal stratifications. Although stratification is more typical in summer, it does occur (usually weakly) in winter as well. In between these seasonal stratifications, the lake undergoes de-stratification or "mixing," which typically occurs in spring (called the "spring overturn") and fall (or "fall overturn"). The degree to which a lake "stratifies" has a major impact on both the chemical and biological activity in a lake, as well as the lake's water quality.

Temperature and DO profiles from data spanning nearly five decades were assembled for Pewaukee Lake; seasonal profiles based on this data are presented in Figure 2.28 for the east basin and Figure 2.29 for the west basin (see explanation of boxplot symbols in Figure 2.27).[84] Pewaukee Lake is a dimictic lake, meaning it completely mixes twice a year and is subject to thermal stratification during summer and winter, particularly in the west basin. The west basin profiles suggest that by August, the Lake is stratified with the thermocline established at depths of 23 to 32 feet in most years. During the spring and fall turnover, the lake has a generally uniform temperature throughout all depths. Winter stratification, although not readily apparent in Figure 2.29, may occur to a minor extent; however, winter profiles would have to be collected for confirmation. Conversely, the absence of stratification in the east basin of the Lake is confirmed through a similar comparison as shown in Figure 2.28. The lack of a defined thermocline in the east basin during summer is not surprising given this basin's shallow depth.

Figure 2.26
Potential Appearance of a Hyper-Eutrophic Lake

Source: University of Wisconsin-Stout and SEWRPC

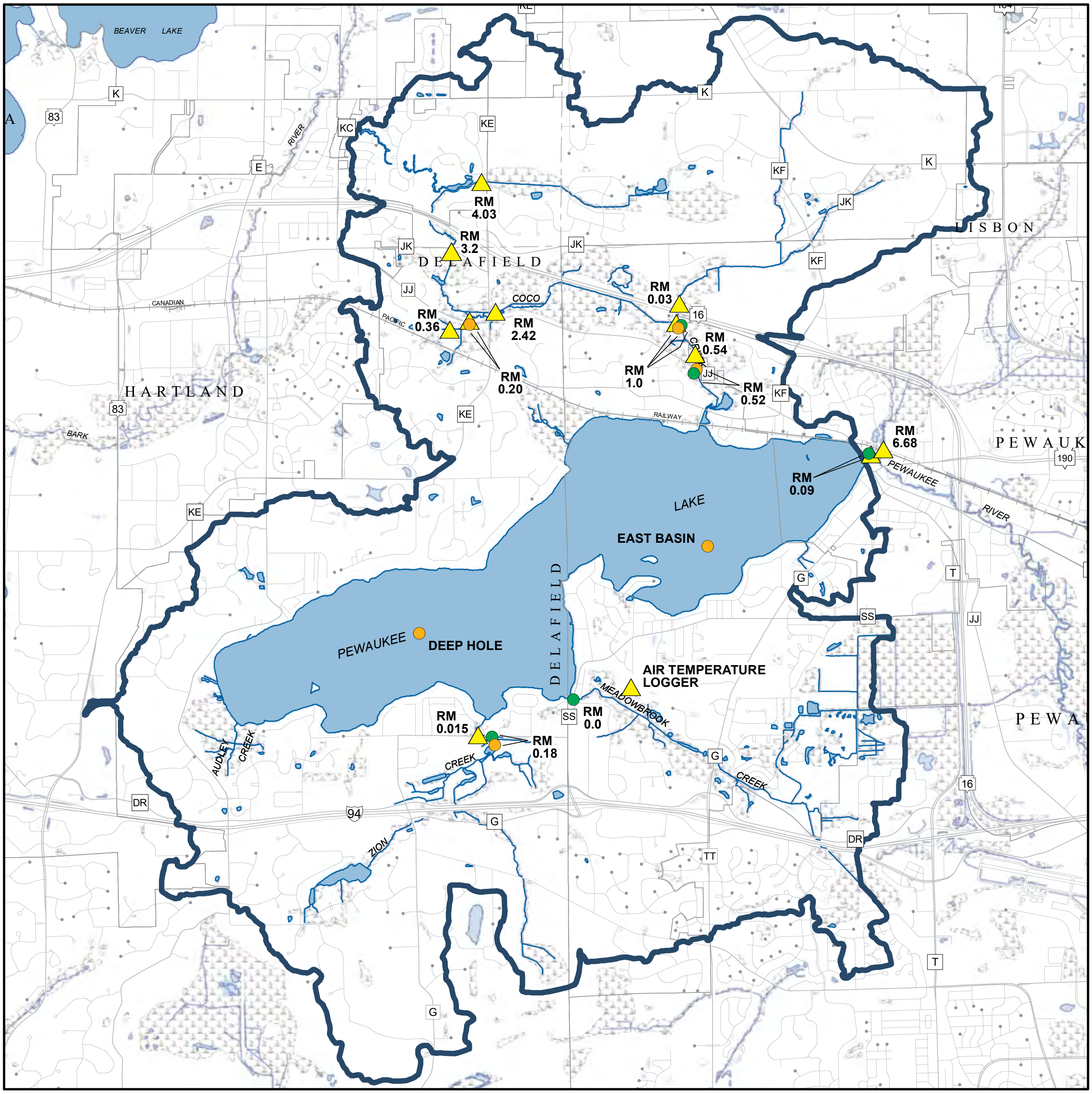
Dissolved oxygen (DO) levels are one of the most critical factors affecting the living organisms of a lake ecosystem. DO is generally higher at the surface of a lake where there is an interchange between the water and atmosphere, stirring by wind action (which aids in the process of diffusion of atmospheric oxygen into the surface waters at the air-water interface), and production of oxygen by plant photosynthesis. However, if a lake thermally stratifies during summer, the thermocline prevents oxygen-rich surface (epilimnion) waters from freely mixing with water in deeper portions (hypolimnion) of the lake. Meanwhile, metabolic processes that consume oxygen continue to occur in the hypolimnion throughout the summer. If oxygen demands in the hypolimnion during this time are high (such as in a nutrient-rich lake) or if the volume of isolated hypolimnetic water is small (limiting oxygen storage potential), oxygen levels in the deep portions of lakes generally begin to decline as summer wears on. A minimum DO concentration of 5 mg/l is considered necessary for survival of most species of fish. In many Southeastern Wisconsin lakes, as summer progresses, oxygen concentration in water below the thermocline may be reduced to less than 1.0 mg/l—a condition known as *anoxia*. Fortunately for fish and other oxygen-dependent organisms in the lake, oxygenated surface waters are able to mix throughout all depths of the lake when the thermocline breaks down during the fall and spring overturns.

Comparing DO profiles to the seasonal temperature profiles reveals the close relationship between DO and temperature, as governed by thermal stratification. In the west basin, the deepest portions of Pewaukee Lake commonly have less oxygen than surface water in all seasons, particularly during summer and winter stratification. Deep water anoxia is a common occurrence in stratified lakes and has been observed in approximately half of all Wisconsin lakes that are deep enough to thermally stratify.[85] By June, summer stratification develops and results in depleted oxygen levels below 23 feet depth (the level of the thermocline) with anoxic conditions at the 40-foot depth and below. Anoxia conditions are closest to the surface in July and August, with depths as shallow as 25 feet and below. During these periods, approximately 15 percent of the Lake's total water volume cannot support fish and most other desirable aquatic life (Figure 2.30) and anoxic waters cover about 450 acres of the Lake's bottom (Figures 2.31 and 2.32). More recently, anoxia has been occurring at shallower depths; however, the number of anoxic days has been decreasing (see Table 2.15). Anoxic conditions change annually based on fluctuations in temperature, precipitation, and supply of nutrients, as shown in (Figure 2.33). The east basin of Pewaukee Lake, which weakly stratifies, has been observed to develop anoxia in late summer and early fall.

[84] *Note that in Figure 2.29, there have been no new data collected during the winter season since the last report in 2003.*

[85] Lillie and Mason, 1983, *op. cit*.

Map 2.19
Water Quality Monitoring Sites Within the Pewaukee Lake Watershed



TEMPERATURE DATA LOGGER
WATER ACTION VOLUNTEERS WATER QUALITY
WDNR WATER QUALITY
RM 0.52 RIVER MILE DESIGNATION
SURFACE WATER
WETLAND
STREAM
WATERSHED BOUNDARY

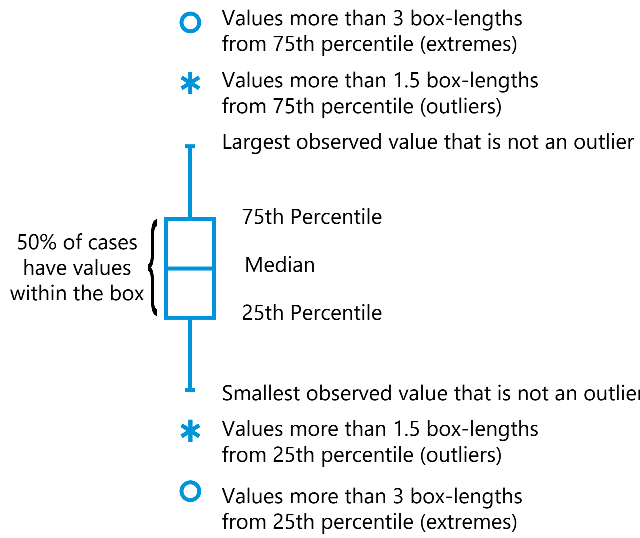
N

0 1,250 2,500 5,000 Feet

Source: Water Action Volunteers, Wisconsin Department of Natural Resources, and SEWRPC

Fall turnover, between September and October in most years, naturally restores the supply of oxygen to the bottom water as the Lake becomes fully mixed. When mixed, oxygen concentrations vary little with depth and the Lake is capable of supporting aquatic life present at essentially all depths above 40 feet. However, winter stratification can also cause hypolimnetic anoxia to establish. Winter anoxia is more common during the years of heavy snowfall, when snow covers the ice, reducing the degree of light penetration and reducing algal photosynthesis that takes place under the ice. Winter DO concentrations in the west basin hypolimnion have historically fallen below the 5 mg/l level, indicating near anoxic conditions. However, a relatively large volume of the Lake retained adequate DO concentrations to sustain fish populations throughout the winter. At the end of the winter, DO concentrations in the bottom waters of the Lake have been restored during the period of spring turnover as the Lake is usually fully mixed by March or April.

Figure 2.27
Explanation of Symbols in Boxplot Figures



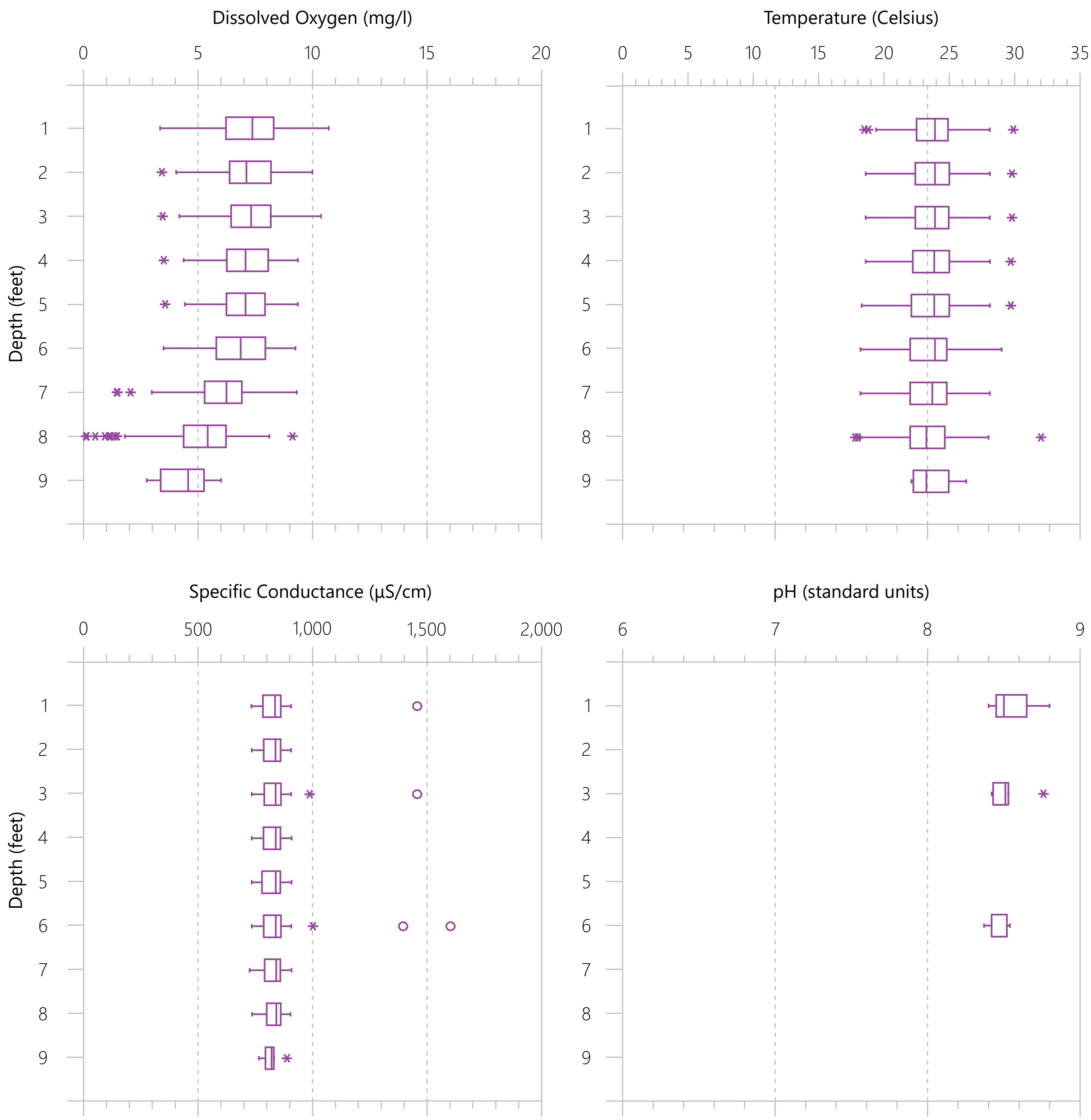
Source: SEWRPC

Temperature and oxygen profiles have noticeably changed over the period of available record. Figure 2.29 profiles show the distribution of temperature and oxygen concentrations for two time periods: data collected between 1972 and 2010, and data collected between 2011 and 2017. Reviewing these profiles, it becomes evident that the Lake's shallower areas are now much warmer in late spring before the Lake stratifies, but that this difference diminishes by late summer. The available data demonstrate that Pewaukee Lake has developed anoxia in its hypolimnion since at least 1972. In the west basin, the frequency of anoxic conditions has decreased over the period of record, with the 62 percent fewer anoxic days recorded in 2010 to 2015 than in 1972 to 2010. The east basin, however, developed anoxia at a depth of only 8 feet in early fall of 2012 and late summer of 2013. The DO data for this basin is extremely limited with more data required to determine how often this occurs.

Hypolimnetic anoxia can affect the concentrations of nutrients, such as phosphorus, in a lake's waters. Phosphorus is typically not particularly soluble in water, and often adheres to particles that settle to the lake-bottom. When bottom waters become void of oxygen, the activities of decomposer bacteria in the bottom sediments, together with certain geochemical reactions that occur only in the complete absence of oxygen, can allow phosphorus in plant remains and lake-bottom sediment to dissolve into the water column. This allows phosphorus that is otherwise trapped in deep lake-bottom sediment to be released into lake water. This release of phosphorus is referred to as "internal loading". The released phosphorus can then mix into the water column during the next turnover period, fueling plant and algae growth. Since the west basin of Pewaukee Lake does stratify, internal loading of phosphorus is a potential concern. For information on current internal loading conditions, refer to the internal loading discussion in Section 2.6, "Pollutant Loads."

Hypolimnetic anoxia can also affect fish populations. Depleted oxygen levels in the hypolimnion cause fish to move upward, nearer to the surface of the lakes, where higher DO concentrations exist. This migration, when combined with temperature, can select against some fish species that prefer the cooler water temperatures that generally prevail in the lower portions of the lakes. When there is insufficient oxygen at these depths, these fish are susceptible to summer kills, or, alternatively, are driven into the warmer water portions of the lake where their condition and competitive success may be severely impaired. In the 2002 survey of Pewaukee Lake, DO concentrations in the surface waters ranged from about 17.6 mg/l during winter to about 5.0 mg/l in the summer; hypolimnetic DO concentrations dropped to zero by mid- to late-June. Even at a depth of approximately 30 feet, oxygen concentrations were at or below the recommended minimum 5 mg/l level necessary to support many fish species.

Figure 2.28
Summer (June-August) Dissolved Oxygen, Temperature, Specific Conductance, and pH Profiles: Pewaukee Lake East Basin 2012-2017

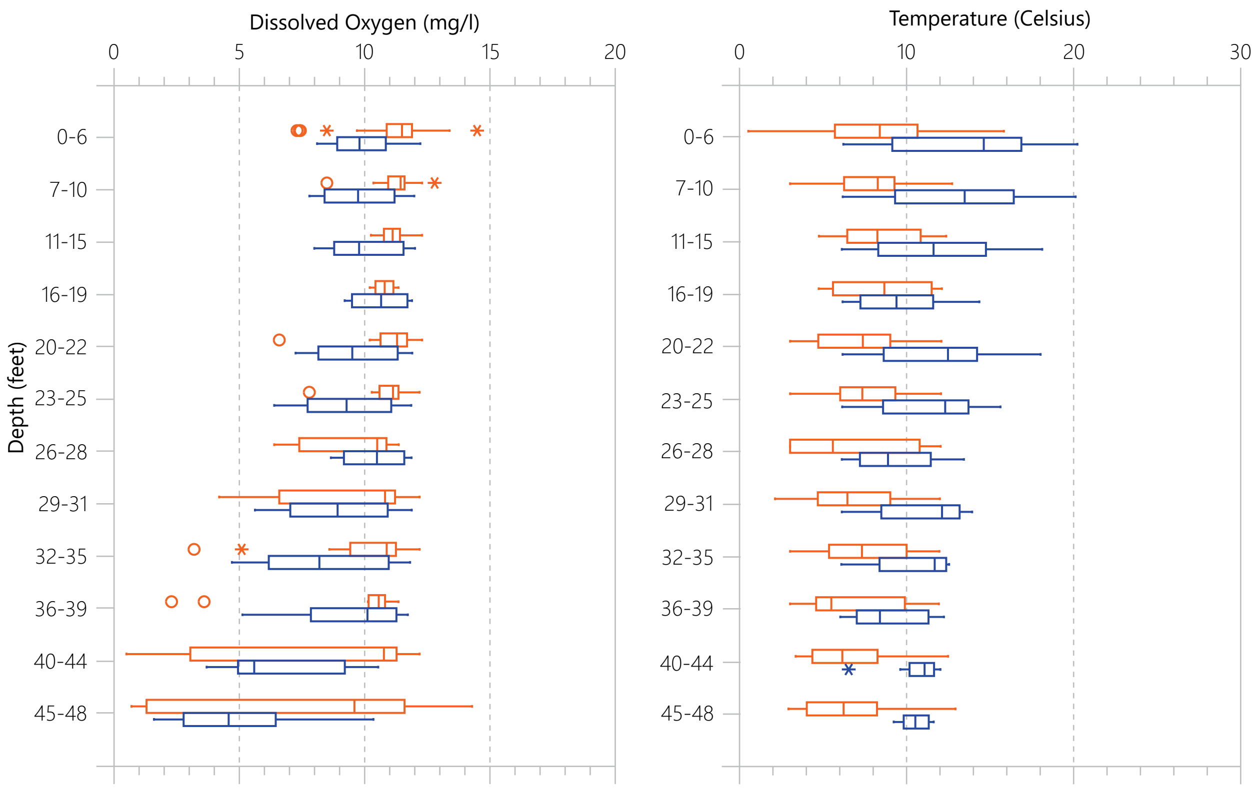


Source: Pewaukee Lake Sanitary District, Wisconsin Department of Natural Resources, and SEWRPC

Up to this point, the discussion of oxygen in lakes has focused on the DO concentration, as measured in mg/l. However, there is another important measure involving oxygen in water: oxygen *saturation*, expressed as a percent. Oxygen saturation refers to the concentration of oxygen measured in water compared to a concentration in equilibrium with the atmosphere at a given temperature; simply put, it is a *ratio* of the amount of oxygen actually dissolved in water to the total amount of oxygen that is possible to be held in that water at a given temperature and pressure. For example, if a sample of water at a given temperature is holding 5 mg/l of oxygen, but is capable of holding 10 mg/l of oxygen at that temperature, the water is said to be at 50 percent saturation—it is holding only half of what it is capable of holding at that temperature and pressure.

Figure 2.29
Pewaukee Lake Seasonal Dissolved Oxygen and Temperature Profiles: Pre-2010 and Post-2010

Spring (March-May)



Summer (June-August)

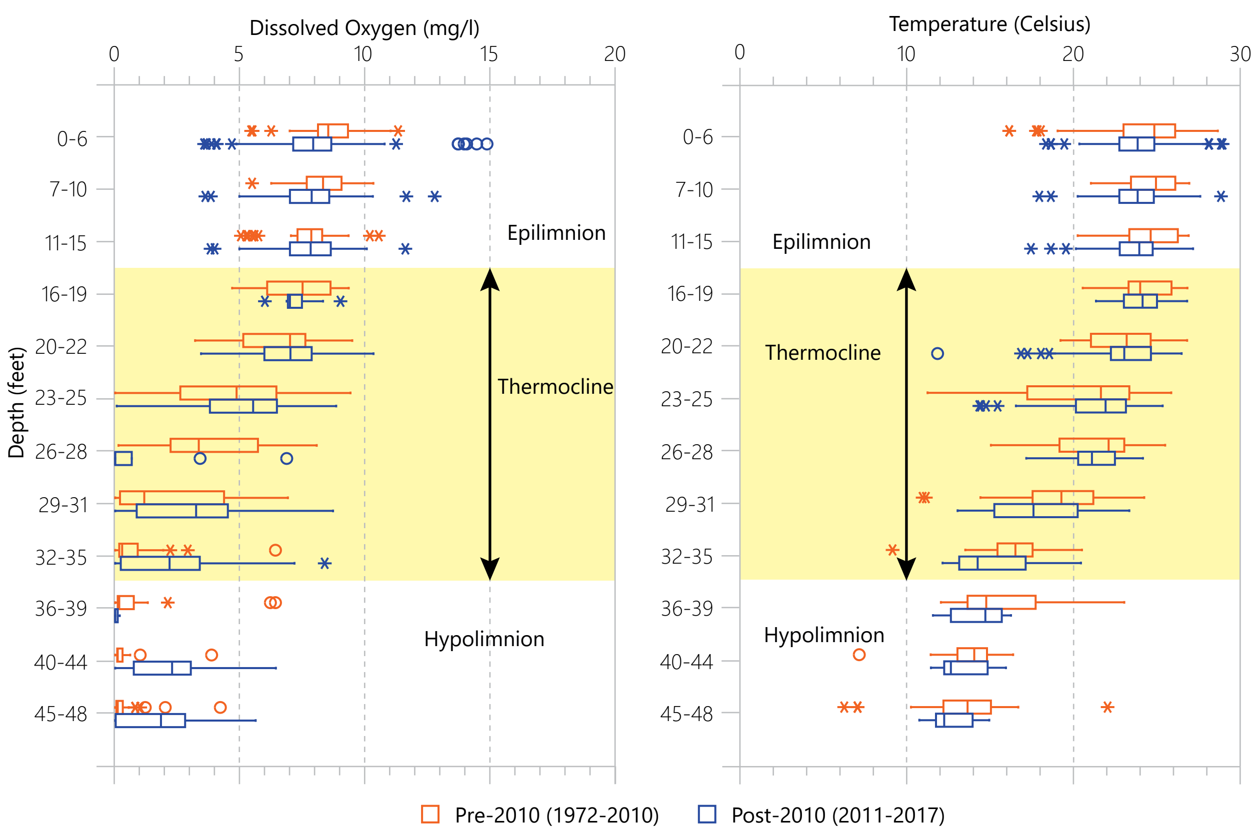
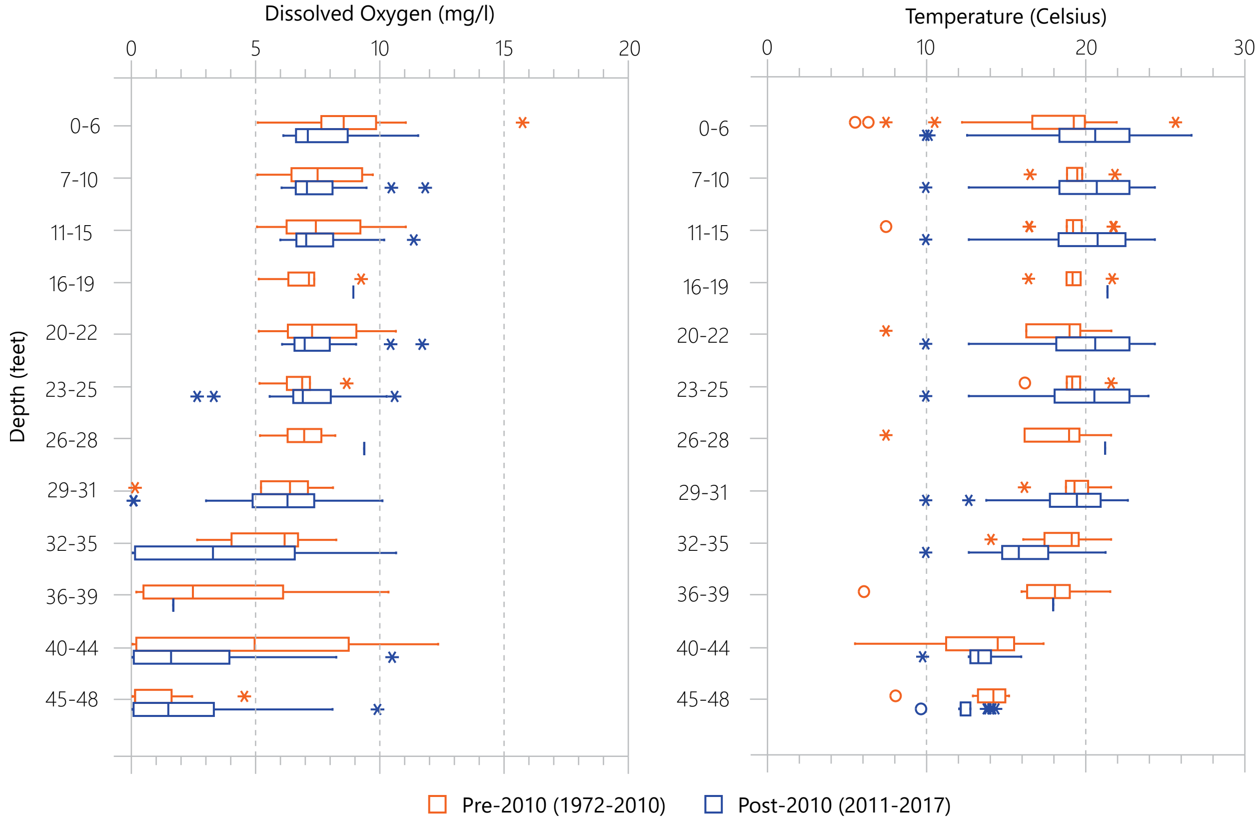


Figure 2.29 (continued)

Fall (September-November)



Note: The maximum concentration of dissolved oxygen in 0 degree celsius water is 14.6 mg/L. Values higher than this range suggest oxygen supersaturation or inaccurate instrument readings.

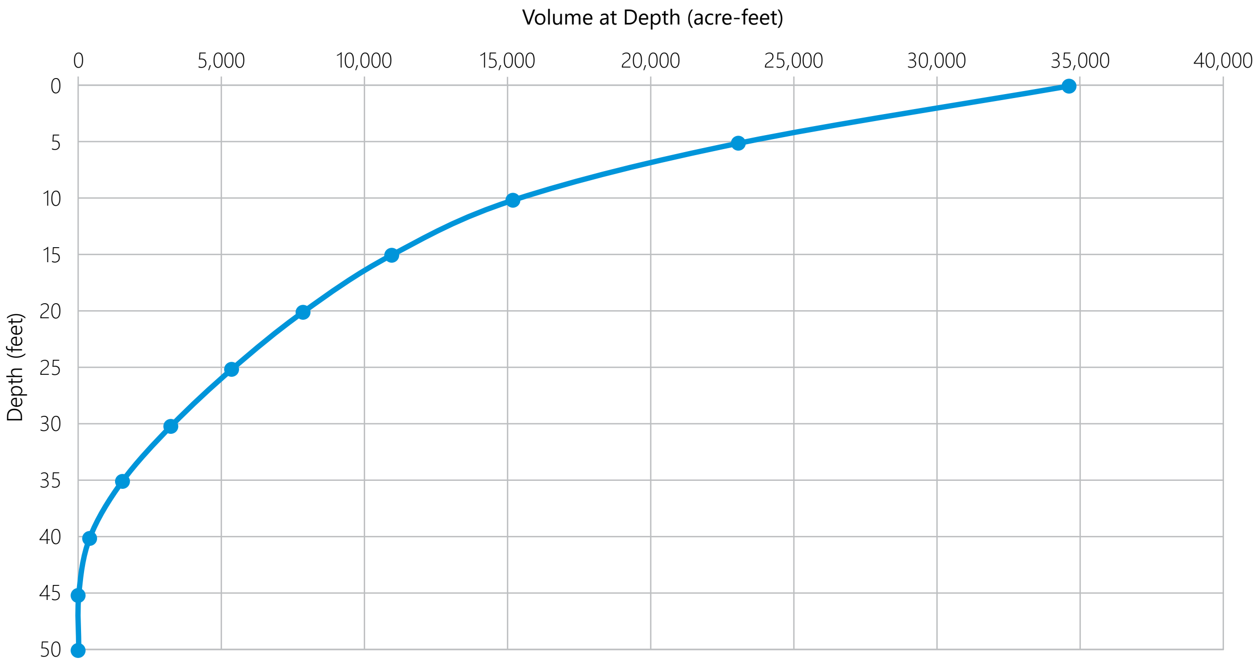
Source: Pewaukee Lake Sanitary District, Wisconsin Department of Natural Resources, and SEWRPC

Warm water holds less oxygen than cold water; consequently, warm water becomes oxygen-saturated at lower concentrations of DO than cold water. For example, at 90 percent saturation, water at 70°F will hold about 8 mg/l of DO while water at 50°F will hold over 10 mg/l of DO at the same saturation level of 90 percent.[86] During summer months, the warm waters at the surface of a lake may become saturated at relatively low DO concentrations. Thus, completely oxygen saturated warm waters can still have too little DO for fish, particularly cold-water species like trout. Additionally, oxygen saturation has its own consequences for aquatic life. Values between 90 and 110 percent saturation are generally considered desirable for aquatic life; however, supersaturation levels above 115 percent can be detrimental. Fish exposed to oxygen saturations greater than 115 percent can develop bubbles in their tissues (a condition similar to "the bends" experienced by deep-water divers).[87] Thus, under conditions of abnormally high surface temperatures in a lake, fish can become "squeezed" into an increasingly narrow range of depths between supersaturated surface waters above and an anoxic hypolimnion below. In addition, oxygen saturation can also fluctuate diurnally. Many waterbodies that experience oxygen supersaturation during the day can also experience low oxygen saturation levels at night, as oxygen-consuming activities such as respiration and decomposition occur at night without oxygen-producing photosynthesis. Such conditions are stressful to aquatic organisms and can also lead to fish kills in summer.

[86] *USGS DOTABLES at water.usgs.gov/software/DOTABLES.*

[87] *Supersaturation refers to a condition when the amount of dissolved substance exceeds the substance's maximum solubility in the solvent under normal circumstances. Such conditions are typically unstable. Dissolved gas comes out of water as bubbles.*

Figure 2.30
Water Depth Versus Lake Volume: Pewaukee Lake



Note: This graph relates the volume of water found at or above a certain lake depth. For example, roughly 15,000 acre-feet of the Lake volume is found in areas equal to or less than the upper 10 feet of the Lake's water column.

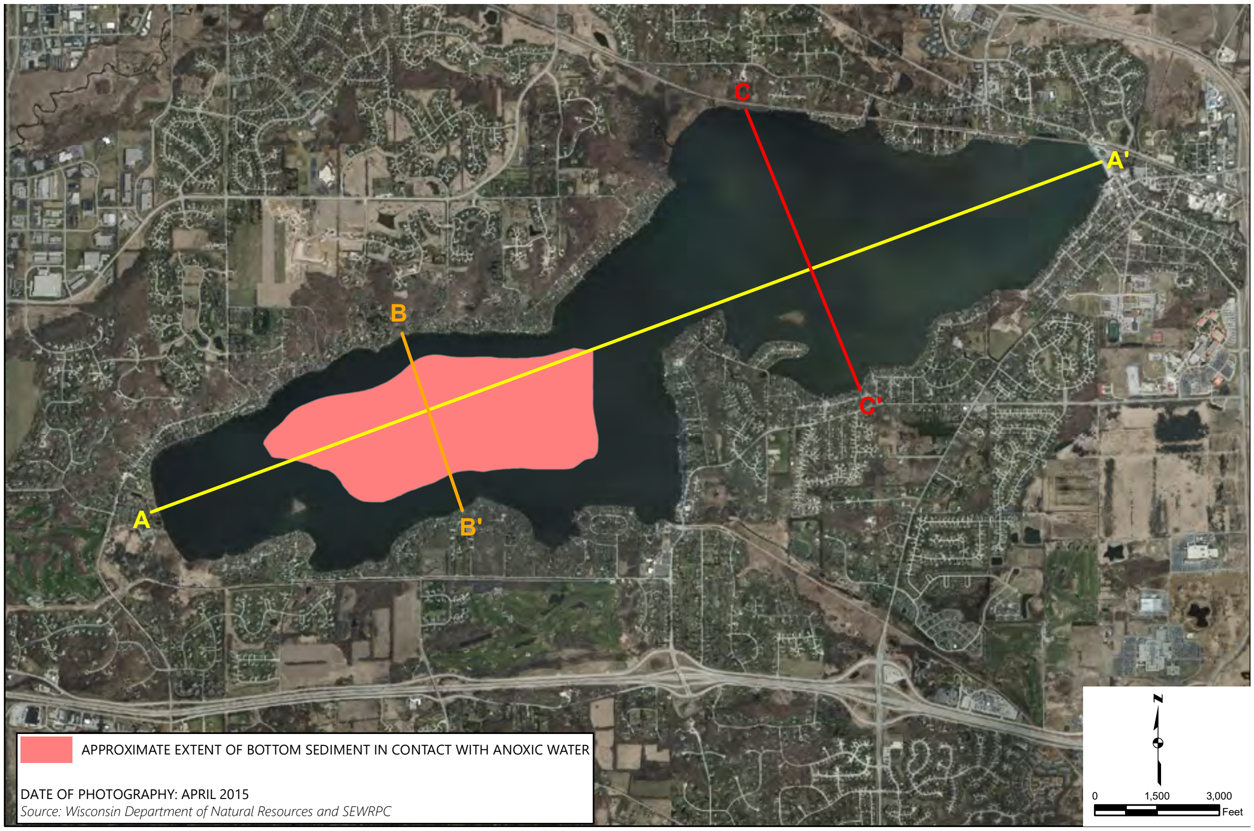
Source: Wisconsin Department of Natural Resources and SEWRPC

Daytime oxygen saturation profiles for the west basin of Pewaukee Lake during the spring and summer of 2014, 2015, and 2016 are presented in Figure 2.34. From these profiles, it would appear that percent saturation of oxygen in the Lake is generally at levels supportive of fish (90-110 percent), especially in the shallower depths of the Lake above the thermocline, with no periods of supersaturation in spring or summer. No such profiles have been collected at nighttime, but the lack of supersaturation indicates low likelihood of nighttime oxygen levels becoming critically low for fish. However, as also shown in these profiles, the oxygen saturation percentages decrease dramatically in the deeper depths below the thermocline from late spring to summer, which, when considered with the measured levels of DO below the 5 mg/l threshold (as presented in Figure 2.29), supports the interpretation that these low oxygen levels in the deeper waters of the Lake are limiting to fish and other oxygen-dependent aquatic life. Although chronic summer fish kills have not been reported for Pewaukee Lake, oxygen concentration profiles should be regularly and consistently measured, including profiles collected at night during the summer. Such proactive measures can detect early onset of oxygen supersaturation in daytime surface waters, or saturation levels peaking within or near the thermocline; both are conditions that could be suggestive of nutrient enrichment sourced in the hypolimnion and, as such, precursors to potential nighttime oxygen deficits.

Specific Conductance

Specific conductance is a measure of the ability of a liquid, such as lake water, to conduct electricity, standardized at a specific temperature (25°C). This ability is greatly dependent on the concentration of dissolved solids in the water: as the amount of dissolved solids increases, the specific conductance increases. During periods of thermal stratification, specific conductance can dramatically increase at the lake bottom due to an accumulation of dissolved materials trapped in the hypolimnion. Such a condition can lead to a significant concentration gradient, with higher conductance measurements in the deeper waters and lower conductance measurements in the surface waters. Such concentration gradients are a consequence of the "internal loading" phenomenon described previously.

Figure 2.31
Typical Extent of Pewaukee Lake's Bottom Sediment Covered with Anoxic Water During Late Summer



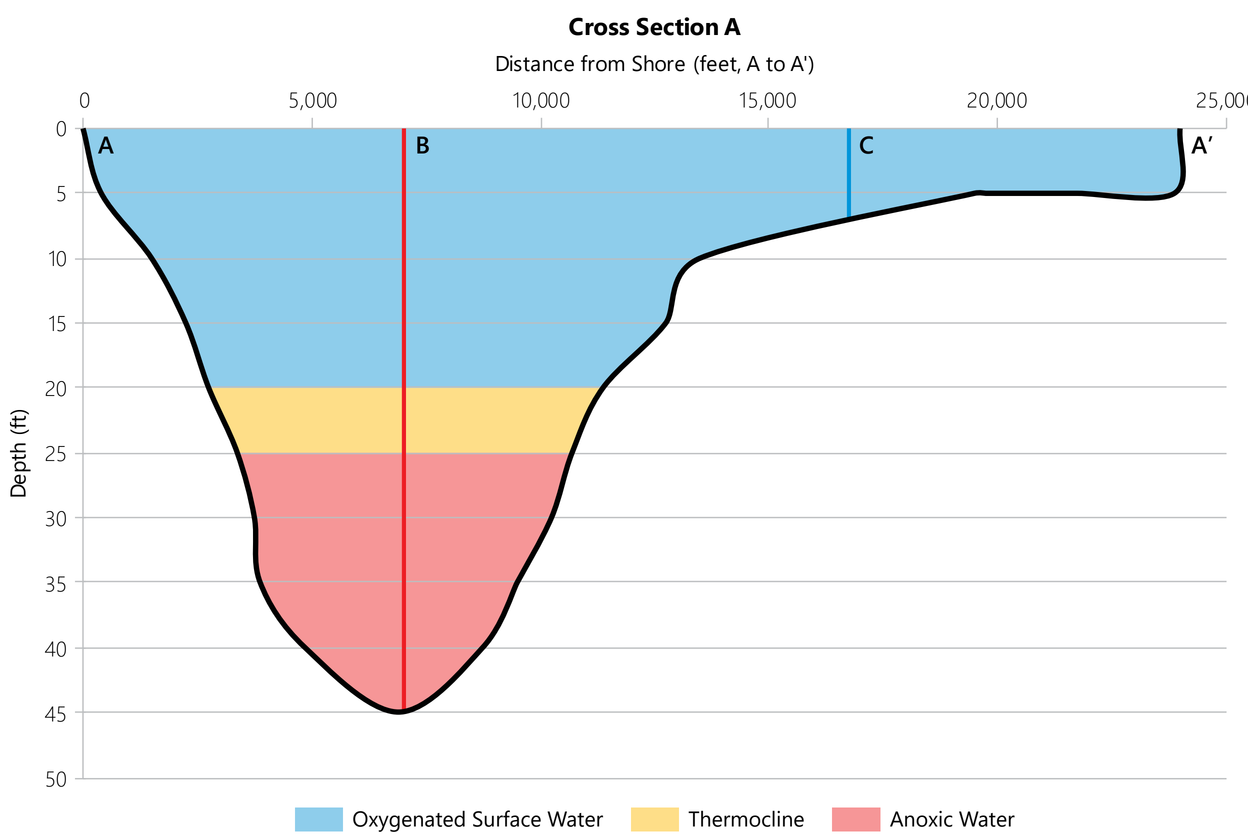
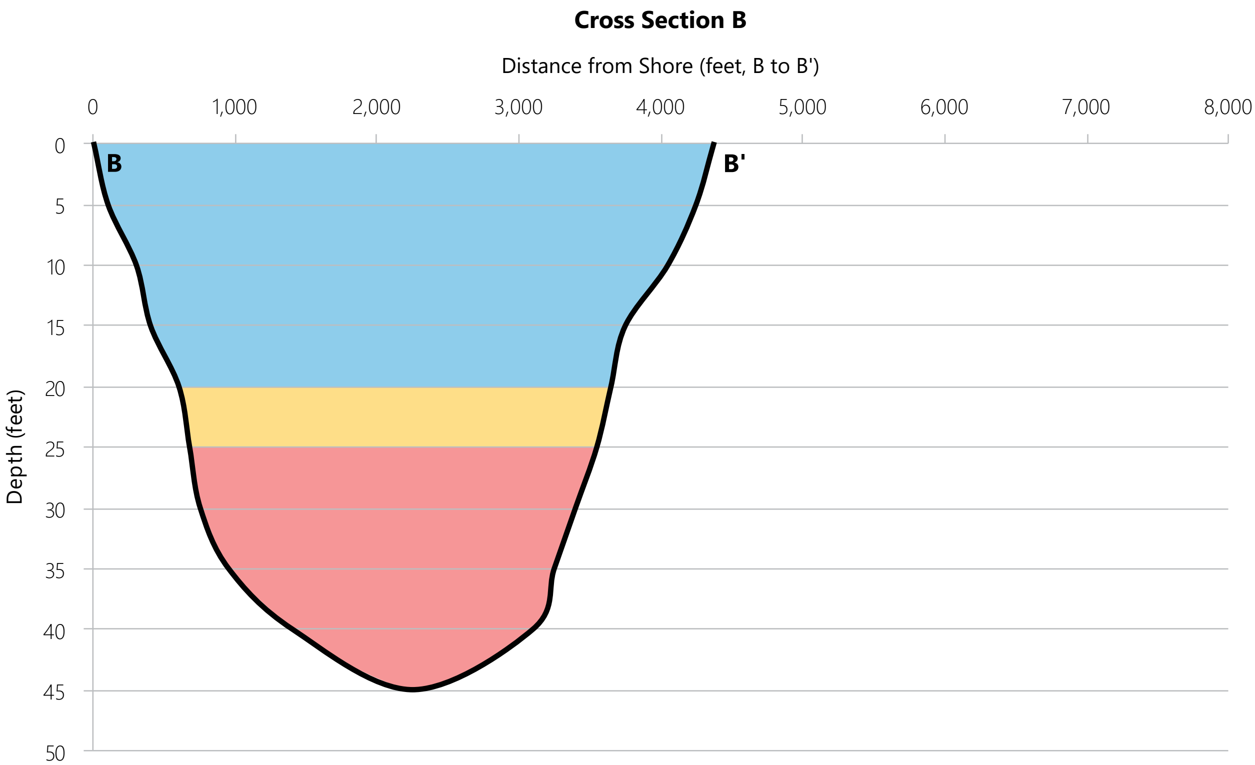
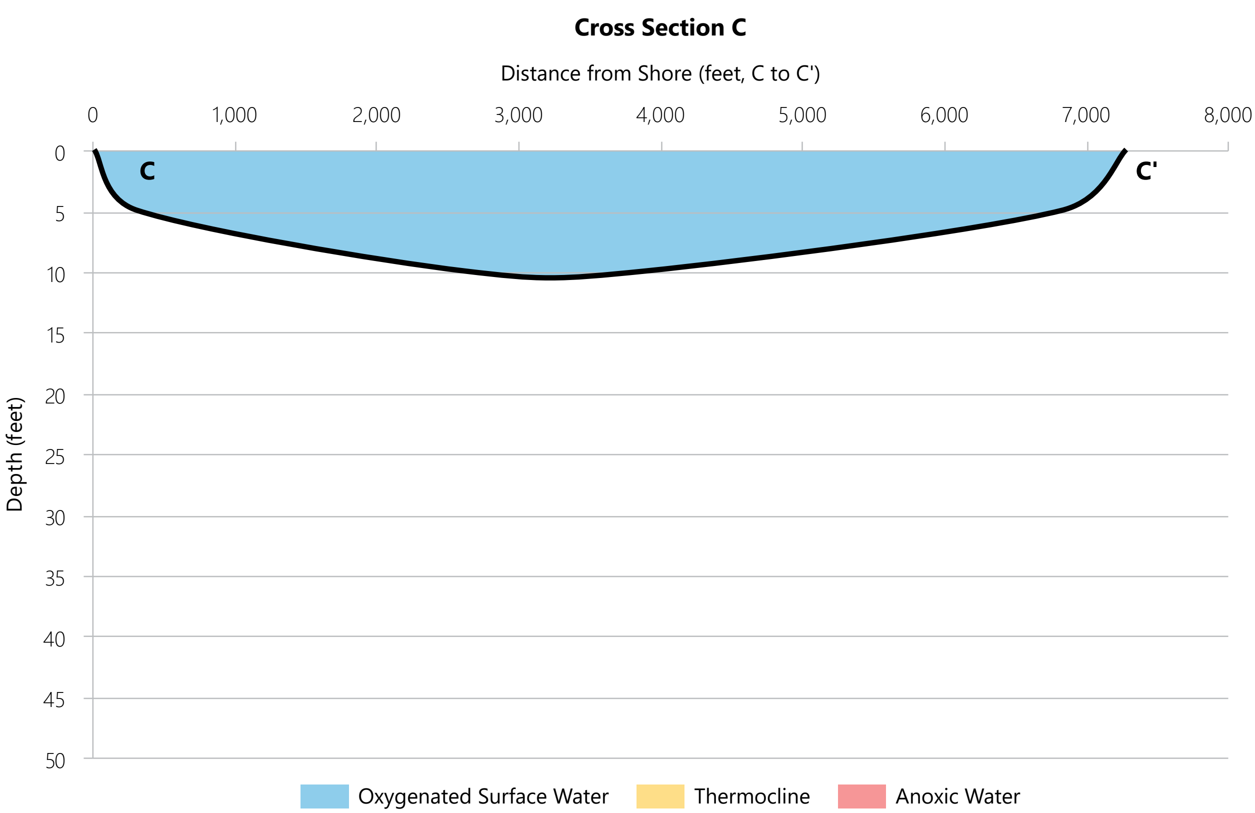


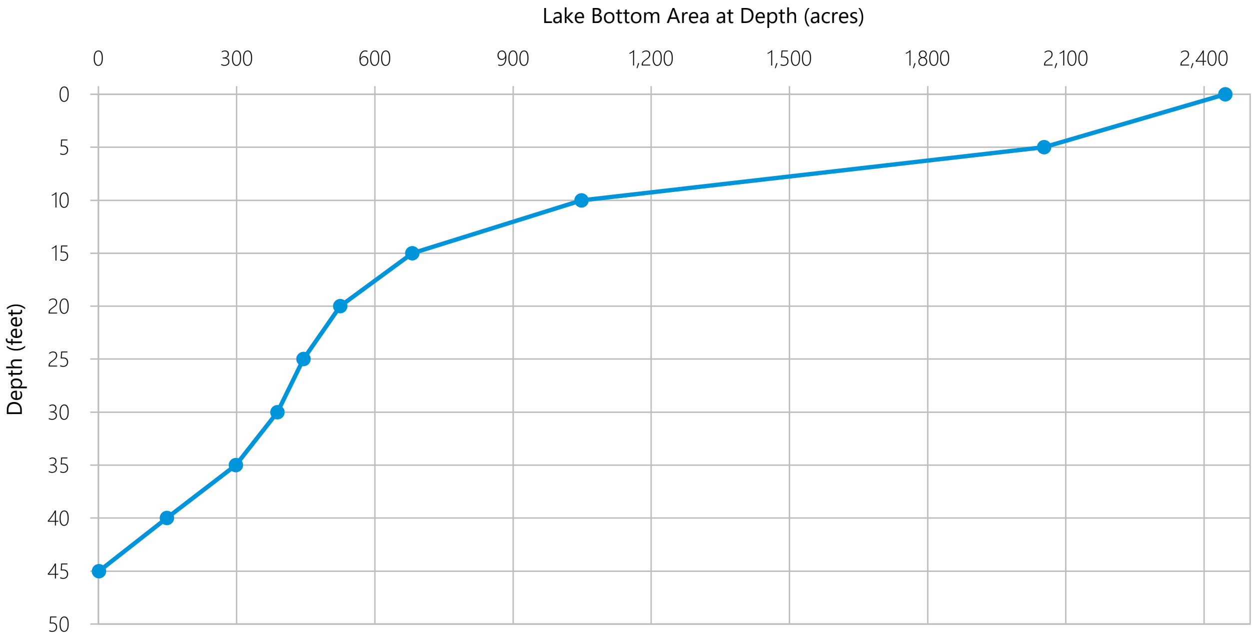
Figure 2.31 (continued)





Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.32
Water Depth Versus Lake Area: Pewaukee Lake



Note: This graph relates the area of the Lake measuring at a prescribed depth. For example, roughly 400 acres of Pewaukee Lake's open water area is underlain by water at least 30 feet deep.

Source: Wisconsin Department of Natural Resources and SEWRPC

During the previous planning study,[88] significant surface to bottom conductivity gradients were observed, especially during the summer period. Although the relative levels of conductance were within the normal range for lakes in Southeastern Wisconsin[89], such gradients were interpreted at the time to be an indication that Pewaukee Lake did experience some degree of internal loading. Figure 2.35 presents seasonal specific conductance profiles for the west basin of Pewaukee Lake measured since the last study. The presented conductance gradients between shallow and deep water indicate that internal loading is likely still occurring.

pH and Acidity

The acidity of water is measured using the pH scale. The pH scale is a logarithmic measure of hydrogen ion (H+) concentration on a scale of 0 to 14 Standard Units (stu, or SU), with 7.0 indicating neutrality. Water with pH values lower than 7.0 stu has higher hydrogen ions concentrations and is more acidic, while water with pH values higher than 7.0 stu has lower hydrogen ion concentrations and is less acidic. Since the scale is logarithmic, each 1.0 pH change reflects a tenfold change in hydrogen ion concentration, e.g., a pH of 4 is *ten* times more acidic than a pH of 5 and a *hundred* times more acidic that a pH of 6. In Wisconsin lakes, pH can range anywhere from 4.5 in some acid-bog lakes to 8.4 in hard-water, marl lakes.[90]

Many chemical and biological processes are affected by pH, as are the solubility and availability of many substances. Different organisms are capable of tolerating different ranges of pH, with most preferring ranges between about 6.5 and 8.0 stu. Although moderately acidic (slightly below a pH of 7) does not usually harm fish, as pH drops to 6.5 or lower, some species can be adversely affected, especially during spawning. For example, at a pH of 6.5, walleye spawning can be inhibited; at a pH of 5.8, lake trout spawning is inhibited; and at a pH of 5.5, smallmouth bass disappear.[91] As pH continues lower, walleye, northern pike and other

[88] *SEWRPC Community Assistance Planning Report No. 58,* A Water Quality Management Plan for Pewaukee Lake, Waukesha county, Wisconsin, *March 1984.*

[89] *Lillie and Mason, 1983, op. cit.*

[90] *Wisconsin Department of Natural Resources, Byron Shaw, Christine Mechenich, and Lowell Klessig,* Understanding Lake Data*: www.uwsp.edu/cnr-ap/UWEXLakes/Documents/ecology/shoreland/background/understanding%20lake%20data.pdf.*

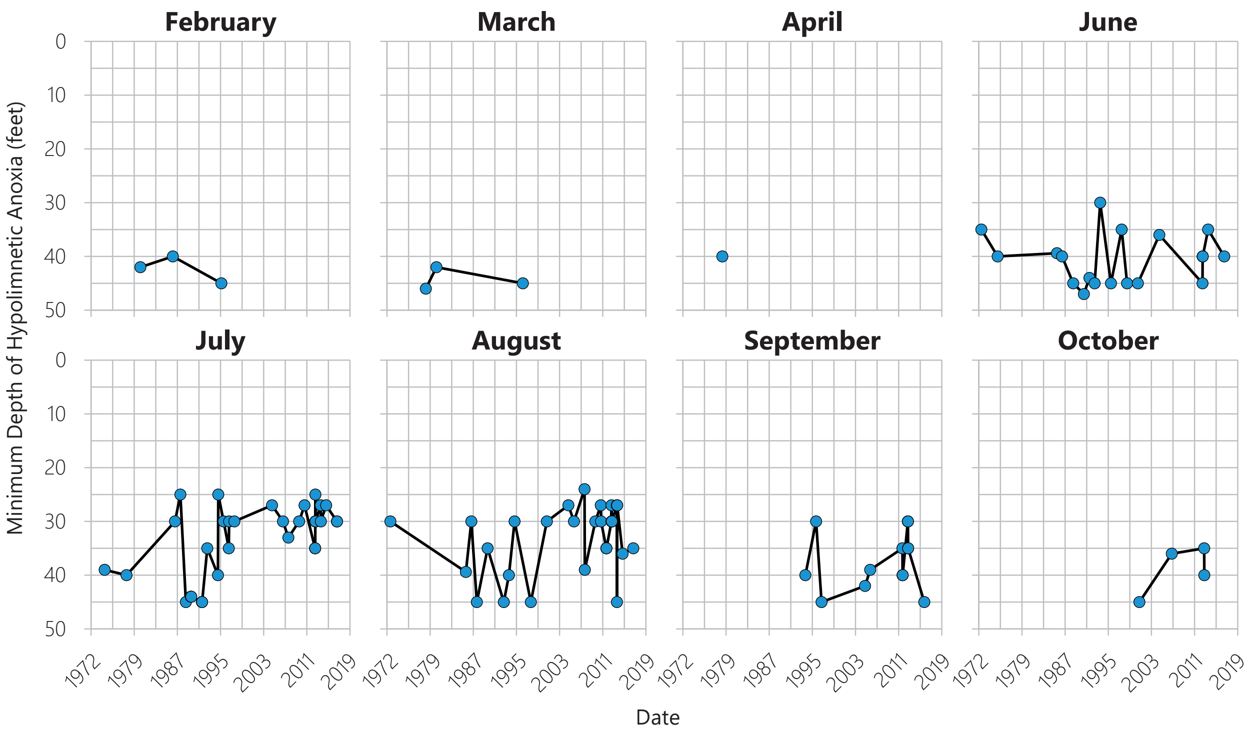
[91] *Ibid.*

Table 2.15
Pewaukee Lake Anoxia Frequency and Depth: Pre-2010 Versus Post-2010

	Pre-2010 (1972-2010)			Post-2010 (2011-2017)			Change: Pre-2010 vs Post-2010	
Month	Total No. Sample Dates	No. Anoxia Days (percent of total sample dates)	Mean Hypolimnetic Anoxia Depth (feet)	Total No. Sample Dates	No. Anoxia Days (percent of total sample dates)	Mean Hypolimnetic Anoxia Depth (feet)	Mean Depth (feet)	Occurrence of Anoxia (percent)
June	15	14 (93)	41	18	5 (28)	40	-1	-70
July	23	20 (87)	35	27	11 (41)	30	-5	-53
August	17	15 (88)	35	27	13 (48)	32	-3	-63
September	10	5 (50)	39	15	8 (53)	36	-3	7

Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.33
Minimum Depth to Hypolimnetic Anoxia: Pewaukee Lake 1972-2017



Note: Anoxia is defined as a dissolved oxygen concentration of 1.0 mg/l or lower.

Source: Wisconsin Department of Natural Resources and SEWRPC

popular sport fishes gradually disappear and a pH of 3.0 is toxic to all fish.[92] In addition, many metals are more soluble in water with low pH than they are in water with high pH. Thus, toxicity of many substances for fish and other aquatic organisms can be affected by pH. Under low pH conditions, toxic metals, such as aluminum, zinc and mercury, can be released from lake sediment if present. At a pH of 5.0, aluminum is at its most poisonous, precipitating onto the gills of the fish in the form of aluminum hydroxide.[93]

Lakes have natural and man-made sources of acidity. Peat-bog lakes are naturally acidic due to the natural release of organic acids during decomposition; many such lakes are without fish.[94] Because of diffusion of carbon dioxide into water and associated chemical reactions, rainfall (in areas that are not impacted by air pollution) has a pH of about 5.6 stu; the pH of rainfall in areas where air quality is affected by oxides of nitrogen or sulfur tends to be lower. The mineral content of the soil and bedrock underlying a waterbody also has a strong influence on the waterbody's pH. Since carbonate bedrock, such as dolomite, underlies much of the Pewaukee Lake watershed, the pH in the Lake tends to be in the alkaline range between about 7.0 and 9.0 stu. Pollutants contained in discharges from point sources and in stormwater runoff can also affect a waterbody's pH. Further, photosynthesis by aquatic plants, phytoplankton, and algae can cause pH variations both on a daily and seasonal basis.

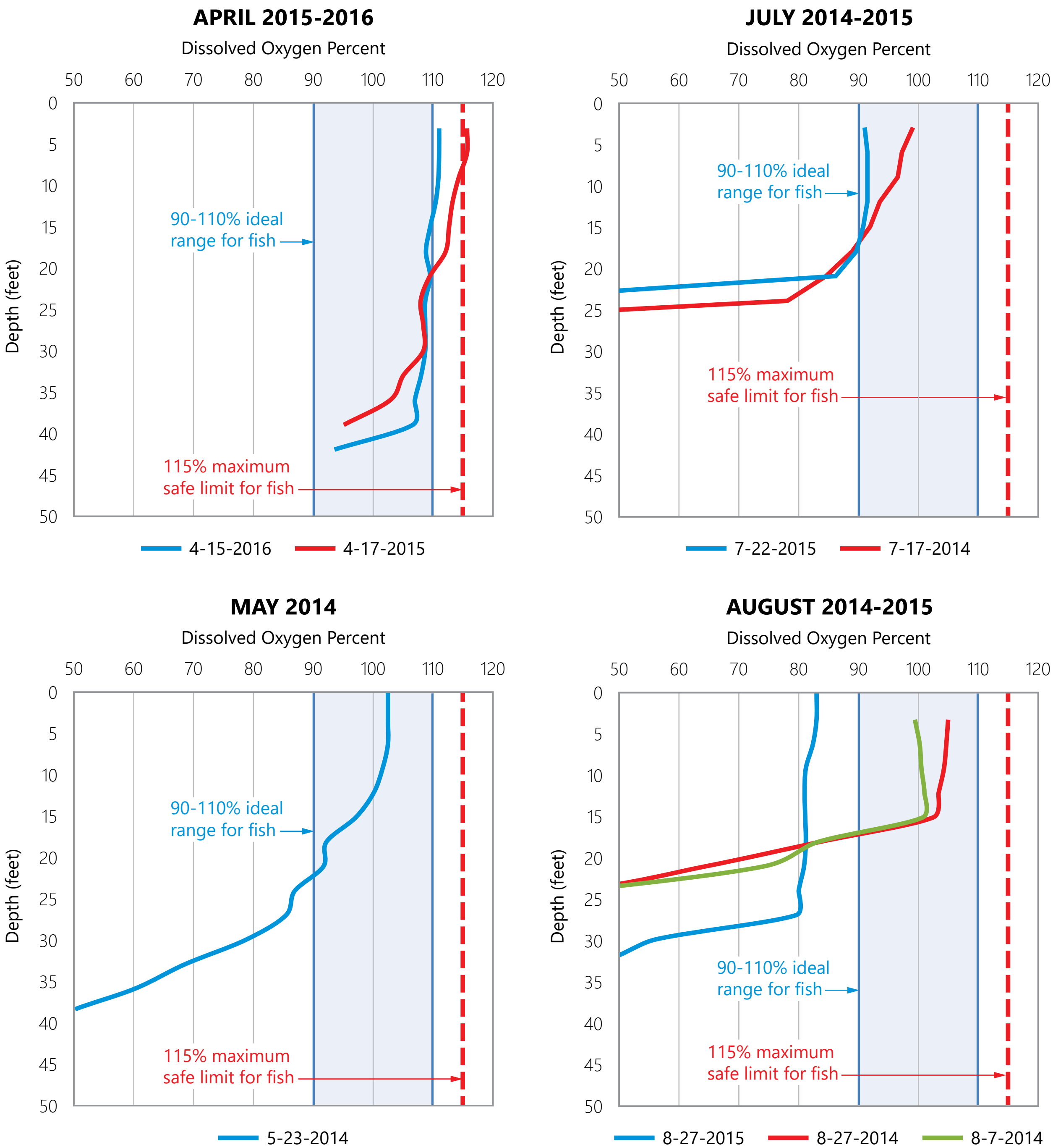
The pH of Pewaukee Lake ranges from 7.2 to 8.8, as determined from previous studies. Figure 2.35 shows seasonal profiles of pH measurements for Pewaukee Lake from 1972 to 2010 and 2010 to 2017. Lake pH has been quite stable; between 7.5 and 8.5 over the past 50 years (which is well within the range for warmwater fish and aquatic life – see Table 2.14). Like most lakes in Southeastern Wisconsin (mean pH

[92] *Ibid.*

[93] *www.air-quality.org.uk/13.php.*

[94] *T. Hellström, "Acidification in Lakes," In L. Bengtsson, R.W. Herschy, R.W. Fairbridge (eds.)* Encyclopedia of Lakes and Reservoirs*, 2012.*

Figure 2.34
Oxygen Saturation Profiles: Pewaukee Lake West Basin 2014-2017



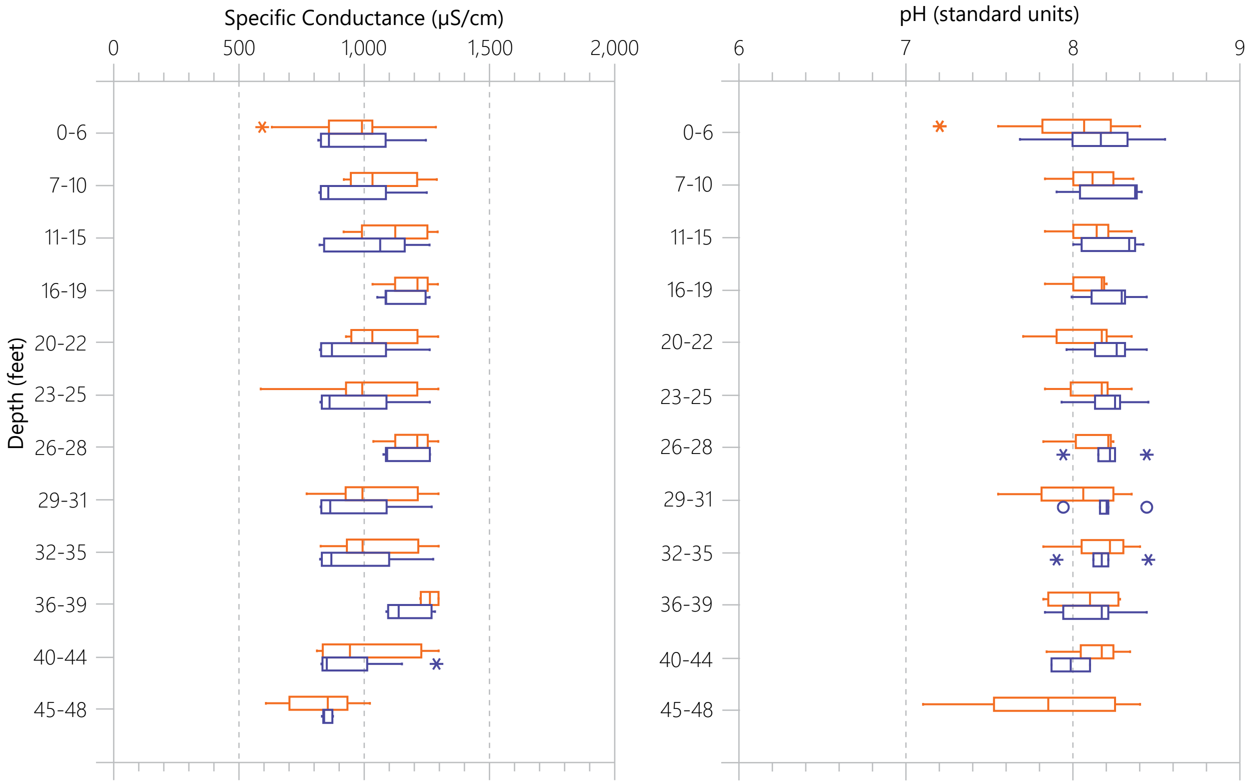
Source: Wisconsin Department of Natural Resources and SEWRPC

of 8.1), Pewaukee Lake is an alkaline waterbody.[95] However, concentrations within Pewaukee Lake did tend to be higher than 8.5 stu during the summer months. The summer pH profiles for the west basin clearly show the pH gradient created by the thermocline, an effect similar to that reflected in the summer profiles for conductivity, oxygen, and percent oxygen saturation. In summer, photosynthesis increases both lake DO concentrations and pH as algae and plants remove carbon dioxide from the water, raising pH, while oxygen is released as a byproduct of the photosynthetic reactions. Thus, summer and fall pH of Pewaukee Lake tends to be slightly higher than spring and winter pH.

[95] *Lillie and Mason, 1983, op. cit.*

Figure 2.35
Seasonal Specific Conductivity and pH Profiles: Pewaukee Lake Pre-2010 and Post-2010

Spring (March-May)



Summer (June-August)

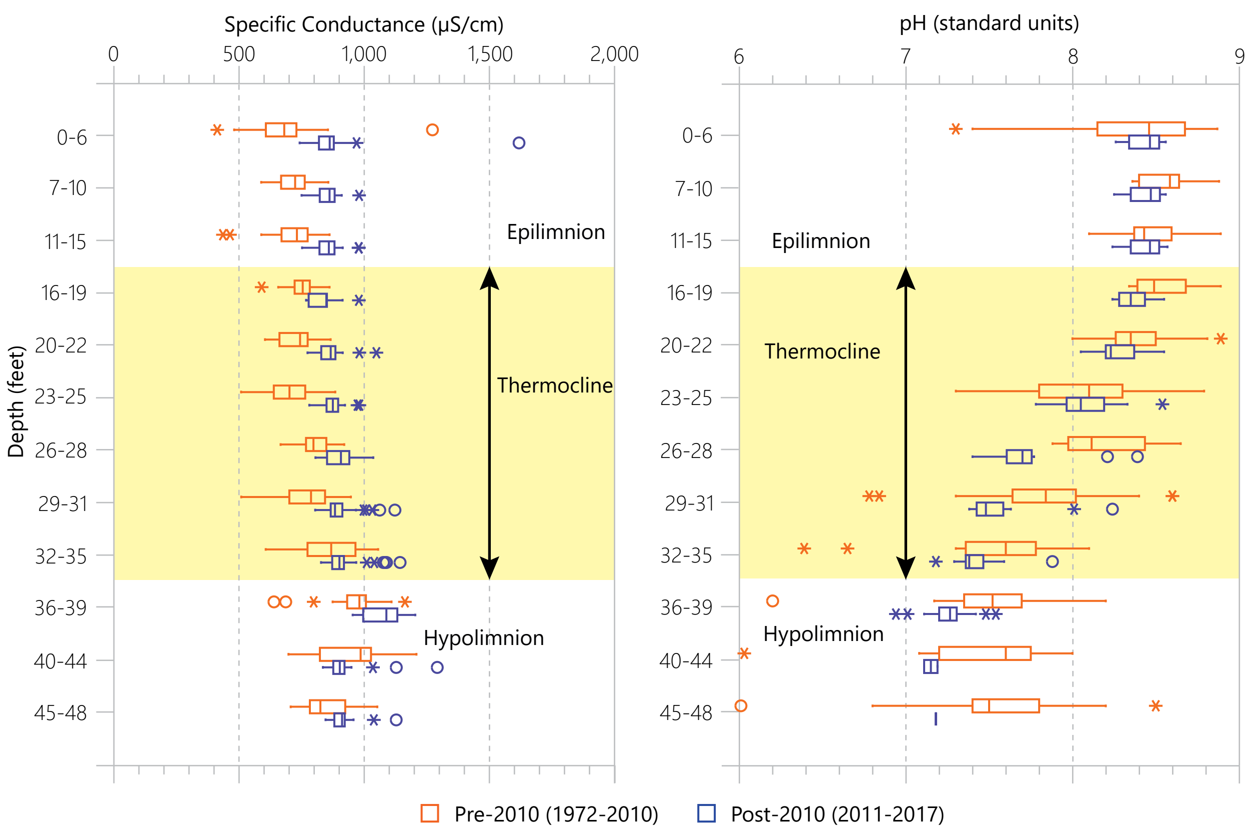
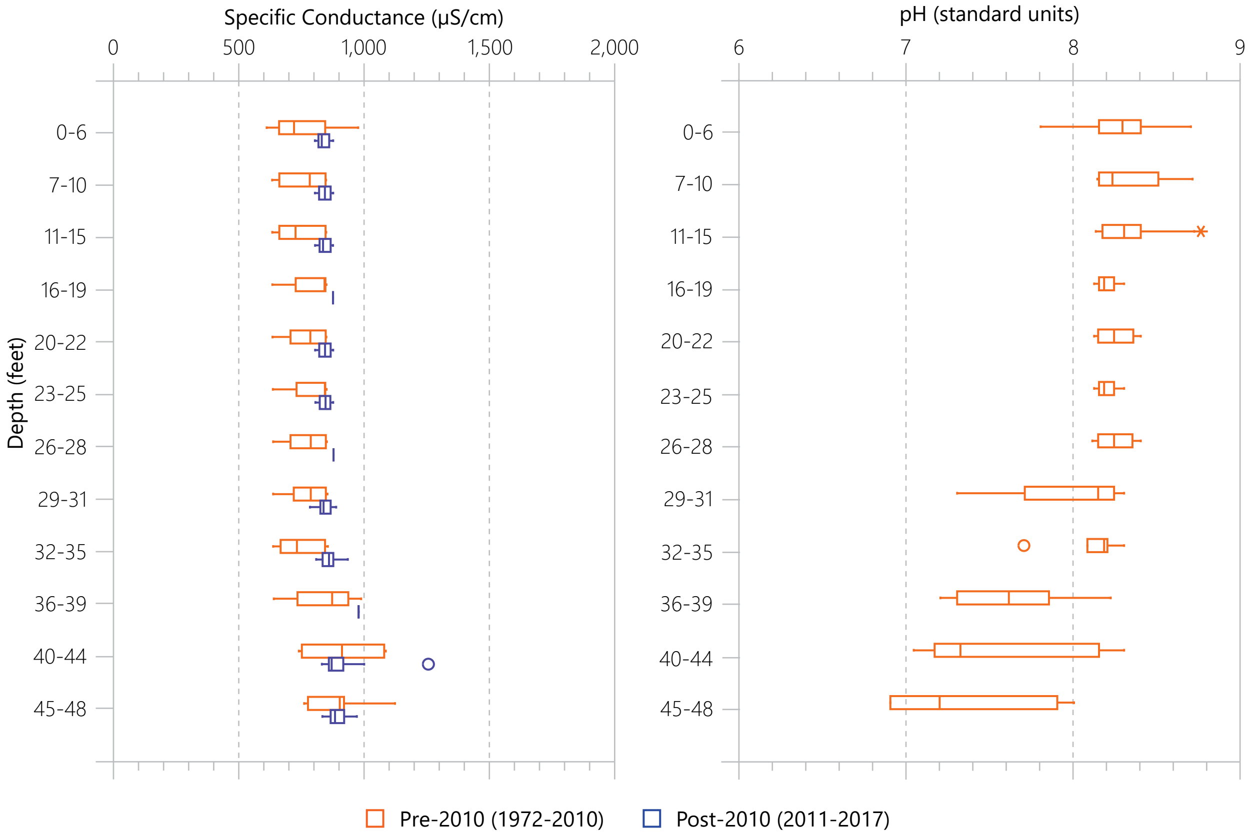


Figure 2.35 (continued)

Fall (September-November)



Source: Pewaukee Lake Sanitary District, Wisconsin Department of Natural Resources, and SEWRPC

Alkalinity and Hardness

Alkalinity is a measure of the capacity of a lake to absorb and neutralize acids, known as "buffering". The alkalinity of a lake depends on the levels of bicarbonate, carbonate, and hydroxide ions present in the water. Lakes in Southeastern Wisconsin typically have a high alkalinity because of the types of soils and underlying bedrock in the Region's watersheds. In contrast, water *hardness* is a measure of the multivalent metallic ion concentrations, such as those of calcium and magnesium, present in a lake. Hardness is usually reported as an equivalent concentration of calcium carbonate ($CaCO_3$), measured in mg/l. If a lake receives groundwater through rock layers containing calcite and dolomite (both are limestone materials), the lake's alkalinity and hardness will be high. Soft-water lakes have calcium carbonate levels less than 60 mg/l; hard-water lakes contain levels over 120 mg/l.

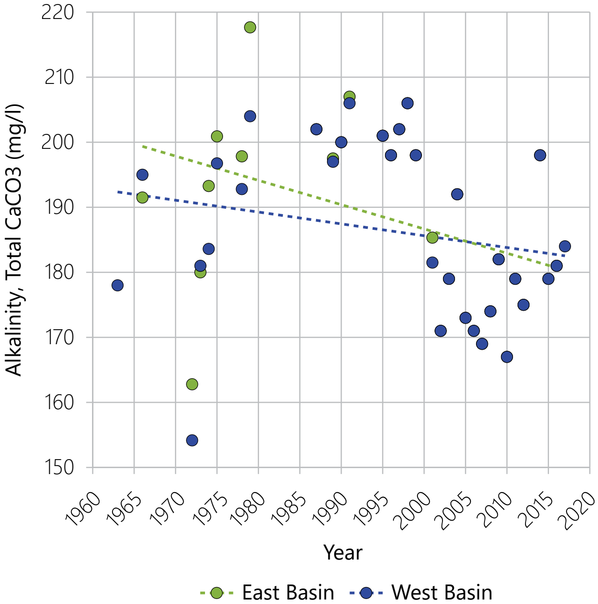
Pewaukee Lake may be classified as a hard-water alkaline lake, with average alkalinities of 201 and 198 mg/l and an average hardness of 249 mg/l in previous studies.[96,97] These alkalinities are within the normal range of lakes in Southeastern Wisconsin.[98] Total alkalinity and hardness in both basins are generally stable, with slight declines in more recent sampling (see Figures 2.36 and 2.37, respectively). Since Pewaukee Lake has a high alkalinity or buffering capacity, and because the pH does not fall below 7, the Lake is not considered susceptible to the harmful effects of acid rain.

[96] *SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* op. cit.

[97] *SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* op. cit.

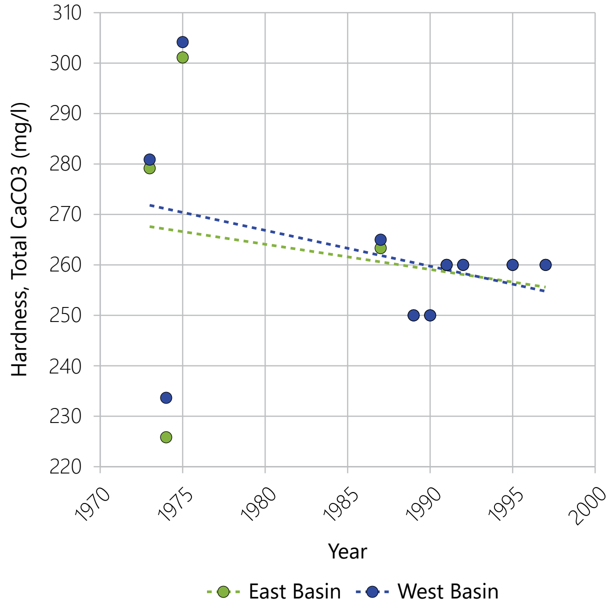
[98] *Ibid.*

Figure 2.36
Pewaukee Lake Mean Annual Alkalinity: 1963-2017



Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.37
Pewaukee Lake Mean Annual Hardness: 1973-1997



Source: Wisconsin Department of Natural Resources and SEWRPC

Nutrients and Trophic Status

Nutrients are elements and compounds needed for plant and algal growth. They are often found in a variety of chemical forms, both inorganic and organic, which may vary in their availability to plants and algae. Typically, growth and biomass of plants and algae in a waterbody are limited by the availability of the nutrient present in the lowest amount relative to the organisms' needs. This nutrient is referred to as the *limiting nutrient*, where additions of this nutrient will increase organism growth and biomass. Phosphorus is usually, though not always, the limiting nutrient in freshwater systems. Under some circumstances nitrogen can act as the limiting nutrient.

Lake biological productivity is referred to in terms of "trophic status." Low productivity lakes with few nutrients, algae, and plants are in an *oligotrophic* status; lakes with moderate nutrients and productivity are in a *mesotrophic* status; and lakes with excessive nutrients and productivity are in a *eutrophic* status. Wisconsin trophic state index (WTSI) equations are used to convert summer water clarity, chlorophyll-*a* concentrations, and phosphorus concentrations to a common unit used to assess lake trophic status and allow comparison of status states between lakes.[99] WTSI values based upon chlorophyll-*a* are considered the most reliable estimators of lake trophic status, as this is the most direct measurement of algal abundance.

Figure 2.38 shows the trophic status of the west basin of Pewaukee Lake, as determined by summer surface measurements of these three parameters. Pewaukee Lake appears to be generally a mesotrophic lake with an average WTSI over the past five years of 44 in the west basin and 52 in the east basin. For a deep lowland drainage lake, these WTSI values are considered "excellent" lake condition for the deep west basin and "good" lake condition for the shallow east basin.[100] Both basins have seen an improvement in water conditions since the earliest measurements in the 1970s, as evidenced by the decline in WTSI values across all three parameters. WTSI values fluctuate slightly in both basins, likely caused by annual differences in temperature and rainfall as well as changes in land use over time.

[99] *R.A. Lillie, S. Graham, and P. Rasmussen,* Trophic State Index Equations and Regional Predictive Equations for Wisconsin Lakes, Research Management Findings, Number 35*, Bureau of Research – Wisconsin Department of Natural Resources, May 1993.*

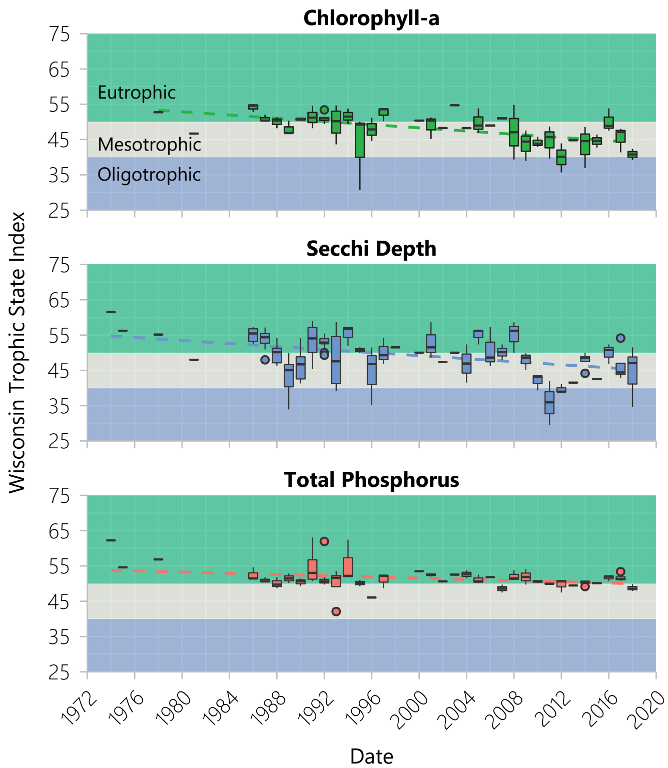
[100] *Wisconsin Department of Natural Resources,* Wisconsin 2020 Consolidated Assessment and Listing Methodology (WisCALM) Clean Water Act Section 303(d) and 305(b) Integrated Reporting, *April 2019.*

Chloride

Humans use chloride bearing materials for a multitude of purposes, such as road salt, water softening, industrial processes, agricultural nutrients and pesticides, pharmaceuticals, petroleum products, and a host of other substances in common use by modern society. As such, chloride concentrations are normally associated with human-derived pollutant concentrations and are, therefore, a good indicator of the overall level of human activity/potential impact and possibly the overall health of a water body. The most important anthropogenic source of chlorides to Pewaukee Lake is believed to be the salts used on roads for winter snow and ice control.[101]

Under natural conditions, surface water in Southeastern Wisconsin contains very low concentrations of chloride. Studies completed in Waukesha County lakes during the early 1900s reported concentrations of three to four mg/l of chloride; in fact, lakes in Southeastern Wisconsin had the lowest levels of chlorides statewide.[102] Most Wisconsin lakes saw little increase in chloride concentrations until the 1960s, but a rapid increase thereafter. Chloride was first measured in Pewaukee Lake during July 1963 at a concentration of 11.9 mg/l.

Figure 2.38
West Basin of Pewaukee Lake Summer (June 1st to September 15th) Trophic State Index Trends: 1972-2017



Source: Wisconsin Department of Natural Resources and SEWRPC

During the initial planning study in 1984,[103] chloride concentrations ranged from 32 to 54 milligrams per liter (mg/l), with an average of 38 mg/l. Samples collected in April 1999 contained 81.1 mg/l chloride, a value close to 700 percent higher than 1963. In August 2018, lake surface waters contained 146 mg/l chloride, which are concentrations much higher than those observed in many other Southeastern Wisconsin lakes.[104] Thus, the rate of chloride accumulation in Pewaukee Lake appears to have increased (see Figure 2.39). While the recent concentrations reported within Pewaukee Lake are below the WDNR standards of 395 mg/l for chronic toxicity and 757 mg/l for acute toxicity (see Table 2.14) established to protect fish and aquatic life, the increasing accumulation of chloride represents a decline in water quality that will be challenging to reverse.

Water Clarity

One of the three major determinants of trophic status is water clarity. Water clarity, or transparency, provides an indication of overall water quality—the greater the clarity, the better the water quality. Clarity may decrease because of turbidity caused by:

- high concentrations of small, aquatic organisms, such as algae and zooplankton

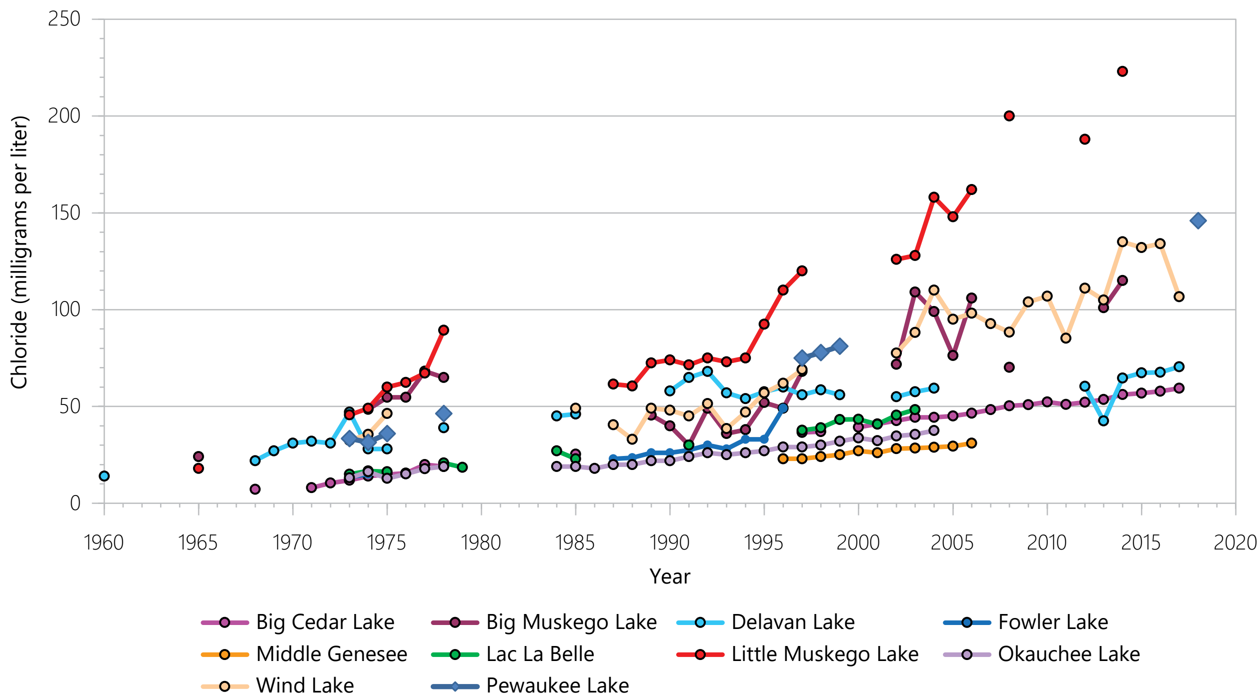
[101] *The major sources of chlorides to lakes in the Southeastern Wisconsin Region include both road salt applications during winter months and salts discharged from water softeners. This latter is of lesser importance to Pewaukee Lake, as such waters are conveyed to the public sewage treatment facility and the effluent therefrom is discharged to the Fox River downstream of the Lake.*

[102] Lillie and Mason, 1983, *op. cit.*

[103] *SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* op. cit.

[104] *Lillie and Mason, 1983, op. cit.*

Figure 2.39
Chloride Concentration Trends in Southeastern Wisconsin Lakes



Source: Wisconsin Department of Natural Resources and SEWRPC

- suspended sediment and/or inorganic particles
- color caused by high concentrations of dissolved organic substances (e.g., tannins that stain water of bog lakes in northern Wisconsin)

In most Southeastern Wisconsin lakes, water clarity is influenced by the abundance of algae and suspended sediment. Water clarity generally varies throughout the year as algal populations increase and decrease in response to changes in lake temperature, sunlight, and nutrient availability. Clarity is measured using a Secchi disk, a black-and-white, eight-inch-diameter disk. This disk is lowered into the water until it is no longer visible, at which point the depth is recorded, and then it is raised until visible again, when depth is recorded again (see Figure 2.40). The average of these depths is called the "secchi depth." Using these measurements, we can determine that the east basin of Pewaukee Lake has generally improved in water clarity since 1973 (see Figure 2.41), with the secchi depth more frequently hitting the lake bottom (8.5 ft.) in recent years. In the west basin, clarity had been steady until about 2008, with increased clarity since then. Large rainfall events and corresponding fluxes in surface water elevations can also influence water clarity. Sediment-induced declines in water clarity can occur due to heavy runoff from major rainstorms. Utilizing surface water elevations from the Lake outlet dam monitoring, we can see the changes in water clarity when surface water elevations peak following heavy rainfall (see Figure 2.42).

Zebra mussels (*Dreissena polymorpha*) can improve water clarity by removing particulate matter through filter-feeding. The WDNR verified the presence of zebra mussels in the Lake in the early 2000s. Zebra mussels may be influencing water clarity in the Lake, but that hypothesis has not been directly tested. Continued monitoring of water clarity will be an important part of any future water quality assessments.

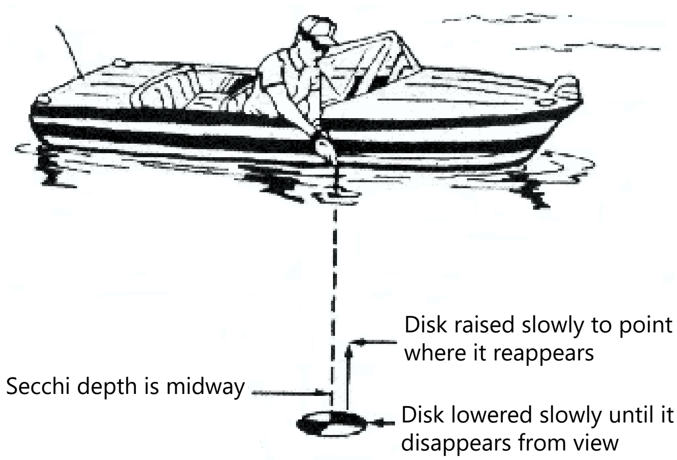
Chlorophyll-a and Algae

Chlorophyll-*a*, a photosynthetic pigment whose abundance is used to indicate algal biomass, is the most reliable metric of a lake's trophic status. Algae is an important and healthy part of lake ecosystems. Algae is a foundational component of lake food chains and produces oxygen in the same way as rooted plants. Many kinds of algae exist, from single-cell, colonial, and filamentous algae to cyanobacteria (see Figure 2.43).

Most algae strains are beneficial to lakes when present in moderate levels. However, the presence of toxic strains (see Figure 2.44), as well as excessive growth patterns, should be considered issues of concern. As with aquatic plants, algae grows faster in the presence of abundant phosphorus (particularly in stagnant areas). Consequently, when toxic or high volumes of algae begin to grow in a lake, it often is a sign of phosphorus enrichment or pollution.

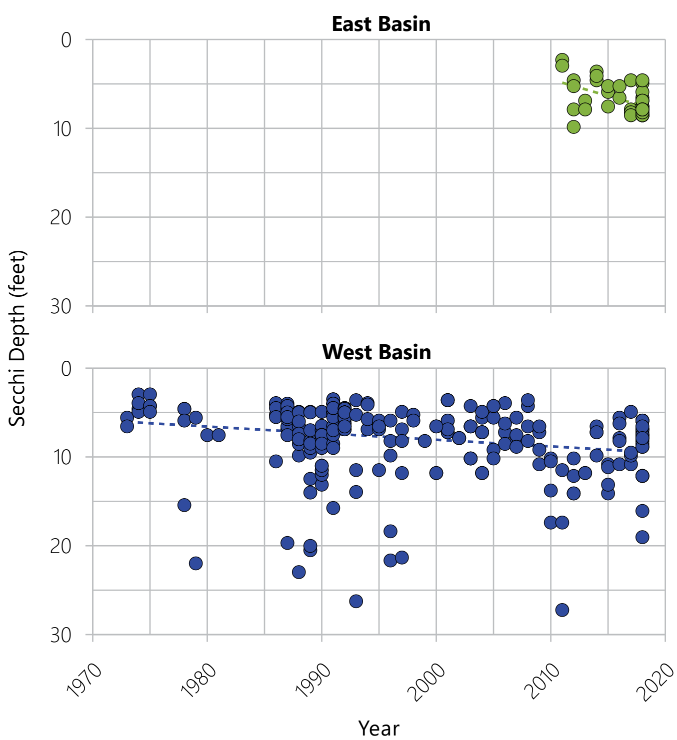
Algae populations are quantified by abundance and composition and can be examined to determine if the algae present are toxin-forming. Suspended algal abundance is estimated by measuring the chlorophyll-*a* concentration in the water column, with high concentrations associated with green-colored water. Mean summer chlorophyll-*a* measurements for both the west and east basins of Pewaukee Lake are always below the 27 μg/l threshold above which aquatic life impairment can occur and algae blooms are more prevalent (see Figure 2.45). Concentrations did occasionally approach the 20 ug/l limit for moderate algal levels, where Wisconsin lake users perceive some impairment to lake enjoyment by algae.[105] In June of 2008 and 2017, algal blooms led to closings at Pewaukee Beach.[106] If blooms become excessive and/or common, or if toxic algae are identified, regular monitoring should be considered. However, the overall trend indicates decreasing chlorophyll-*a* concentrations, indicative of reduced algal abundance. This trend is consistent with efforts by the LPSD to reduce pollutant loading by purchasing and protecting wetland parcels as well as implementing shoreline and stream buffers within the watershed (see Section 2.6, "Pollutant Loads" for more information).

Figure 2.40
Measuring Water Clarity with a Secchi Disk



Source: lakes.chebucto.org and SEWRPC

Figure 2.41
Pewaukee Lake Secchi Depth: 1973-2018



Source: Wisconsin Department of Natural Resources and SEWRPC

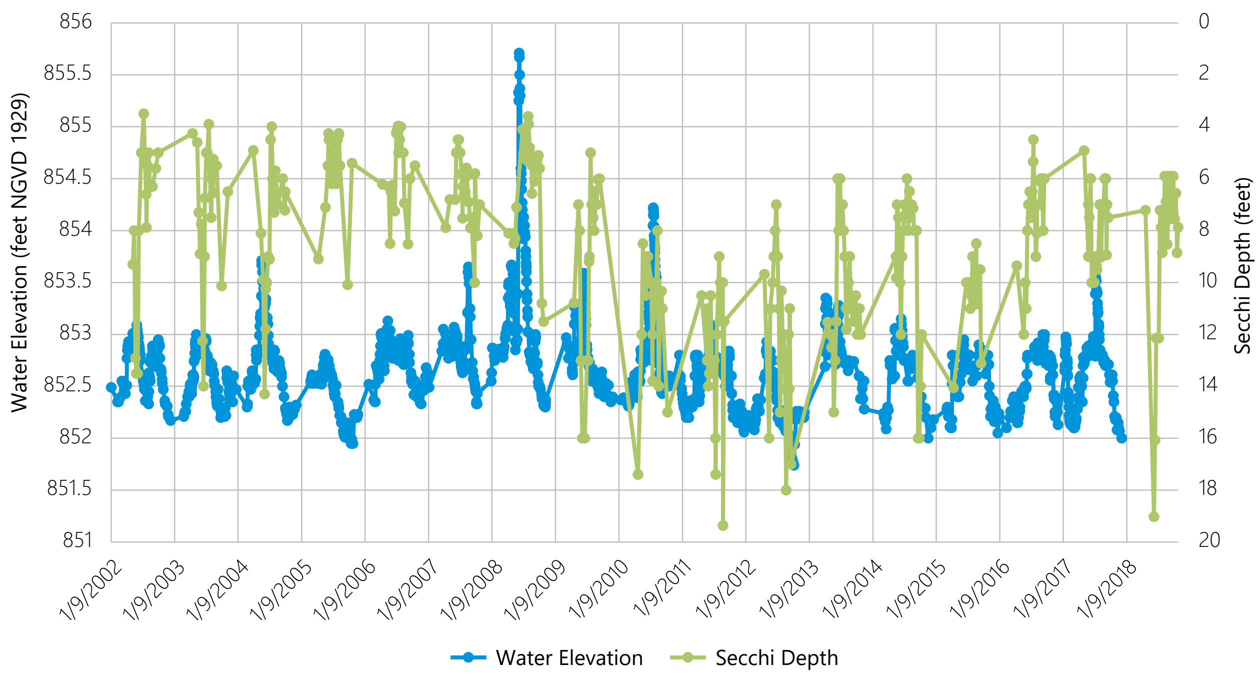
Phosphorus

The third major determinant of a lake's trophic status is the concentration of total phosphorus in the lake's water. Phosphorus is a key nutrient for aquatic plants and algae, with the availability of phosphorus often limiting their growth and abundance. Sources of phosphorus can vary across a watershed, with agricultural fertilizers and animal manure as the predominant phosphorus sources in rural areas while stormwater discharge and onsite wastewater treatment systems contribute phosphorus in urban areas.

[105] *Wisconsin Department of Natural Resources,* Wisconsin 2020 Consolidated Assessment and Listing Methodology (WisCALM) Clean Water Act Section 303(d) and 305(b) Integrated Reporting, *April 2019.*

[106] *"Pewaukee Beach closed due to blue-green algae" WBay News. 25 Jun 2017. www.wbay.com/content/news/Pewaukee-Beach-closed-due-to-blue-green-algae--430683173.html.*

Figure 2.42
Relationship Between Lake Surface Water Elevation and Secchi Depth: Pewaukee Lake 2002-2018



Source: Lake Pewaukee Sanitary District and SEWRPC

Two forms of phosphorus are commonly sampled in surface waters: total phosphorus and dissolved phosphorus. Total phosphorus consists of all of the phosphorus contained in material dissolved or suspended in water. Dissolved phosphorus consists of the phosphorus contained in material dissolved in water. In both these types, the phosphorus may be present in a variety of chemical forms. However, as the degree of eutrophication in freshwater systems correlates more strongly with total phosphorus concentration than with dissolved phosphorus concentration, the State's water quality criteria are expressed in terms of total phosphorus. Thus, water quality sampling tends to focus on assessing total phosphorus concentrations rather than dissolved phosphorus concentrations.

Total phosphorus in both basins of Pewaukee Lake has been decreasing since 1988, as shown in Figure 2.46. This trend indicates that either phosphorus loading to the Lake has declined or phosphorus removal from the water column, such as through aquatic plant harvesting, has increased; both of these topics are explored further in Section 2.6, "Pollutant Loads." Surface water samples collected during the growing season (June through August) generally have the lowest total phosphorus concentrations, with an average of 0.024 mg/l (see Figure 2.47). This phosphorus concentration is below the aquatic life impairment threshold of 0.030 mg/l for deep lowland drainage lakes[107] mandated by administrative code[108] (see Table 2.14). Samples collected in the west basin deeper than 30 feet have greater total phosphorus concentrations (mean of 0.16 mg/l) than surface water samples (mean of 0.02 mg/l) (see Figure 2.48), a pattern that may be indicative of internal phosphorus loading (see Section 2.6, "Pollutant Loads").

Nitrogen

Surface waters contain a variety of nitrogen compounds that are nutrients for plants and algae. Typically, only a small number of forms of nitrogen are examined and reported in water quality sampling. Total nitrogen includes all of the nitrogen in dissolved or particulate form in the water, excluding all gaseous forms of nitrogen. Total nitrogen is a composite of several different compounds that vary in their availability to algae and aquatic plants and in their toxicity to aquatic organisms. Many nitrogen-containing organic

[107] *Wisconsin Department of Natural Resources,* Wisconsin 2020 Consolidated Assessment and Listing Methodology (WisCALM) Clean Water Act Section 303(d) and 305(b) Integrated Reporting, *April 2019.*

[108] *Wisconsin Administrative Code Chapter NR 102,* op. cit.

compounds, such as amino acids, nucleic acids, and proteins that commonly occur in natural and polluted waters are included in total nitrogen. Common inorganic constituents of total nitrogen include ammonia, nitrate, and nitrite. These are the forms that most commonly support algal and plant growth. While nitrate (NO_3^-) can be toxic to humans at high concentrations (WDNR drinking water limit is 10 mg/l), nitrate concentrations in the Lake have been declining and now rarely exceed detection limits (0.19 mg/l). Thus, nitrate toxicity is not a concern in Pewaukee Lake.

A variety of point and nonpoint sources contribute nitrogen compounds to surface waters. In urban settings, nitrogen compounds from lawn fertilizers and other sources may be discharged through storm sewer systems and direct runoff into streams. Cross-connections between sanitary and storm sewer systems, illicit connections to storm sewer systems, and decaying sanitary and storm sewer infrastructure may contribute sanitary wastewater to waterbodies through discharges from storm sewer systems. In rural settings, nitrogen compounds from chemical fertilizers and animal manure may be contributed through discharges from drain tiles or direct runoff into waterbodies. Poorly maintained or failing onsite wastewater treatment systems can also contribute nitrogen compounds. In addition, some species of lake cyanobacteria "fix" nitrogen by converting otherwise inert gaseous nitrogen into ammonia or another compound usable by algae and plants.

Occasionally, nitrogen acts as the limiting nutrient for algal and plant growth in freshwater systems, typically when phosphorus concentrations are very high. In general, when the ratio of total nitrogen (N) to total phosphorus (P) concentrations is 15:1 or greater, the availability of phosphorus limits algal growth. Conversely, when this proportion is less than 10:1, nitrogen concentrations limit plant growth. Ratios between 15:1 and 10:1 are considered transitional.[109] During spring turnover on the Lake between 1987 and 2001, N/P ratios typically averaged in the high forties, and ranged from as low as 20:1 to as high as 100:1 (see Figure 2.49); such ratios clearly indicate that phosphorus is the main limiting factor for plant and algae growth. Spring nitrogen concentrations in the Lake fluctuated between 0.6 and 0.9 mg/l from 1987 to 2001, when the most recent spring measurement was taken (see Figure 2.50). Summer nitrogen concentrations have declined over time, from a high of 1.2 mg/l in 1992 to 0.5 mg/l in 2017. As the limiting nutrient in Pewaukee Lake, phosphorus should be the major focus of nutrient loading and algae bloom management decisions.

Figure 2.43
Common Types of Non-Toxic Algae

Hydrodictyon

Spirogyra

Chlamydomonas

Source: (1) Lewis Lab (2) University of New Mexico (3) Taranaki Regional Council & Landcare Research

[109] *Lillie and Mason, 1983, op. cit.*

Bacteria

The concentration of certain bacteria in water is measured in order to assess the quality of the water for drinking water supply and recreational uses. A variety of disease-causing organisms can be transmitted through water contaminated with fecal material. These organisms include bacteria, such as those causing cholera and typhoid fever; viruses, such as those causing poliomyelitis and infectious hepatitis; and protozoa, such as Giardia and Cryptosporidium. It is not practical to test surface waters for all of these diseasecausing organisms as rapid and inexpensive tests do not currently exist for many of these organisms. Instead, the sanitary quality of surface water is assessed by examining samples for the presence and concentrations of organisms indicating fecal contamination. Two groups of bacteria are commonly examined in surface waters of the Greater Milwaukee watersheds: fecal coliform bacteria and *Escherichia coli* (*E. coli*). All warm-blooded animals have these bacteria in their feces, so the presence of high concentrations of fecal coliform bacteria or *E. coli* in water indicates a high probability of fecal contamination. While most strains of these two bacterial groups have a low probability of causing illness they do act as indicators of the possible presence of other pathogenic agents in water, particularly when present in high concentrations.

Figure 2.44
Appearance of Toxic Algae Blooms

Microcystis

Cylindrospermopsis

Source: (1) National Oceanic and Atmospheric Administration
(2) St. John's River Water Management District

Fecal coliform bacteria are currently used to indicate the suitability of inland waters in Wisconsin for recreational uses.[110] The State requires that counts of fecal coliform bacteria in waters of the State not exceed 200 colony-forming-units (a measure of living cells) per 100 milliliters (cfu per 100 ml) as a geometric mean based on not less than five samples per month, nor exceed 400 cfu per 100 ml in more than 10 percent of all samples during any month. Pewaukee Lake has not exceeded fecal coliform limits.

E. coli is a species of fecal coliform bacteria. The USEPA recommends using either *E. coli* or enterococci as indicators of fecal pollution in recreational waters for freshwater systems. Agencies participating in the monitoring of beaches in the Wisconsin Beach Monitoring program use *E. coli* as the indicator of sanitary quality of the associated waters. Water quality advisories are issued for beaches whenever the concentration of *E. coli* in a sample exceeds 235 cfu per 100 ml or whenever the geometric mean of at least five samples taken over a 30-day period exceeds 126 cfu per 100 ml. Beaches are closed whenever the concentration of *E. coli* exceeds 1,000 cfu per 100 ml. The City of Pewaukee Parks and Recreation Department monitors levels of *E. coli* at Pewaukee Beach. They post a green sign when *E. coli* counts are less than 235 cfu per 100 mL, a yellow sign when *E. coli* counts are between 235 and 999 cfu per 100 mL of water of water, and a red "closed" sign when *E. coli* counts exceed 1,000 cfu per 100 mL of water. These levels are in accordance to the EPA's good water quality guideline. The water is retested daily until the counts reach a safe level and the beach can be reopened.

Tributary Streams

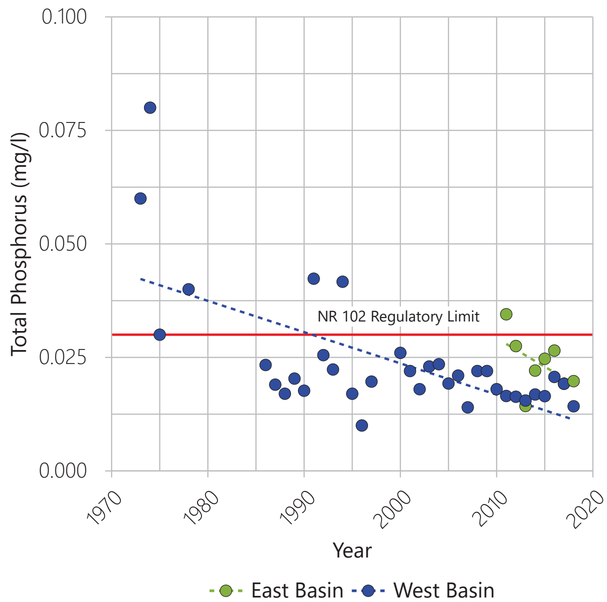
Lakes and streams have strikingly different environments. This presents special challenges when dealing with water quality issues. This subsection will present data collected from the three main tributaries of

[110] *Wisconsin Department of Natural Resources,* Wisconsin 2020 Consolidated Assessment and Listing Methodology (WisCALM) Clean Water Act Section 303(d) and 305(b) Integrated Reporting, *April 2019.*

Figure 2.45
Mean Summer Chlorophyll-*a*: Pewaukee Lake 1973-2018

Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.46
Mean Summer (June 1st to September 15th) Total Phosphorus: Pewaukee Lake 1973-2018



Source: Wisconsin Department of Natural Resources and SEWRPC

Pewaukee Lake: Coco Creek, Meadowbrook Creek, and Zion Creek. An analysis of these data will provide context to the water quality characteristics of Pewaukee Lake since a lake's tributaries play an important role in the overall health of the lake into which they flow. An understanding of these data should aid in developing management strategies for both the Lake and its tributaries.

Temperature and Oxygen

The interplay between temperature and oxygen in streams is different than that which occurs in lakes in several ways. For example, without stratification, streams avoid many of the complexities (hypolimnetic anoxia, internal loading, etc.) imposed on lakes that stratify. In addition, the continual movement of water in streams makes for a constant mixing of waters at the surface and below.

As in lakes, however, temperature is one of the most significant physical characteristics of a stream. In fact, along with flow, temperature is one of the key determinants of the biotic communities into which streams are commonly classified. Table 2.16 shows the water quality criteria for temperature for those streams that have a seven-day, 10-percent probability low flow (7Q10)[111] of less than 200 cubic feet per second (cfs). The 7Q10 of all of the streams in the Pewaukee Lake watershed is less than 200 cfs. Streams in temperate climates tend to range between freezing and around 80°F; the main Pewaukee tributaries fall into this range as shown in Figure 2.51. However, it should be noted that the temperatures in this figure are based on "grab samples"[112] that, while they can provide some useful data, are not able to reflect the comprehensive temperature dynamics that a more continual monitoring, such as from an electronic logging device, can achieve.

Commission staff deployed continuous monitoring devices at these locations to measure water temperatures and at one additional site to monitor air temperatures from 2010 through 2011.[113] Reaches within Zion Creek contained the warmest sites while Coco Creek and CTH JJ Tributary had the coldest sites. Due to the inability to recover the continuously recording temperature data logger at Meadowbrook Creek, it was not possible to compare the daily maximum temperatures of this system to other sites in the watershed.

[111] *Seven-day consecutive low flow with an annual probability of occurrence of 10 percent.*

[112] *A "grab sample" refers to a sampling taken once a day or even as infrequently as once a month, but not a continuous 24-hour measuring.*

[113] *SEWRPC Community Assistance Planning Report No. 313*, op. cit.

However, the samples collected by the Water Action Volunteers on Meadowbrook Creek indicate that the summer average temperatures from 2006 through 2012 was 72.3°F and the maximum temperature recorded at that site was 83.3°F. These temperatures suggest that Meadowbrook Creek is likely receiving groundwater input that is lowering water temperatures; a hypothesis supported by the Creek's classification as a cool headwater fishery. More detailed temperature information would need to be collected to verify this.

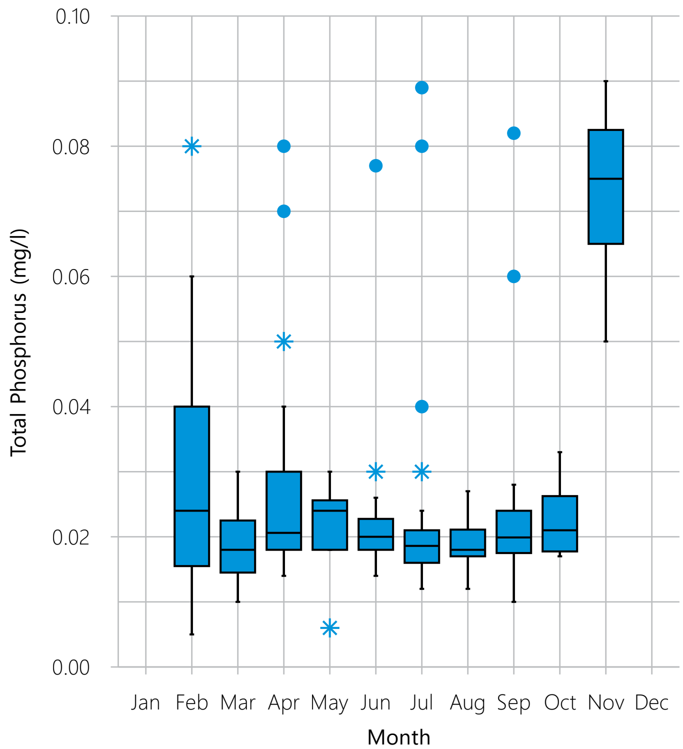
Coco Creek is the only designated coldwater fishery within the Pewaukee Lake watershed. Based upon the acute water quality criteria for temperature, coldwater streams should not exceed a daily maximum of 72.0°F in June or 73.0°F in July or August. The stations at RM 0.54 and RM 2.42 on the mainstem of Coco Creek and the Unnamed Tributary-2 at RM 0.36 meet these criteria 100 percent of the time. The remaining tributary sites to Coco Creek at RM 1.04 generally meet the coldwater criteria for the summer months more than 95 percent of the time. In addition, the mainstem site on Coco Creek at RM 1.00 met the coldwater criteria for the summer months between 75 percent to more than 95 percent of the time over a four year period from 2008 through 2011. In contrast, the two most upstream sites on the mainstem of Coco Creek at RM 3.20 and RM 4.03 only meet the summer month coldwater criteria about 50 percent of the time.

Brook trout and brown trout were recently found to not occur within streams where summer maximum daily water temperatures exceeded 81.7°F,[114] consistent with the fisheries findings summarized in Section 2.9, "Fisheries." Based on this limit, every site sampled on the main stem and tributary of Coco Creek can be considered capable of supporting trout (i.e., water temperatures are within thermal tolerance ranges for trout), except for the most upstream site at RM 4.03 (see Figure 2.51).

The acute water quality criteria for temperature in warmwater streams should not exceed a daily maximum of 84.0°F in June or August or 84.9°F in July. The Pewaukee Lake Outlet and Zion Creek are meeting the criteria about 75

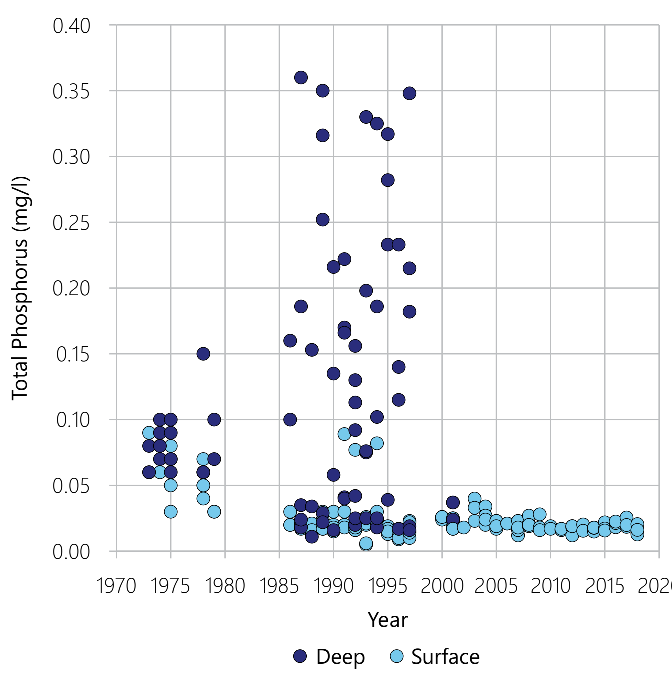
[114] *K.E. Wehrly, L. Wang, and M. Mitro, "Field-Based Estimates of Thermal Tolerance Limits for Trout: Incorporating Exposure Time and Temperature Fluctuation,"* Transactions of the American Fisheries Society, *139: 365-374, 2007.*

Figure 2.47
Monthly Near Surface Total Phosphorus Concentrations: Pewaukee Lake West Basin 1973-2018



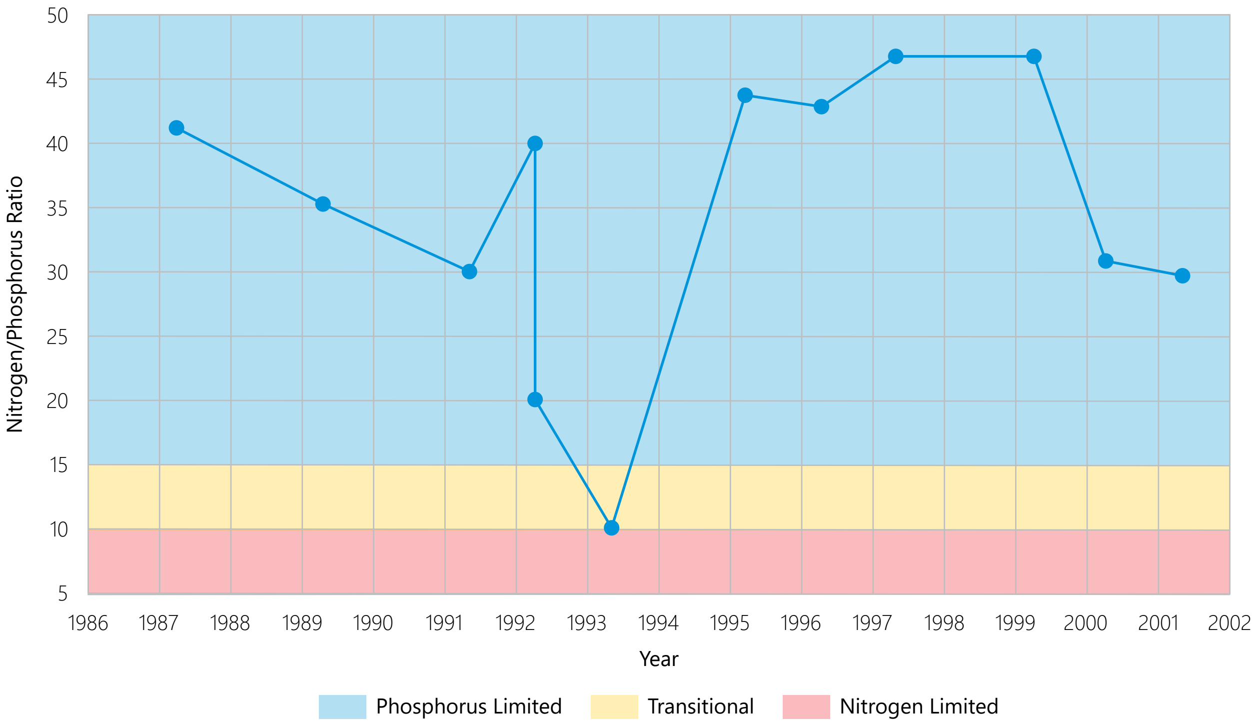
Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.48
Total Phosphorus Concentrations of Water Collected from Various Depths: Pewaukee Lake West Basin 1972-2017



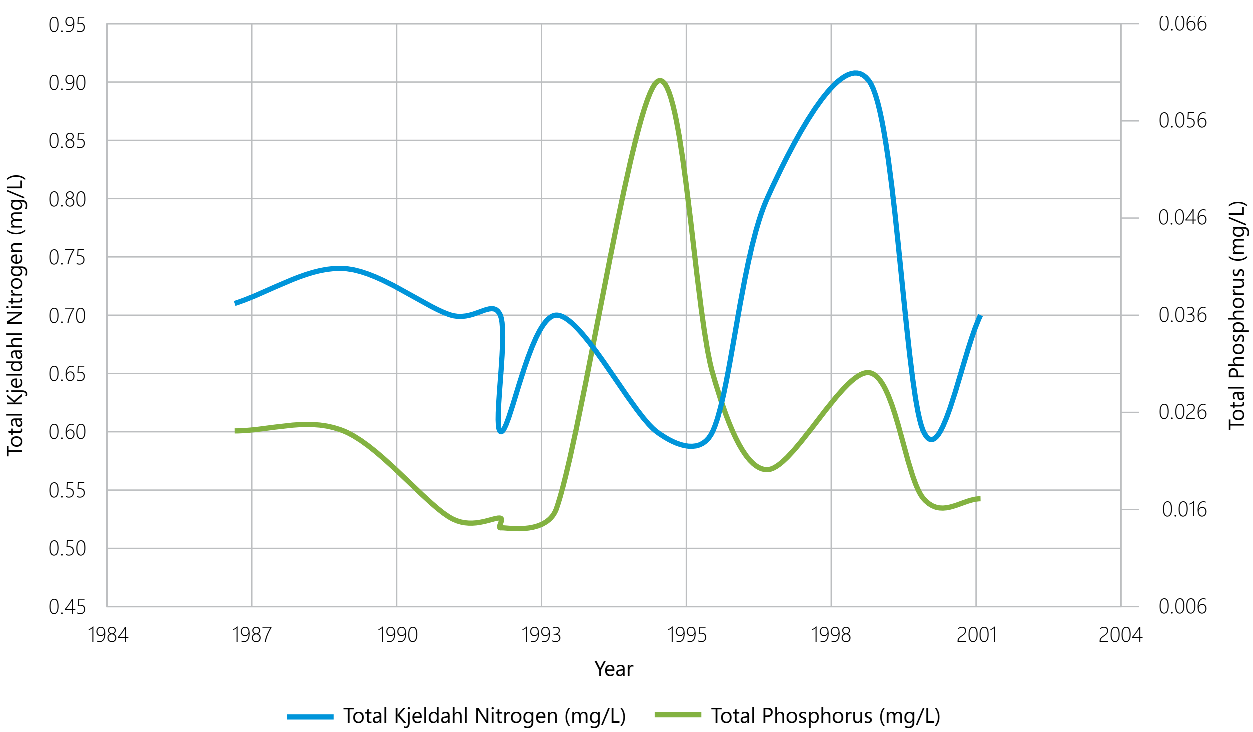
Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.49
Spring (Fully Mixed) Nitrogen to Phosphorus Ratio Trend: Pewaukee Lake 1987-2001



Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.50
Spring (Fully Mixed) Nitrogen and Phosphorus Trends: Pewaukee Lake 1987-2001



Source: Wisconsin Department of Natural Resources and SEWRPC

Table 2.16
Ambient, Sublethal, and Acute Water Quality Temperature Criteria (°F) for Designated Use Streams[a]

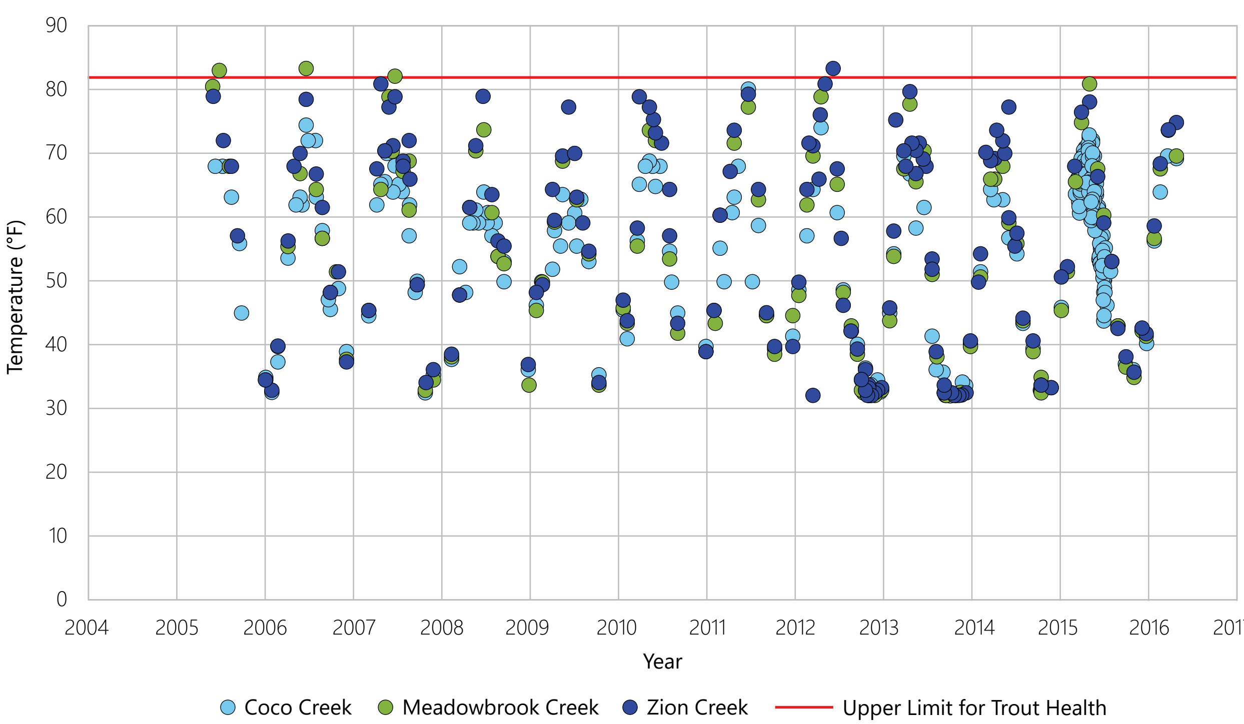
	Designated Use Category and Associated Temperature Criterion (°F)[b]								
	Cold Water Communities			Warmwater Sportfish or Forage Fish Communities			Limited Forage Fish Communities		
Month	Ambient	Sublethal	Acute	Ambient	Sublethal	Acute	Ambient	Sublethal	Acute
January	35.1	46.9	68.0	33.1	48.9	75.9	37.0	54.0	73.0
February	36.0	46.9	68.0	34.0	50.0	75.9	39.0	54.0	79.0
March	39.0	51.1	69.1	37.9	52.0	77.0	43.0	57.0	80.1
April	46.9	57.0	70.0	48.0	55.0	79.0	50.0	63.0	81.0
May	55.9	63.0	72.0	57.9	64.9	82.0	59.0	70.0	84.0
June	62.1	66.9	72.0	66.0	75.9	84.0	64.0	77.0	84.9
July	64.0	66.9	73.0	69.1	81.0	84.9	69.1	81.0	86.0
August	63.0	64.9	73.0	66.9	81.0	84.0	68.0	79.0	86.0
September	57.0	60.1	72.0	60.1	73.0	82.0	63.0	73.0	84.9
October	48.9	53.1	70.0	50.0	61.0	80.1	55.0	63.0	82.9
November	41.0	48.0	69.1	39.9	48.9	77.0	46.0	54.0	80.1
December	37.0	46.9	69.1	35.1	48.9	75.9	39.9	54.0	79.0

[a] *As set forth in Section NR 102.25 of the* Wisconsin Administrative Code, *small streams are waters with unidirectional 7Q10 flows less than 200 cubic feet per second. The 7Q10 flow is the seven-day consecutive low flow with a 10 percent annual probability of occurrence (10-year recurrence interval).*

[b] *The ambient, sublethal, and acute water quality temperature criterion specified for any calendar month shall be applied simultaneously to establish the protection needed for each identified fish and other aquatic life use. The sublethal criteria are to be applied as the mean daily maximum temperature over a calendar week. The acute criteria are to be applied as the daily maximum temperatures. The ambient temperature is used to calculate the corresponding acute and sublethal criteria and for determining effluent limitations in discharge permits under the Wisconsin Pollutant Discharge Elimination System.*

Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.51
Pewaukee Lake Tributary Summer Temperatures Trends: 2005-2016



Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, Water Action Volunteers, and SEWRPC percent of the time. Most surprising, not only is the CTH JJ Tributary meeting the warmwater criteria 100 percent of the time, this site never exceeded 78.8°F, which means it is technically capable of supporting a coldwater trout fishery, as described above.

Whereas water temperature influences the types of species that can live in rivers (each aquatic species has a preferred range), temperature also governs the amount of oxygen that can be held in water (warmer water holds less oxygen than cool water[115]). The minimum DO standards for coldwater (trout) and warmwater streams, as set forth in Chapter NR 102 of the *Wisconsin Administrative Code*, are 6.0 and 5.0 mg/l, respectively. Minimum DO standards for coldwater streams are to maintain concentrations of 7.0 mg/l or greater during the trout spawning season. If the water in a stream, or other waterbody, becomes too warm, DO levels may be suboptimal (i.e., less than 5.0 mg/l) for many species of fishes and other aquatic organisms. However, streams can also become supersaturated with oxygen, generally above 15 mg/l, which can also be injurious to fish. Because the warmest water temperatures occur in the summer, this is the most important time of the year for determining physiological limitations for aquatic organisms based on DO concentrations.

Dissolved oxygen concentrations are generally within the range consider healthy for fish population, but Meadowbrook Creek and Zion Creek do attain concentrations outside of this range (see Figure 2.52). Meadowbrook Creek occasionally falls below 2.0 mg/l and almost never achieves 5.0 mg/l in summer, indicating that this system may be limiting to fish and other aquatic organisms. This Creek contains a high amount of organic matter, the decomposition of which can lower dissolved oxygen concentrations. Zion Creek had several measurements below the 5.0 mg/l level, as well as several measurements above the 15 mg/l level that roughly translates into 150 percent oxygen saturation (140 percent saturation can cause fish kills). Only Coco Creek had all oxygen measurements above the 5.0 mg/l level and below the 15 mg/l level, indicating the best conditions for supporting fish populations.

Specific Conductance

Meadowbrook Creek consistently had the highest specific conductance of the tributaries between 2006 and 2016 (see Figure 2.53). Specific conductivity is highest in the winter in all three tributaries, which is indicative of salt application before and during snow storms. Beginning in the fall of 2013, the average specific conductance appears to have shifted upward in all three tributaries, but it is unclear whether this is due to a change in sampling methodology or the actual condition of these streams.

Chloride

Chloride concentrations in Coco, Meadowbrook, and Zion Creeks are presented in Figure 2.54. Although there are relatively little data available on chloride in these three tributaries, it would appear that all three tributaries have elevated chloride concentrations. The samples collected from Meadowbrook Creek exceed the NR 102 Chronic toxicity threshold of 395 mg/l; however, Meadowbrook Creek has only been sampled in winter, when chloride attains its seasonal peak with contributions from road salt applications. Summer sampling of all three tributaries would better reflect whether chloride remains elevated throughout the year.

pH

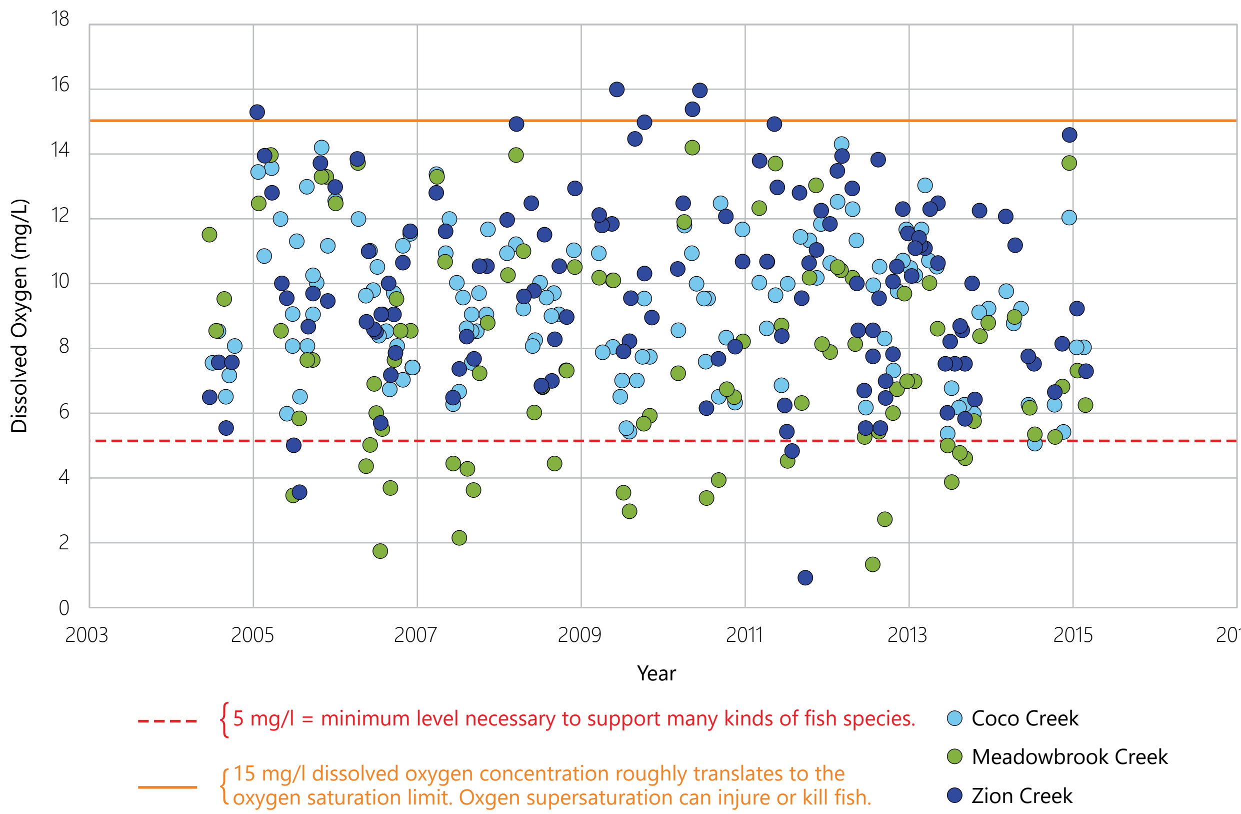
Coco, Meadowbrook, and Zion Creeks have pH levels that are consistent with each other and with the general range found in Pewaukee Lake (between 7.5 and 8.5 stu), as well as in Southeastern Wisconsin (8.1 stu) (see Figure 2.55). These pH levels indicate that these waters are neutral to slightly alkaline. Stream pH can vary with water sources, as precipitation is generally acidic to neutral while groundwater is neutral to alkaline.

Phosphorus

Tributaries can be a major source of phosphorus to lowland drainage lakes. Phosphorus data for the three tributaries of Pewaukee Lake is extremely limited (see Figure 2.56). There have been seven samples taken in Coco Creek, one of which was taken in 1990 and the remainder of which were taken in 2013. Zion Creek has been sampled nine times between 2012 and 2016 and no samples have been collected on Meadowbrook Creek. However, as flow rates (see Figure 2.57) were not measured during phosphorus sample collections, the total amount of phosphorus each tributary is contributing cannot be calculated. Thus, only phosphorus

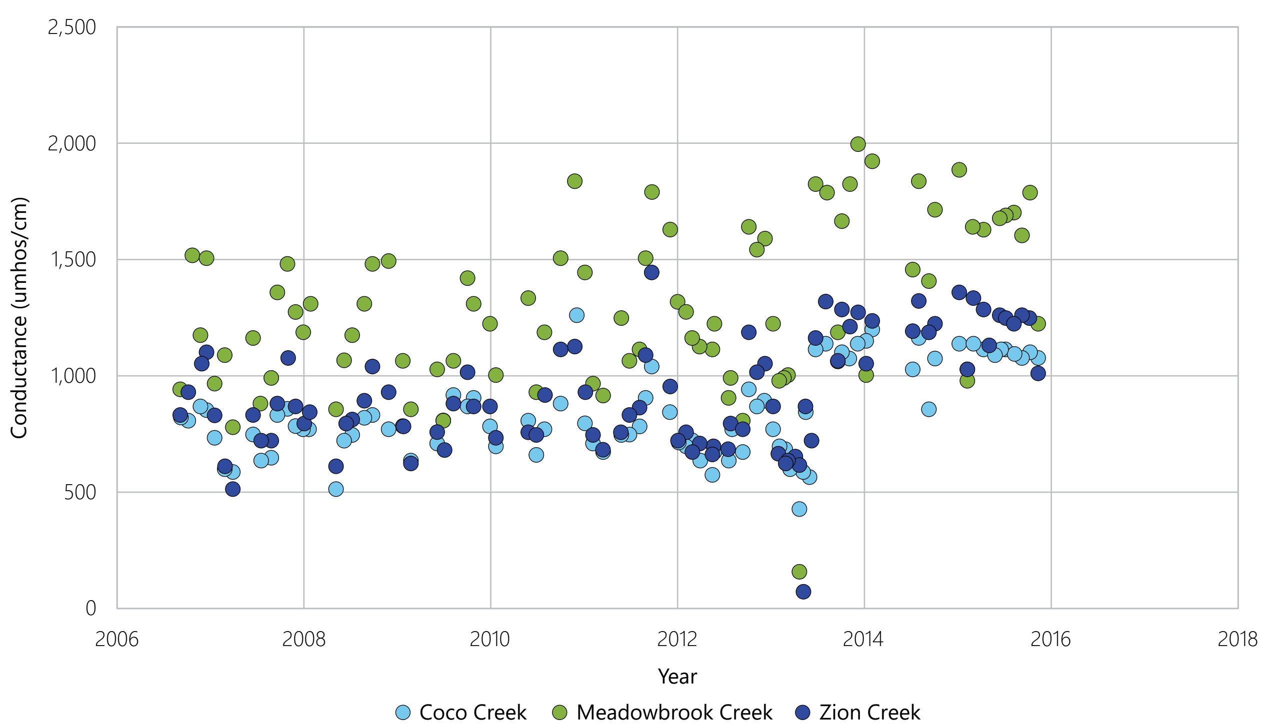
[115] *A key cause of increased stream temperatures is impervious surfaces (roadways, parking lots, buildings), which restrict infiltration of water, as discussed in Section 2.2, "Lake and Watershed Physiography."*

Figure 2.52
Pewaukee Lake Tributary Dissolved Oxygen Trends: 2005-2016



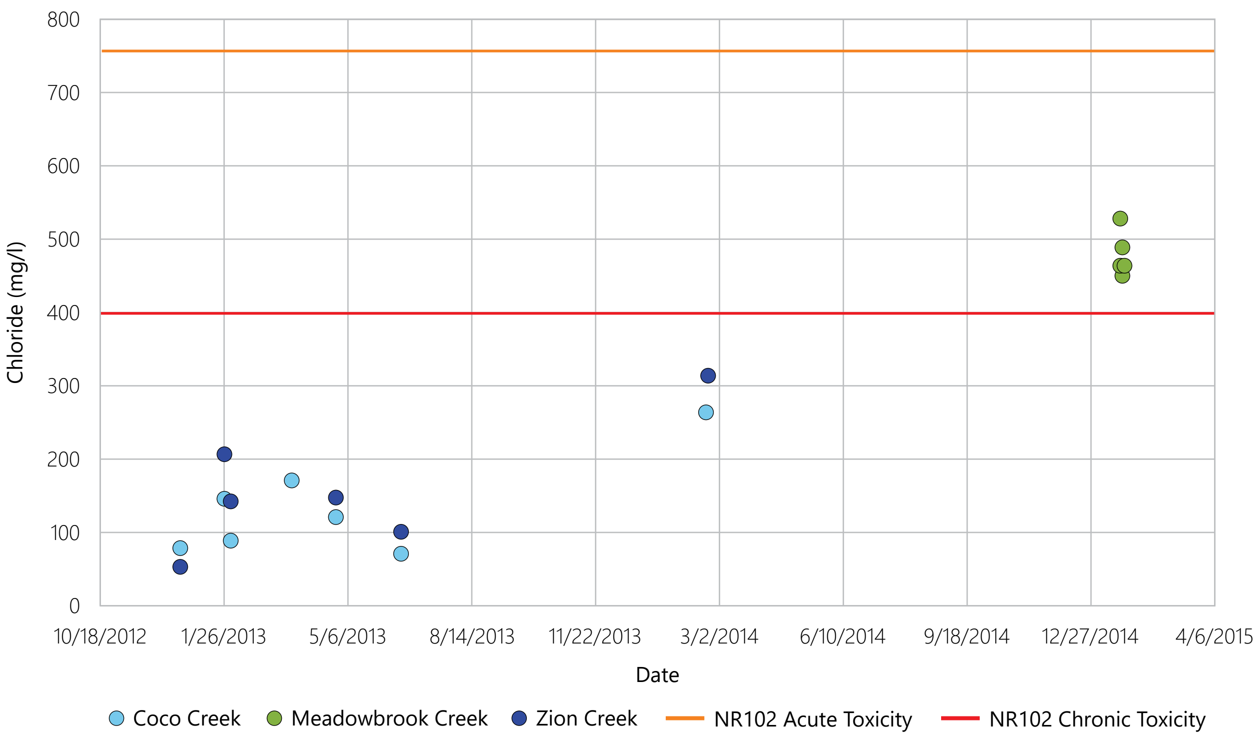
Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, Water Action Volunteers, and SEWRPC

Figure 2.53
Pewaukee Lake Tributary Specific Conductivity Trends: 2006-2016



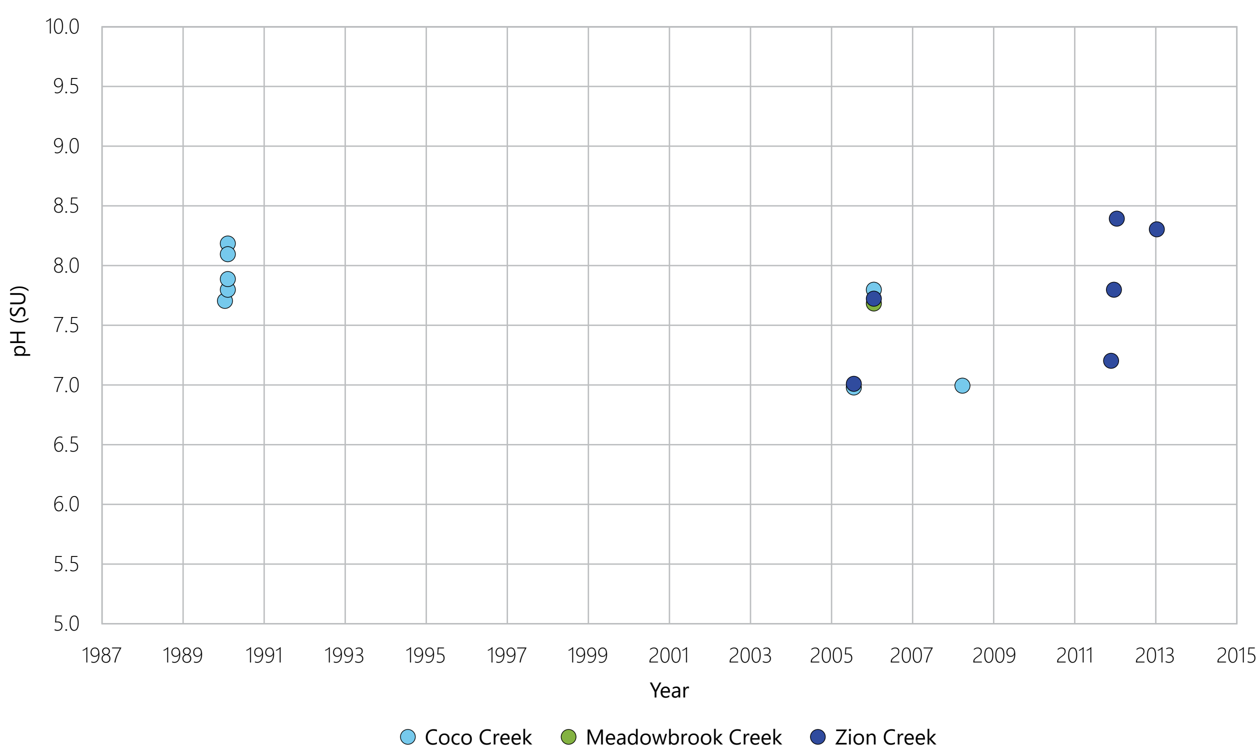
Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, and SEWRPC

Figure 2.54
Pewaukee Lake Tributary Chloride Concentration Trends: 2012-2014



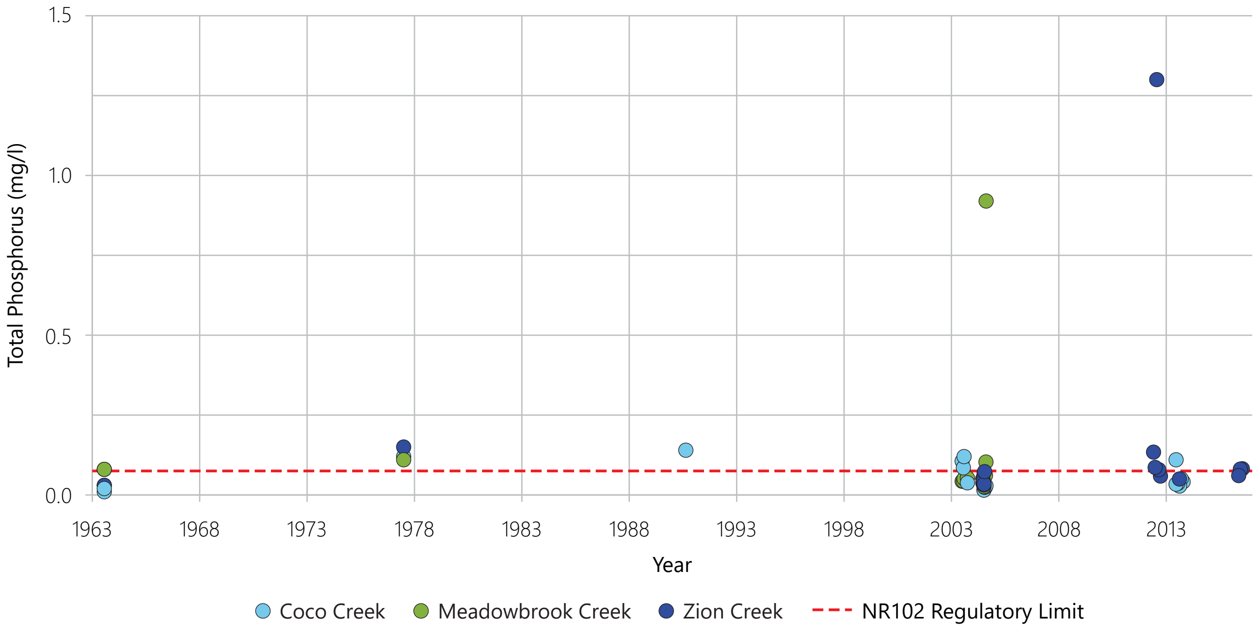
Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, and SEWRPC

Figure 2.55
Pewaukee Lake Tributary pH Trends: 1989-2013



Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, Water Action Volunteers, and SEWRPC

Figure 2.56
Pewaukee Lake Tributary Total Phosphorus Concentration Trends: 1990-2016



Source: Wisconsin Department of Natural Resources, Wisconsin Lutheran College, and SEWRPC

concentrations can be used to evaluate water quality. One sample taken in Zion Creek in 2012 was ten to twenty times higher than the other values,[116] causing the overall mean value to be tenfold higher than that of Coco Creek. However, the number of samples was very limited. Five samples taken in Coco Creek during 2013 averaged 0.034 mg/l (0.06 mg/l if the single sample from 1990 is included). Nine samples taken in Zion Creek during 2012 through 2016 averaged 0.210 mg/l, although the measurement taken in May of 2012 appears to be significantly outside the range of all other measurements (without that single high measurement, the average for Zion Creek would be 0.081 mg/l—just slightly above the 0.075 regulatory criteria designated for warmwater fish and aquatic life shown in Table 2.17). To better understand phosphorus contributions by the tributaries, phosphorus sampling should be concurrently measured with streamflow, allowing total phosphorus loads to be calculated.

Potential Biological Use

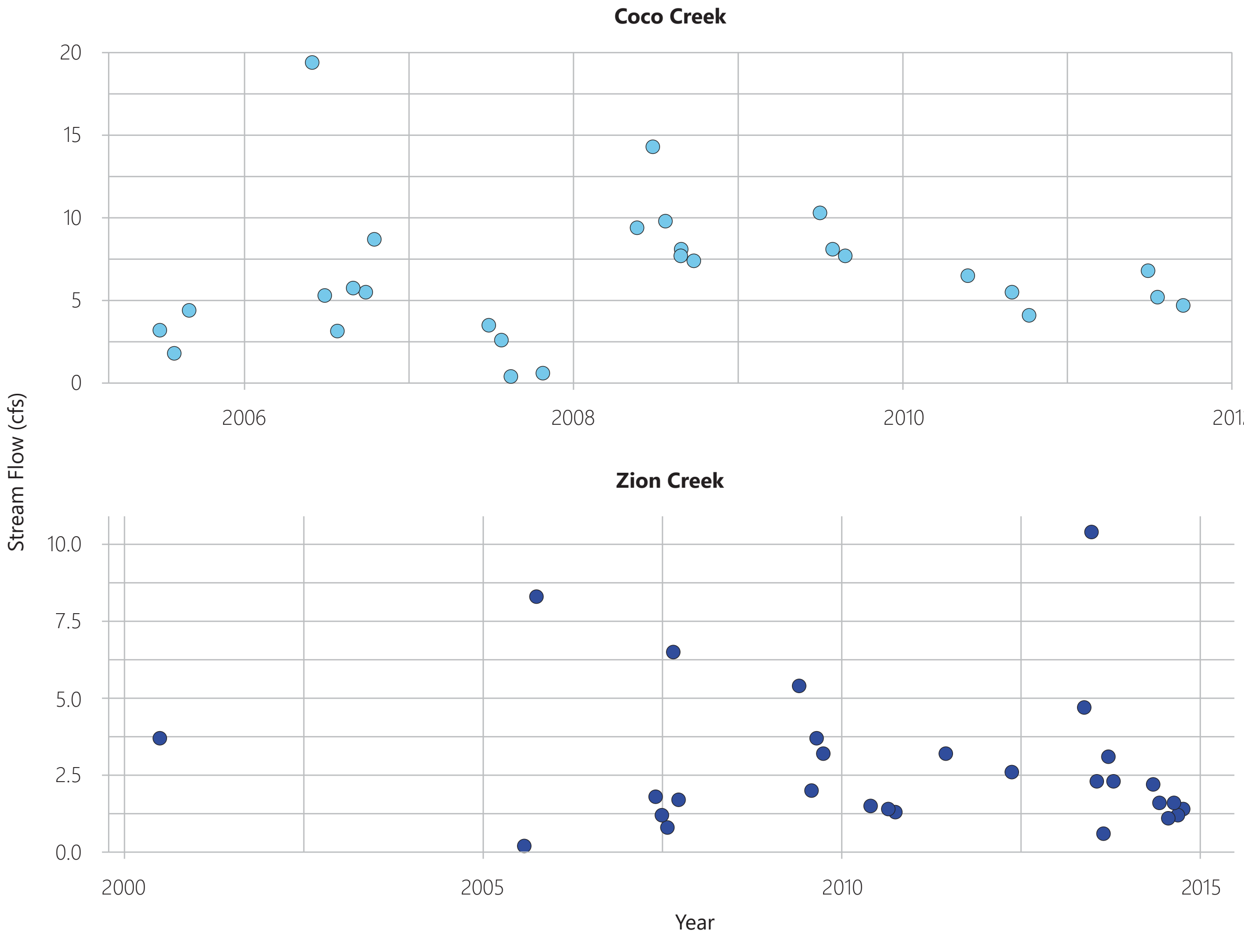
None of the streams or tributaries within the Pewaukee Lake watershed fully meets their potential biological uses or the fishable and swimmable water use goals set for the waters of the United States in the Federal Clean Water Act.[117] Coco Creek has been identified to be partially meeting its potential biological use designation, but Meadowbrook Creek and Zion Creek were reported as not meeting their potential biological uses. The cause or source of impairments identified by WDNR staff as part of their 2002 state of the basin report for this watershed include ditching or channelization, hydrologic modification, cropland erosion, barnyard or excessive lot runoff, construction site erosion, urban stormwater runoff, unspecified nonpoint source pollution, and storm sewers. These have caused numerous impacts to Pewaukee Lake and its tributaries in terms of degraded habitat (lack of cover, sedimentation, scouring, etc.), nutrient enrichment, temperature fluctuations or extremes, reductions in DO, sedimentation, stream flow fluctuations caused by land use development, bacteriological contamination, turbidity, and pesticide/herbicide toxicity (see Section 2.8, "Stream Habitat" for more information).[118]

[116] *The highest maximum recorded total phosphorus concentration ever observed within the Pewaukee Lake watershed was 1.3 mg/l on July 23, 2012, in Zion Creek. This observation indicates that Zion Creek remains impaired from excessive nutrient loading.*

[117] *Wisconsin Department of Natural Resources, Publication No. PUBL-FH-806-2002,* Wisconsin Trout Streams, *April 2002.*

[118] *Ibid.*

Figure 2.57
Pewaukee Lake Tributary Stream Flow Measurements: 1998-2017



Source: U.S. Geological Survey, Wisconsin Department of Natural Resources, and SEWRPC

Despite these impairments, all of Coco Creek, beginning at CTH JJ (just upstream of Pewaukee Lake), has been designated by the WDNR as having the potential to support a Class I and Class II brown trout fishery.[119] A Class I trout stream is characterized as a high-quality trout water that has sufficient natural reproduction to sustain the native or naturalized populations. Consequently, streams of this category do not require stocking of hatchery raised trout. A Class II trout stream may have some natural trout reproduction, but not enough to utilize available food and space. Consequently, stocking is generally required to sustain a desirable sport fishery. In this regard, it should be noted that brown trout have been collected by the WDNR staff from Coco Creek as recently as July 2017 (see Section 2.9, "Fisheries").

Water Quality Summary

Overall, in many ways Pewaukee Lake represents a typical hard-water, alkaline lake that is considered to have relatively good water quality, especially since the implementation of public sewage treatment measures during the 1970s. The Lake is dimictic and stratifies during the summer at a depth of about 25 feet, below which depth waters become anoxic during late summer with internal loading of phosphorus being indicated, although not at levels deemed problematic since neither chronic summer algae blooms nor fish kills have been recorded; waters in the west basin above the thermocline remain well-oxygenated above the 5.0 mg/l threshold year round. Notwithstanding, Pewaukee Lake does show signs of stress from human influence and the potential for algal blooms, especially in the shallow east basin. Winterkill is not a problem in Pewaukee Lake as cross-sectional analysis shows that a substantial volume of the Lake provides adequate oxygenated water volume for the support of fish throughout the winter.

[119] *Ibid.*

Table 2.17
Water Quality Criteria for Streams Within the Pewaukee Lake Watershed

Water Quality Parameter	Designated Use Category[a]						Source
	Coldwater Community	Warmwater Fish and Aquatic Life	Limited Forage Fish Community (variance category)	Special Variance Category A[b]	Special Variance Category B[c]	Limited Aquatic Life (variance category)	
Temperature (°F)	--[d]	--[d]	--[d]	--[d]	--[d]	86.0	NR 102 Subchapter II
Dissolved Oxygen (mg/l)	6.0 minimum 7.0 minimum during spawning	5.0 minimum	3.0 minimum	2.0 minimum	2.0 minimum	1.0 minimum	NR 102.04(4) NR 104.04(3) NR 104.06(2)
pH Range (S.U.)	6.0-9.0	6.0-9.0	6.0-9.0	6.0-9.0	6.0-9.0	6.0-9.0	NR 102.04(4)[e] NR 104.04(3)
Fecal Coliform Bacteria (MFFCC)							NR 102.04(5) NR 102.04(6) NR 102.06(2)
Geometric Mean	200	200	200	1,000	1,000	200	
Maximum	400	400	400	2,000	--	400	
Total Phosphorus (mg/l)							NR 102.06(3) NR 102.06(4) NR 102.06(5) NR 102.06(6)
Designated Streams[f]	0.100	0.100	0.100	0.100	0.100	0.100	
Other Streams	0.075	0.075	0.075	0.075	0.075	--	
Chloride (mg/l)							NR 105.05(2) NR 105.06(5)
Acute Toxicity[g]	757	757	757	757	757	757	
Chronic Toxicity[h]	395	395	395	395	395	395	

[a] *NR 102.04(1) All surface waters shall meet the following conditions at all times and under all flow conditions: substances that will cause objectionable deposits on the shore or in the bed of a body of water, floating or submerged debris, oil, scum or other material, and materials producing color, odor, taste or unsightliness shall not be present in such amounts as to interfere with public rights in waters of the State. Substance in concentrations or combinations which are toxic or harmful to humans shall not be present in amounts found to be of public health significance, nor shall substances be present in amounts which are acutely harmful to animal, plant, or aquatic life.*

[b] *As set forth in Chapter NR 104.06(2)(a) of the* Wisconsin Administrative Code.

[c] *As set forth in Chapter NR 104.06(2)(b) of the* Wisconsin Administrative Code.

[d] *See Table 2.16.*

[e] *The pH shall be within the stated range with no change greater than 0.5 unit outside the estimated natural seasonal maximum and minimum.*

[f] *Designated in Chapter NR 102.06(3)(a) of the* Wisconsin Administrative Code. *There are no designated streams in the Pewaukee Lake watershed.*

[g] *The acute toxicity criterion is the maximum daily concentration of a substance that ensures adequate protection of sensitive species of aquatic life from the acute toxicity of that substance and will adequately protect the designated fish and aquatic life use of the surface water if not exceeded more than once every three years.*

[h] *The chronic toxicity criterion is the maximum four-day concentration of a substance that ensures adequate protection of sensitive species of aquatic life from the chronic toxicity of that substance and will adequately protect the designated fish and aquatic life use of the surface water if not exceeded more than once every three years.*

Source: Wisconsin Department of Natural Resources and SEWRPC

Key water quality parameters indicate the Lake is mesotrophic with regard to its level of nutrient enrichment. Like the majority of lakes in the Region, phosphorus is the key limiting nutrient regarding aquatic plant growth in Pewaukee Lake. Summer water clarity, and levels of chlorophyll-*a* and total phosphorus, have all shown improvement in recent years in both the west and east basins of the Lake, indicating that watershed management efforts have been effecting positive change in lake conditions. However, increasing chloride concentrations have been observed in Pewaukee Lake and should be a priority for future monitoring efforts.

The principal tributaries of Pewaukee Lake (Coco Creek, Meadowbrook Creek, and Zion Creek) are all important to the overall water quality of the Lake. As noted above, Coco Creek and its tributaries are the only streams in the Lake's watershed that are achieving coldwater standards. Coco Creek consistently provides a healthy oxygen-rich environment for aquatic life, while Meadowbrook Creek experiences occasional oxygen levels below the 5.0 mg/l threshold; Zion Creek experiences oxygen levels that drop below the 5.0 mg/l level and above the toxic supersaturation level of 15 mg/l. All three main tributaries have shown increases in chloride and specific conductivity over the past several years, with Meadowbrook experiencing the highest levels. As these tributaries are likely contributing to the increasing chloride concentrations in Pewaukee Lake, greater monitoring of chloride in these streams should be considered as well. Continued monitoring of the tributaries that includes rate of flow would greatly aid in the measuring of phosphorus entering the Lake, informing models of phosphorus loading. Further discussion of lake and tributary monitoring and management recommendations are provided in Section 3.3, "Water Quality", Section 3.4, "Pollutant and Sediment Sources and Loads," and Section 3.6, "Cyanobacteria and Floating Algae."

2.6 POLLUTANT LOADS

At the present time, most pollutants delivered to the Lake and its tributary streams are carried by runoff and wind. Very little pollution is deliberately discharged by humans to the Lake and its tributaries through wastewater discharge points. In-Lake processes are another significant contributor to overall phosphorus loads in many lakes and human activity can intensify their contribution.

The Commission estimated probable pollutant loads and in-lake phosphorous concentrations using the Unit Area Loading (UAL) model and the Wisconsin Lake Modeling Suite (WiLMS) model. The data generated by these models can help identify pollutants that may impinge upon the health of the Lake as well as the land uses and land areas responsible for elevated loads. To supplement model results, the Commission reviewed previous stream studies and completed an on-the-ground inventory during 2015 of sites with pronounced erosion along Coco, Meadowbrook, and Zion Creeks.

Historical Nutrient Budgets

Using measured concentrations from the Lake and its tributaries, a study conducted for the first Pewaukee Lake management plan determined that 14 percent of the nitrogen and 13 percent of the phosphorus entering the Lake came from direct drainage; 35 and 34 percent, respectively, from the inlets; 14 and 7 percent, respectively, from precipitation; and 37 and 46 percent, respectively, from dry fallout on the lake surface. Of the total mass of nutrients and sediment entering Pewaukee Lake, 72 percent of the nitrogen, 26 percent of the phosphorus, and 61 percent of the sediment was estimated to have remained in the Lake.[120]

Watershed-Sourced Loads

The most prevalent pollutants to lakes include sediment and nutrients, both of which have natural sources and sources that are attributable to human activity. Sediment and nutrients contribute to lake aging. Sediment and nutrient loads can greatly increase when humans disturb land cover and runoff patterns through activities such as tilling and construction, both of which typically loosen soil, increase runoff and in turn allow soil to more easily erode and eventually enter streams and lakes. In contrast, heavy metals, detergents, oils, and fertilizers were not common in the watershed under natural conditions and are essentially completely attributable to human activity.

Different human land use types contribute different types of pollution to water bodies. For example, phosphorus sources in rural areas may be correlated with agricultural fertilizers and animal waste delivered to waterbodies through overland runoff. In contrast, in urban areas, phosphorus from lawn fertilizers,

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[120] *SEWRPC Community Assistance Planning Report No. 58,* op. cit.

clippings and leaves from ornamental plantings, and cleaning agents are often quickly conveyed to water bodies with little opportunity for attenuation. In 2010, the State of Wisconsin placed restrictions on the sale of some phosphorus-containing cleaning agents.[121] The State has also adopted a turf management standard limiting the application of lawn fertilizers containing phosphorus within the State,[122] potentially acting to reduce the amount of phosphorus discharged from urban settings. In both rural and urban areas, poorly maintained or failing onsite wastewater treatment systems have been found to contribute phosphorus to surface-water features.

Urban leaf litter can also be a substantial source of phosphorus pollution, particularly in urban sections of the watershed. A study conducted in the Lake Wingra watershed in Dane County indicates that 55 percent of the total annual residential phosphorus loading occurs during autumn, largely attributable to curbside and street-area leaf litter.[123] Leaves crushed by vehicular traffic leach greater amounts of phosphorus, particularly during wet weather. Runoff then washes the leached phosphorus into the stormwater drainage system and eventually into surface waters.

Effectively managing leaves on residential streets during the fall can significantly reduce the phosphorus loading from urban areas within the Lake watershed. The City of Pewaukee presently provides a City Recycling Center that accepts leaves and yard waste; the Village of Pewaukee and City of Waukesha offer curbside pickup of leaves on several dates each fall; residents of other municipalities whose property lies within the Pewaukee Lake watershed (see Map 2.15) should check with their local municipalities for proper disposing of leaves. Keeping leaves from collecting on residential streets through prompt leaf collection, and especially the timing of that collection from the streets, is a critical part of reducing external phosphorus loading from residential areas.

Tributary Nutrient Loading

A 2003-2004 study of phosphorus loading into Pewaukee Lake conducted by Wisconsin Lutheran College found that Coco Creek contributed the most phosphorus of any major tributary, with 48.4 percent of total tributary phosphorus loading.[124] Zion Creek contributed the second most at 34.0 percent, while Meadowbrook Creek contributed the least at 17.6 percent. Current predicted phosphorus loadings for the four main tributaries to Pewaukee Lake (Audley Creek, Coco Creek, Meadowbrook Creek, and Zion Creek), were estimated using the Pollutant Load Ratio Estimation Tool (PRESTO)[125] developed by the Wisconsin Department of Natural Resources, and are presented in Table 2.18. These findings do not completely agree with the Wisconsin Lutheran College study, as Coco Creek is still the main tributary contributor of phosphorus to Pewaukee Lake, at 2,337 pounds annually, but Meadowbrook Creek is the second largest contributor, at 1,547 pounds annually. Zion Creek falls to third, at 614 pounds annually, while Audley Creek only contributes 94 pounds annually. It is important to keep in mind that these values are estimates (80 percent confidence level) based on land uses within the sub-watershed of each tributary and assuming a typical year of average rainfall.

Streambank Erosion

Accelerated streambank erosion can contribute to total phosphorus and suspended sediment loading that is not accounted for in model estimates as well as impede navigation, and destroy aquatic habitat, spawning, and feeding areas. In general, urbanization increases runoff quantity during and immediately after precipitation or snowmelt. Higher runoff rates increase water velocity and overall stream power, resulting in

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[121] *Section 100.28 of the* Wisconsin Statutes *bans the sale of cleaning agents for non-household dishwashing machines and medical and surgical equipment that contain more than 8.7 percent phosphorus by weight. This statute also bans the sale of other cleaning agents containing more than 0.5 percent phosphorus by weight. Cleaning agents for industrial processes and cleansing dairy equipment are specifically exempted from these restrictions.*

[122] *On April 14, 2009, 2009 Wisconsin Act 9 created Section 94.643 of the* Wisconsin Statutes *relating to restrictions on the use and sale of fertilizer containing phosphorus in urban areas throughout the State of Wisconsin.*

[123] *Roger Bannerman of the USGS has described the findings of the Lake Wingra study in his presentation entitled* "Urban Phosphorus Loads: Identifying Sources and Evaluating Controls."

[124] *Wisconsin Lutheran College, Chemistry Department Technical Bulletin 001,* Pewaukee Lake Phosphorus Monitoring 2003-2004*, March 2005.*

[125] *dnrmaps.wi.gov/H5/?viewer=WI_TMDL.*

greater streambank erosion and bottom scour. These effects can be mitigated by sound land use planning combined with installing proper stormwater management practices.

Table 2.18
Predicted Values for Average Annual Phosphorus Load to Pewaukee Lake Tributaries from Nonpoint Sources

Waterbody	Average Predicted Phosphorus Load (lb/yr)	80 Percent Confidence Interval (lb/yr)
Audley Creek	94	45 – 197
Coco Creek	2,337	993 – 5,500
Meadowbrook Creek	1,547	649 – 3,684
Zion Creek	614	279 – 1,348

Source: Wisconsin Department of Natural Resources and SEWRPC

Where active streambank erosion was observed, Commission staff recorded information on bank height, length of eroding bank, and depth of undercutting and took photos. Most of the streambanks within the areas surveyed seemed stable and in generally good condition. In addition, the streambanks were generally not excessively high and seemed well-connected to the adjacent floodplain. For example, average maximum streambank height was 2.3 feet, but a few locations did exceed five feet in height (see Appendix A, Table A.1 on page 289). Hence, only about 0.5 mile (2,805 feet) of stream, or about 5.5 percent of the total 9 miles assessed, was observed to be potentially actively eroding as shown on Map A.5 and A.6 on pages 311 and 312 in Appendix A. These sites occur throughout the entire length of the tributaries, but the majority of the sites are located at the headwaters of Coco Creek. Within this sub-basin, the creek is less meandered (likely due to channelization in the past), is less buffered by natural vegetation due to encroachment of urban development, and contains a more restrictive floodplain. In contrast, the other reaches of the tributaries contain fewer actively eroding sites and are located within areas that contain much more extensive riparian buffers (see Map 2.20 and Insets 1 and 2) and are much more highly meandered. Intervention in the case of the headwaters of Coco Creek could include remeandering the stream to its historic condition, two-stage channel design construction, or slope stabilization with bioengineering and/or selective hard armoring with riprap stone, where appropriate (see Chapter 3 for more details).

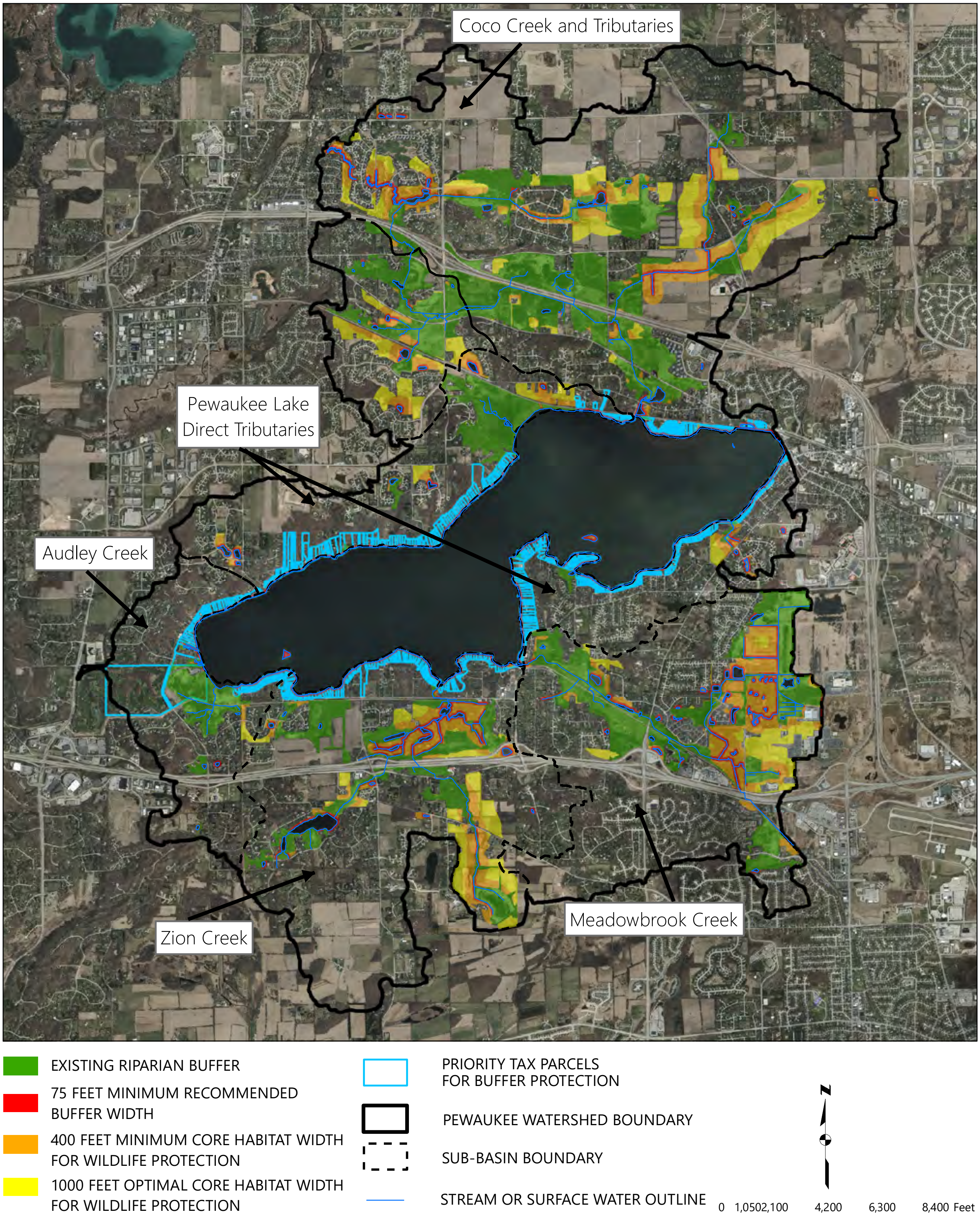
The reaches of surveyed tributaries have a slope of about 0.0066 feet/feet (35 feet per mile) or lower, which is consistent with a low gradient stream condition and the field observations of limited streambank erosion. Since lateral recession rates were unknown and could not be determined, it was not possible to calculate a pollutant load rate or the overall severity among these potentially actively eroding locations. However, there were a few sites that seemed more active than others sites and may be cause for concern as shown in Maps A.5 and A.6 in Appendix A, since this sediment is potentially contributing to the degradation of instream fisheries habitat and to pollutant loads into Pewaukee Lake. Therefore, this is an important issue of concern and recommendations related to streambank stability are included in Chapter 3.

Simulated Nonpoint Source Loads

The Commission simulated nonpoint source pollutant loads for suspended solids (sediment), phosphorus, and urban-derived metals to Pewaukee Lake using two land use based models. One simulation used the Wisconsin Lake Model Spreadsheet (WiLMS version 3.3.18) while the other used the Commission's unit area load-based (UAL) model developed for the Southeastern Wisconsin Region. These two models assume that a given land use type emits a set rate of pollutants on an annual basis.

Land use data for various time periods were entered into both models to predict pollutant loads to Pewaukee Lake. The loads predicted by the UAL model are summarized in Table 2.19. These calculations assume that urban land use is the only significant source of heavy metals. Heavy metals monitoring has not occurred within the Lake. However, urban areas should be targeted for mitigation measures if heavy metals become an issue within the Lake in the future. The UAL model estimates that 771 tons of suspended sediment and 3,941 pounds of total phosphorus are delivered to Pewaukee Lake each year from surface runoff under year 2015 land use conditions. Agricultural land uses are the major sediment and phosphorus contributors, at 62 percent of the sediment and 47 percent of the phosphorus reaching Pewaukee Lake. Low density residences and their associated roadways were the next largest contributors of phosphorus and sediment. Under planned conditions, current agricultural lands will be converted to urban land use. Consequently, the overall mass of sediment and phosphorus anticipated to be delivered to the Lake will decrease by 44 tons and 98 pounds, respectively. With proactive and aggressive pursuit of runoff water quality measures, sediment and phosphorus loading to the Lake can be even further reduced. Practices to reduce urban loading are addressed in more detail in Chapter 3.

Map 2.20
Potential Pewaukee Lake Watershed Shoreline and Riparian Buffers



Note: Date of Orthophotography: April 2015

Source: SEWRPC

Map 2.20 – Inset 1
Potential Pewaukee Lake East Basin Shoreline and Riparian Buffers

EXISTING RIPARIAN BUFFER

75 FEET MINIMUM RECOMMENDED BUFFER WIDTH

400 FEET MINIMUM CORE HABITAT WIDTH FOR WILDLIFE PROTECTION

1000 FEET OPTIMAL CORE HABITAT WIDTH FOR WILDLIFE PROTECTION

PRIORITY TAX PARCELS FOR BUFFER PROTECTION

PEWAUKEE WATERSHED BOUNDARY

SUB-BASIN BOUNDARY

STREAM OR SURFACE WATER OUTLINE

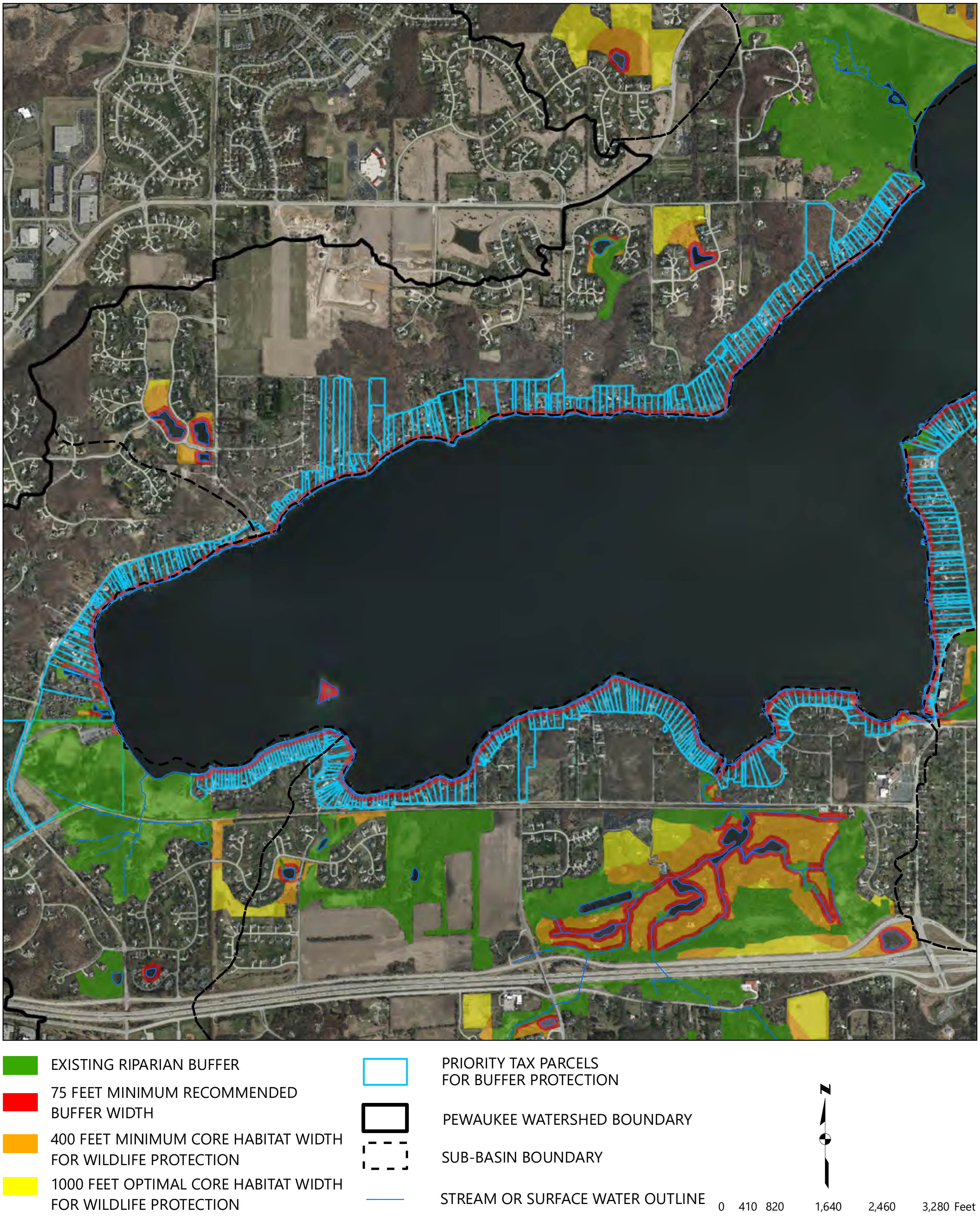
N

0 370 740 1,480 2,220 2,960 Feet

Note: Date of Orthophotography: April 2015

Source: SEWRPC

Map 2.20 – Inset 2
Potential Pewaukee Lake West Basin Shoreline and Riparian Buffers



Note: Date of Orthophotography: April 2015

Source: SEWRPC

Table 2.19
Estimated Annual Land Use Pollutant Loads Within the Pewaukee Lake Watershed

Land Use Category	Pollutant Loads: 2015 Land Use Sediment (tons)	Phosphorus (pounds)	Copper (pounds)	Zinc (pounds)
Urban				
Residential	97.5	1,159.7	42.6	329.5
Commercial	33.2	101.5	18.6	126.1
Industrial	14.3	44.4	8.3	56.5
Governmental	33.2	175.6	9.1	104.1
Transportation	85.0	178.4	389.3	1,323.2
Recreational	8.0	178.9	--	--
Urban Subtotal	271.1	1,838.6	447.9	1,939.3
Rural				
Agricultural	486.4	1,990.2	--	--
Wetlands	2.5	54.3	--	--
Woodlands	2.1	45.0	--	--
Water	9.8	13.5	--	--
Rural Subtotal	500.8	2,089.6	--	--
Total	771.9	3,928.2	447.9	1,939.3

Land Use Category	Pollutant Loads: Planned Land Use Sediment (tons/year)	Phosphorus (pounds/year)	Copper (pounds/year)	Zinc (pounds/year)
Urban				
Residential	112.1	1,361.5	47.0	367.6
Commercial	103.5	316.9	58.1	393.4
Industrial	51.9	161.4	30.3	205.5
Governmental	68.9	364.3	18.9	215.9
Transportation	90.2	180.5	393.7	1,410.8
Recreational	9.0	201.7	--	--
Urban Subtotal	435.6	2,586.2	548.0	2,593.2
Rural				
Agricultural	277.5	1145.1	--	--
Wetlands	2.5	54.3	--	--
Woodlands	2.1	45.0	--	--
Water	9.7	13.5	--	--
Rural Subtotal	291.2	1,257.9	--	--
Total	727.4	3,844.1	548.0	2,593.2

Source: SEWRPC

Similar to the approach employed by the UAL model, the WiLMS model uses land use, hydrologic, and watershed area information to estimate the total flux of phosphorus to a lake during a typical year.[126] The WiLMS model produces a range of probable phosphorus load values (low, most likely, and high). In Southeastern Wisconsin, The Commission has found that WiLMS low range estimates best match the UAL model predictions, and therefore typically uses these estimates to predict in-lake phosphorus concentrations. Moreover, the USGS has found that models tend to over-predict phosphorus values for hard-water lakes (such as Pewaukee Lake). Given the significance of carbonate-induced phosphorus sequestration in hard-water lakes, this seems reasonable. For this reason, the WiLMS low range estimate is believed to best portray local conditions. The model uses the calculated load estimates to predict water quality in the receiving lake using regression equations that have been designed to fit a variety of lake types (e.g., deep

[126] *These models do not account for groundwater influx and exit from the lake. Models can be adjusted to include this variable if sufficient interest is expressed by lake users and managers as part of a future study. Groundwater is a very important component of the water budget of Pewaukee Lake. Including groundwater in future models may not necessarily improve the accuracy of the models, but will account for and potentially eliminate a currently untested variable from the simulation process.*

lakes, reservoirs, and general lake models). Using the low-range loading estimates for the reason discussed above, the Canfield-Bachmann 1981 model for natural lakes best fits observed conditions in Pewaukee Lake as the predicted surface water phosphorus concentrations (0.028 mg/l) most closely matched average concentrations (0.024 mg/l) in the Lake.

Using the WiLMS model, we predicted loading rates under three different land use scenarios: pre-settlement (circa 1830), year 2015, and planned conditions based on local government comprehensive plans. For 2015 land use, the WiLMS model predicts between 3,318 and 10,970 pounds of phosphorus could be delivered to Pewaukee Lake each year from nonpoint sources, with the most likely value at 6,284 pounds per year. The lowest WiLMS rate of 3,318 pounds per year is slightly lower than the predictions of 3,941 pounds per year from the UAL model and the combined 4,592 pounds per year from the Lake tributaries calculated by the WDNR PRESTO-lite model. These loading rates are two to three times greater than those predicted under presettlement land use (1,081 to 5,068 pounds per year). The planned land use estimates indicate that phosphorus loading rates to the Lake are most likely to remain stable or just slightly increase with anticipated changes in land use within the watershed, such as the shift from agricultural and pasture lands to low density residential use (see land use discussion in Section 2.2, "Lake and Watershed Physiography" for greater detail).

WiLMs model outputs suggest that before settlement, Pewaukee Lake's phosphorus concentrations averaged around 0.012 mg/l, suggesting that the Lake was an oligotrophic waterbody. Model outputs for year 2015 conditions suggest that phosphorus concentration should be 0.028 mg/l, a value slightly exceeding typical phosphorus concentrations detected in the Lake and indicative of a mesotrophic waterbody. The slightly lower phosphorus values detected in Lake water may be reflective of the relatively large mass of phosphorus removed from lake water by aquatic plant harvesting, and is thought to be a fairly good match for actual conditions. Using the model to look forward, land use changes are not expected to significantly change phosphorus values in the Lake for the next 30 years.

In-Lake Phosphorus Sources

Internal Loading

Phosphorus concentrations tend to vary widely in the deepest parts of the Lake. As shown in Figure 2.48, samples drawn from the Lake's deep water hypolimnion during the summer months commonly contain phosphorus concentrations more than ten times higher than near-surface lake water, with values averaging 0.173 mg/l, and ranging from 0.019 mg/l to 0.360 mg/l. Large discrepancies between surface and deep water phosphorus concentrations are an indication of internal loading. Under oxygenated conditions, phosphorus remains tightly bound to lake-bottom sediment; however, during anoxic conditions, geochemical reactions release this phosphorus from the bottom sediment into the water column where it is then free to mix throughout the entire water column during the next overturn period. Phosphorus released in stratified lakes in this condition is a well-documented phenomenon and can account for up to 39 percent of a lake's total phosphorus load;[127] indeed, concentrations of phosphorus as high as 1.0 mg/l (1000 ug/l) have been observed.[128]

Lake stratification can signal when internal loading is occurring. Hypolimnetic phosphorus concentrations rapidly increase immediately after the Lake stratifies (usually early to mid-June), commonly reaching their maximum values during July. This is a common occurrence on many lakes as biological productivity and attendant organic loading to hypolimnetic waters peaks in late spring. Temperature, DO, and specific conductivity profiles suggest that mixing between the hypolimnion and epilimnion typically occurs during late summer. Consequently, late summer hypolimnetic phosphorus concentrations are occasionally lower than midsummer concentrations. This peak in hypolimnetic phosphorus concentrations during summer stratification signals the occurrence of internal loading.

Exposure of sediment to anoxic (without oxygen) water can exacerbate internal loading issues. When anoxic conditions are present, the amount of exposed sediment is influenced by the shape of the lake basin. Even though two lakes may have equivalent maximum depths, a lake that has broad shallow areas and a small

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[127] *G.K. Nurnberg, and R.H. Peters, "The Importance of Internal Phosphorus Load to the Eutrophication of Lakes With Anoxic Hypolimnia: With 8 Figures in the Text,"* Verhandlung Internationale Vereinigung Limnologie*, 22(1): 90-194, 1984.*

[128] *B.K. Holstrom et al.,* Water resources data, Wisconsin, water years 1985-1991, *U.S. Geological Survey Water-Data Report WI-85-1 to WI-91-1, 1985-1992 (published annually).*

deep hole has less deep water bottom sediment area than an equal depth lake that is uniformly deep. Since sediment exposed to anoxic water can release phosphorus into the water column, lakes with more deep water sediment area are more susceptible to significant phosphorus internal loading. Moderate depth/size stratified lakes are among the most prone to internal phosphorus loading. Such lakes lack large water volumes, and, hence, have comparatively little stored oxygen in the hypolimnion, making them prone to anoxia. As discussed in Section 2.5, "Water Quality," summer anoxia forms in Pewaukee Lake below 25 feet depth in July and August most years, resulting in about 450 acres of anoxic lake bottom that could contribute to internal phosphorus loading (see Figure 2.31).

To evaluate the contribution of internal loading to total Lake phosphorus loads, we calculated the internal loading rate for Pewaukee Lake using the difference in spring and summer hypolimnetic phosphorus concentrations multiplied by the volume of anoxic water within the Lake. This calculation assumes that the hypolimnetic phosphorus concentrations are entirely driven by release of phosphorus from lake-bottom sediment, which may be an overestimation of these rates. Using the mean hypolimnetic phosphorus concentrations from 1973 to 2018, the internal loading rate for Pewaukee Lake was 1,818 pounds per year. However, the data used for this calculation was primarily collected prior to 2000, at which point the frequency of hypolimnetic sampling decreased. As surface water phosphorus concentrations have declined since 2000, it is possible that internal loading rates have declined as well, but there are not enough data available to support this hypothesis. In addition, the frequency of anoxic days has been declining in the Lake, which could also potentially reduce the impacts of internal loading.

Internal Recycling

Another process that can contribute significantly to a lake's phosphorus load is *internal recycling*. As rooted aquatic plants grow, they take up phosphorus from the lake sediment through their roots and incorporate it into the plant itself. Aquatic plants also absorb nutrients from the water column directly.[129] When the plant dies and decays, this phosphorus can then be released back into the water column. In a study done on Lake Wingra in Madison, Wisconsin,[130] internal recycling of Eurasian watermilfoil (EWM) (*Myriophyllum spicatum*) represented 47 percent of the annual external phosphorus input to the lake. In a study conducted on Whitewater and Rice lakes in 1991,[131] internal recycling was found to account for approximately 51 percent of the combined internal and external total phosphorus input to Whitewater Lake, equivalent to 582 pounds of phosphorus, and 82 percent of the total to Rice Lake, equivalent to 295 pounds of phosphorus. According to this study, "at Whitewater Lake, by late July, in-lake phosphorus mass had exceeded inputs by a factor of more than 3, and at Rice Lake, the in-lake phosphorus mass had exceeded the external inputs by a factor of more than 13." Clearly, internal loading (the release of phosphorus from bottom sediments through anoxic-stimulated chemical reactions), is not the only internal factor increasing lake phosphorus concentrations; internal recycling can play a key role as well. Just how important recycling of phosphorus is in Pewaukee Lake has yet to be determined and will require a separate study beyond the scope of this report.

There are other minor events and processes related to physical disruption of bottom sediments, especially in shallow lakes, that can cause phosphorus levels in a lake's water column to increase: movement through sediment by benthic organisms, propeller-caused stirring of bottom sediments by motorboats, and wind/wave action. Such physical disruptions tend to re-suspend bottom sediments and cause phosphorus concentrations in the water column to increase.

Pollution Mitigation Strategies

Properly implemented pollution mitigation strategies, such as managing stormwater, restoring wetlands, minimizing shoreline erosion, and creating riparian buffers, can reduce pollutant loading into lakes and streams. This subsection discusses these strategies and their implementation in the Pewaukee Lake watershed.

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[129] *G. Thiébaut, "Phosphorus and Aquatic Plants," In P.J. White and J.P. Hammond (eds), The Ecophysiology of PlantPhosphorus Interactions,* Plant Ecophysiology *7, 2008.*

[130] *C.S. Smith and M.S. Adams, "Phosphorus Transfer From Sediments by* Myriophyllum spicatum*,"* Limnology and Oceanography, *31(6): 1312-1321, 1986.*

[131] *G.L. Goddard and S.J. Field,* Hydrology and Water Quality of Whitewater and Rice Lakes in Southeastern Wisconsin, 1990-91, *U.S. Geological Survey Water-Resources Investigations Report 94-410, 1994.*

Stormwater Management

To meet the requirements of the Federal Clean Water Act, the WDNR developed a permit program under Wisconsin Administrative Code NR 216, "Storm Water Discharge Permits." A municipal separate storm sewer system (MS4) permit is required for a municipality that is either located within a Federally-designated urbanized area, has a population of 10,000 or more, or is designated for permit coverage by the WDNR. Municipal permits require stormwater management programs to reduce polluted stormwater runoff by implementing best management practices. Chapter NR 216 also requires certain types of industries to obtain stormwater discharge permits from the WDNR, but there are no industrial stormwater permits issued in the Pewaukee Lake watershed. The general permit requires an MS4 holder to develop, maintain, and implement stormwater management programs to prevent pollutants from the MS4 from entering State waters. Examples of stormwater best management practices (BMPs) used by municipalities to meet permit conditions include detention basins, street sweeping, filter strips, bioretention facilities, and rain gardens.

In cooperation with the WDNR, Waukesha County, and the Commission, storm sewer system inventory information was obtained from each of the MS4 municipalities, as well as from Waukesha County records, and combined into a composite map for the entire watershed (see Map 2.21). Under their MS4 permit, each of these communities is required to provide detailed and accurate inventories in a digital geographic information systems (GIS) software format for the following elements summarized below:

- Identification of all known MS4 outfalls discharging to waters of the State or another MS4 including minor outfalls and major outfalls[132]

- Location and permit number of any known discharge to the MS4 that has been issued Wisconsin Pollutant Discharge Elimination System permit coverage by the WDNR

- Location of structural stormwater facilities including detention basins, infiltration basins, and manufactured treatment devices

- Identification of publicly owned park and recreational areas and other open lands

- Location of municipal garages, storage areas and other public works facilities

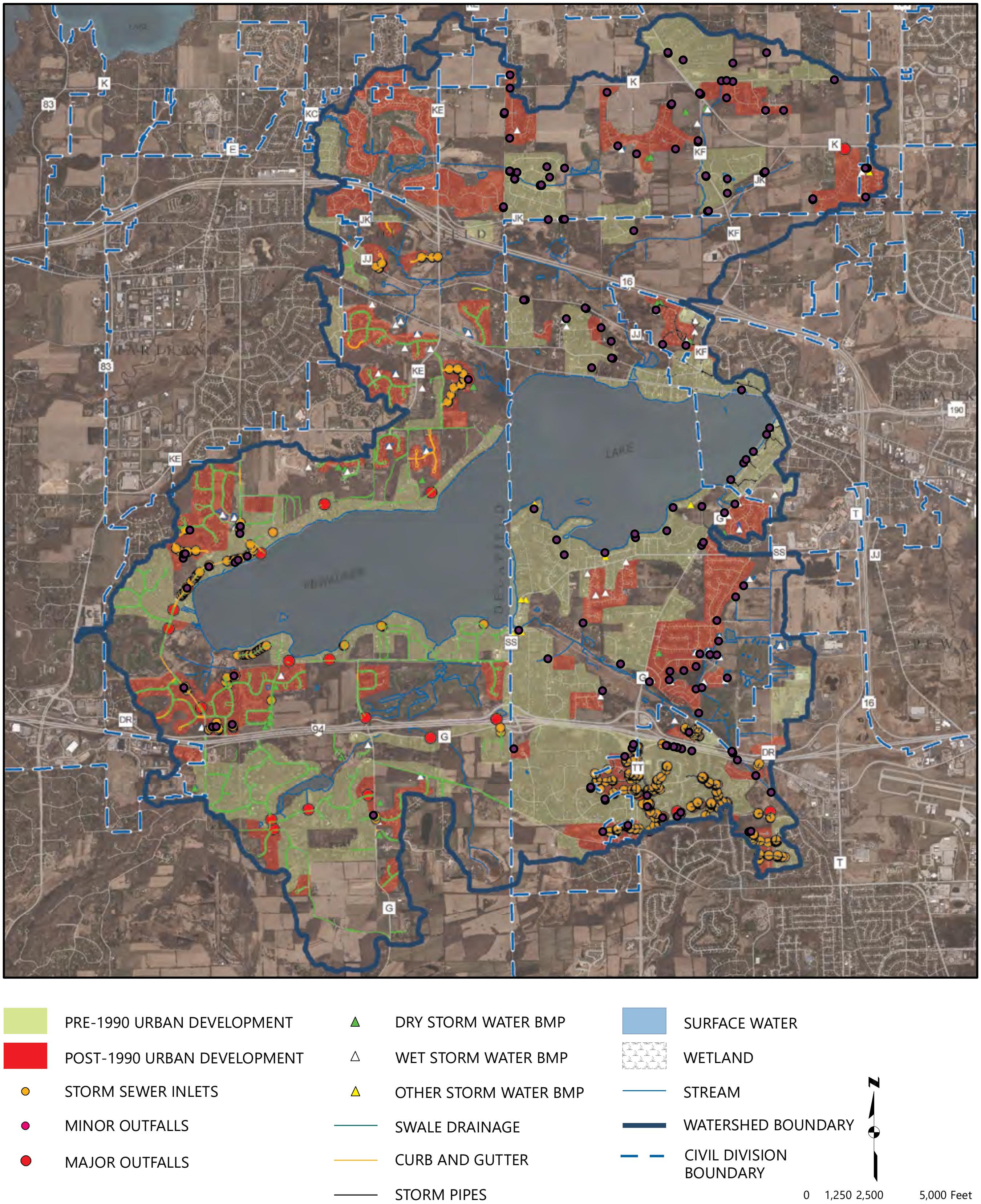
- Identification of streets

Map 2.21 shows stormwater information throughout the watershed as reported from 2015 through 2018. The map is not intended to show every element of the stormwater infrastructure in each community. Information on specific characteristics of municipal stormwater management systems can be located in individual reports for each community as documented in Table 2.20.

Since each of the MS4 communities compiled its inventories using different digital formats and categories, the GIS data files were integrated to the extent practicable by Waukesha County staff. The main categories include major outfalls, minor outfalls, storm sewers, swale drainage, curb and gutter, and stormwater BMPs (wet basins and dry basins). Based upon this inventory data, there are a total of 18 major outfalls, 149 minor outfalls, 22 dry basins, and 24 wet basins (having a permanent pond) within the Pewaukee Lake watershed. The storm sewers shown on Map 2.21 include both culverts and storm sewers. In addition, some communities also mapped the sewer inlets, curb and gutter, and swale information, which helps to better understand how stormwater is routed across the landscape within portions of the watershed. The majority of the storm sewer inlets throughout the watershed are located in the Meadowbrook sub-basin in Waukesha, although some are located in the Pewaukee Lake sub-basin in the Town of Delafield. Those inlets are connected to numerous minor and major outfalls that discharge directly into Meadowbrook Creek and Pewaukee Lake (see Stream Inventory Conditions above and Appendix A). There are additional outfalls located directly adjacent to the Zion Creek in the Town of Delafield. As noted in the inventory summary

[132] *A major outfall is a municipal separate storm sewer outfall that meets one of the following criteria: 1) a single pipe with an inside diameter of 36 inches or more or equivalent conveyance (cross sectional area of 1,018 square inches), which is associated with a drainage area of more than 50 acres, or 2) an MS4 that receives stormwater runoff from lands zoned for industrial activity or from other lands with industrial activity that is associated with a drainage area of two acres or more.*

Map 2.21
Storm Drainage Systems Within the Pewaukee Lake Watershed



Source: SEWRPC

Table 2.20
MS4 Community Stormwater Infrastructure Inventory
Within the Pewaukee Lake Watershed: 2010-2018

	Stormwater Management System Category					
		Outfalls		Best Management Practices (BMP)		
Community	Sewer Inlets	Minor	Major	Dry Basin	Wet Basin	Other
City of Pewaukee	0	56	0	5	6	1
City of Waukesha	222	21	15	1	0	0
Town of Delafield	121	17	18	16	25	0
Town of Lisbon	0	52	1	4	9	0
Village of Pewaukee	0	10	0	5	27	8
Village of Sussex	0	3	0	0	2	2
Total	343	149	34	31	69	11

Source: City of Pewaukee, AECOM; City of Waukesha, GRAEF; Town of Delafield, R.A. Smith National, Inc.; Town of Lisbon, Strand Associates, Inc.; Village of Pewaukee, STANTEC; Village of Sussex, Ruekert & Mielke, Inc.; Waukesha County PLU – Land Resources Division; and SEWRPC

section above, several of these outfalls may be good candidates for modification or improvement to reduce the volume of stormwater pollutants entering Meadowbrook Creek and, ultimately, Pewaukee Lake.

These data were projected over the total extent of urban lands under pre-1990 versus post-1990 conditions, because stormwater rules and practices began to be implemented more widely during the post-1990 period. Hence, nearly all of the stormwater BMPs on the landscape reside within the urban lands developed after 1990. Consequently, most of the stormwater BMPs directly around Pewaukee Lake within the Pewaukee Lake watershed consisted of storm sewers, curb and gutter, and swales. It is also important to note that there are several minor and major outfalls that discharge stormwater with limited treatment directly into Pewaukee Lake, and which could be contributing pollutants including sediments into nearshore areas of the Lake, especially in the west basin. Such outfalls might be good candidates for modification or improvement to reduce stormwater pollutants from entering the Lake.

In contrast, since many areas upstream of Pewaukee Lake in the Meadowbrook and Coco Creek sub-basins were developed after 1990, BMPs include the aforementioned practices, but wet and dry stormwater detention basins are much more prevalent among these sub-basins. Nearly 50 of these wet and dry basins have been constructed since about 1990 and more continue to be constructed with each new development throughout the watershed. These basins are designed to capture the stormwater runoff water and release it at a reduced rate. Wet basins allow the total suspended solids particles, nutrients, and associated materials to settle out. Dry basins generally provide little control of nonpoint source pollution, because they have no permanent pool for settling and subsequent storage of particulate pollutants. Stormwater is diverted into these basins prior to discharging into the surface water of the Lake or local tributaries and streams within the Pewaukee Lake system.

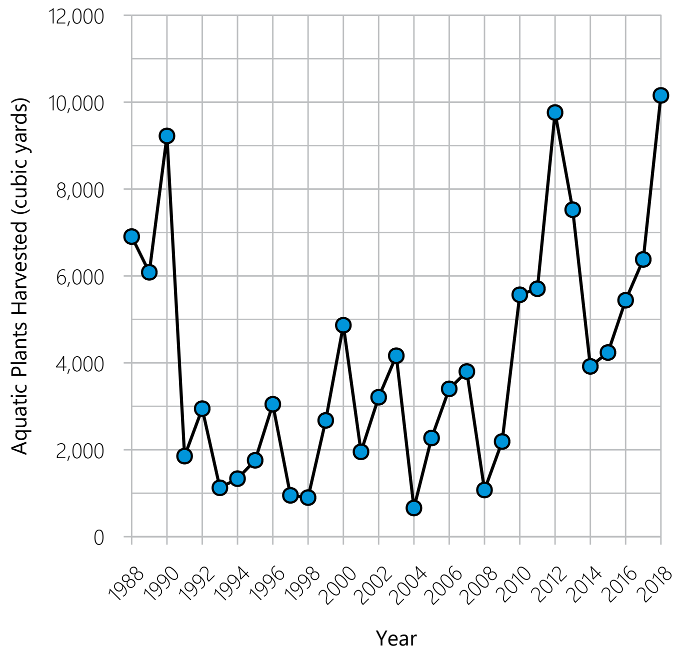
Phosphorus Removal Through Macrophyte Harvesting

A benefit of aquatic plant harvesting versus chemical treatment is that harvesting physically removes plant mass, and the nutrients contained therein, from the Lake. In some lakes, plant harvesting removes enough phosphorus to tangibly reduce lake phosphorus loads. Plant harvesting is already underway in the Lake for navigation purposes. The LPSD has kept records of the approximate amounts of harvested plants since at least 1988 (see Figure 2.58). In addition, the Village of Pewaukee harvested 1,000 yd^3 of plants in 2018. The Commission calculated the pounds of total phosphorus removed through harvesting by multiplying the annual mass of aquatic plant removed by the phosphorus concentration of those aquatic plants, with the following notes and assumptions:

- The amount of aquatic plants harvested is typically reported as a volume (often in cubic yards). To determine the mass removed, the density of the wet harvested plants was assumed to be 900 pounds per cubic yard.
- The amount of phosphorus contained by aquatic plants varies by species, lake, and time. The phosphorus content of harvested plants was estimated using information collected by the Wisconsin

Lutheran College (WLC) on Pewaukee Lake, the U.S. Geological Survey on Whitewater and Rice lakes (Whitewater-Rice), and a study conducted on a eutrophic lake in Minnesota (Minnesota). The WLC study assumed that plant dry weight is 6.7 percent of wet weight and that total phosphorus constitutes 0.2 percent of the total dry weight of the plant. The Whitewater-Rice and Minnesota studies assumed that dry weight is 15 and 7 percent of the wet weight, respectively, and phosphorus constituted 0.31 and 0.30 percent of the dry plant weight, respectively. Assumed values for the percent of dry weight to wet weight and the total phosphorus concentrations are similar to those found in other studies.[133,134]

Figure 2.58
Annual Aquatic Plant Volume Harvested in Pewaukee Lake: 1988-2018



Source: Lake Pewaukee Sanitary District, Village of Pewaukee, and SEWRPC

Using this method, the Commission estimates that aquatic plant harvesting removes an average of 786 to 2,729 lbs. of phosphorus each year, for a cumulative phosphorus removal of up to 52,348 lbs. since 1988 (see Figure 2.59). This phosphorus removal constitutes between 15 and 51 percent of the annual nonpoint source phosphorus loading into Pewaukee Lake. The cumulative impact of annually removing phosphorus from Pewaukee Lake through harvesting is significant. Improvements in water clarity, phosphorus, and chlorophyll-*a* measurements on the Lake since 1988 indicate that phosphorus removal through aquatic plant harvesting may be helping to offset phosphorus inputs.

Reducing Erosion Through Shoreline Protection

Many property owners abutting Pewaukee Lake are concerned with jointly maintaining the Lake's shorelines, recreational use, and aesthetic appeal without jeopardizing Lake health. This issue of concern is further emphasized by the fact that water quality, sedimentation, and aquatic plant growth can all be affected by shoreline maintenance practices.

Before discussing shoreline characteristics, it is important to understand the difference between two terms: *shoreline protection* and *buffers*.

- *Shoreline protection* encompasses various measures—engineered or natural—that shield the immediate shoreline (water-land interface) against the erosive forces of wave action

- *Buffers* are areas of plant growth—engineered or natural—in the riparian zone (lands immediately back from the shoreline) that trap sediment and nutrients emanating from upland and nearshore erosion

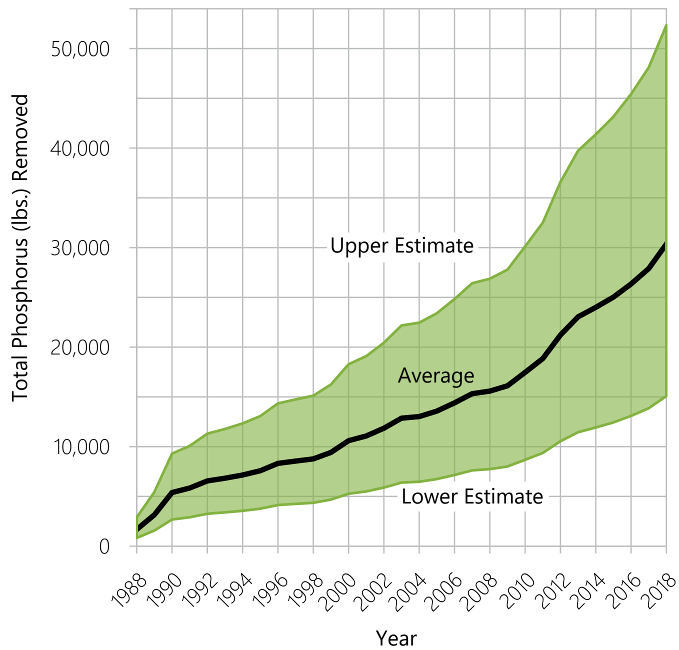
"Hard" engineered seawalls of stone, riprap, concrete, timbers, and steel, once considered "state-of-the-art" shoreline protection, are now recognized only as options to protect and restore a lake's water quality, wildlife, recreational opportunities, and scenic beauty. Indeed, the inability of hard shorelines to absorb wave energy can reflect that energy back into a lake, increasing wave energy in other portions of a lake. Manmade "hard" options available to home owners include: "bulkheads," where a solid *vertical* wall of erosion-

[133] *K.M. Carvalho and D.F. Martin, "Removal of Aqueous Selenium by Four Aquatic Plants," Journal of Aquatic Plant Management, 39: 33-36, 2001.*

[134] *G. Thiébaut, 2008,* op. cit.

resistant material (e.g., poured concrete, steel, or timber) is erected; "revetments," where a solid, *sloping* wall (usually asphalt, as in the case of a roadway, or poured concrete) is installed; "riprap," where loose stone material is placed along the shoreline. However, these options are only available with a WDNR permit.

Figure 2.59
Cumulative Mass of Phosphorus Removed by Aquatic Plant Harvesting from Pewaukee Lake: 1988-2018



Source: Lake Pewaukee Sanitary District, Village of Pewaukee, and SEWRPC

"Soft" shoreline protection techniques, such as vegetated shoreline protection, are increasingly required pursuant to Chapter NR 328, "Shore Erosion Control Structures In Navigable Waterways," of the *Wisconsin Administrative Code*. These techniques include natural shoreline, native planting, maintenance of aquatic plants along shorelines, and "fish sticks" (see Figure 2.58). Vegetative shoreline protection is becoming more popular as people living along lakes and streams become increasingly aware of the value of protecting their shorelines, improving overall aesthetic appeal of their shoreline, and promoting natural and nature-like habitat for both terrestrial and aquatic wildlife. Additionally, shorelines protected with vegetation help shield a lake from both land-based and shoreline pollution and sediment deposition**.** These "soft" techniques can be incorporated with "hard" shoreline protection in order to reduce erosion, mitigate pollutant loading, and improve aquatic habitat (see Figure 2.60). Examples of techniques that incorporate "hard" and "soft" techniques into "living" shorelines are presented in Appendix B on page 313.[135]

Given the benefits of "soft" shoreline protection measures, the WDNR no longer grants permits for construction of new "hard" structures in lakes that do not have extensive wave action threatening the shoreline, although existing structures may be repaired. Consequently, the recommendations in this plan related to shoreline restoration focus on "soft", vegetative shoreline protection measures. Beach areas, which by law need to be made from pea gravel,[136] are considered as a separate category. Placing pea gravel may be permitted; however, this must be evaluated by WDNR on a case-by-case basis.

It should be emphasized that shoreline protection need not always rely on manmade, engineered structures. Many types of natural shoreline offer substantial protection against erosive force. For example, the boulders and rock cliffs found along Lake Superior function as natural riprap or bulkheads checking excessive shoreline erosion. Additionally, marshlands containing areas of exposed cattail stalks and lily pads effectively mitigate shoreline erosive forces as exposed marshland plant stalks disperse and dampen waves and dissipate energy.

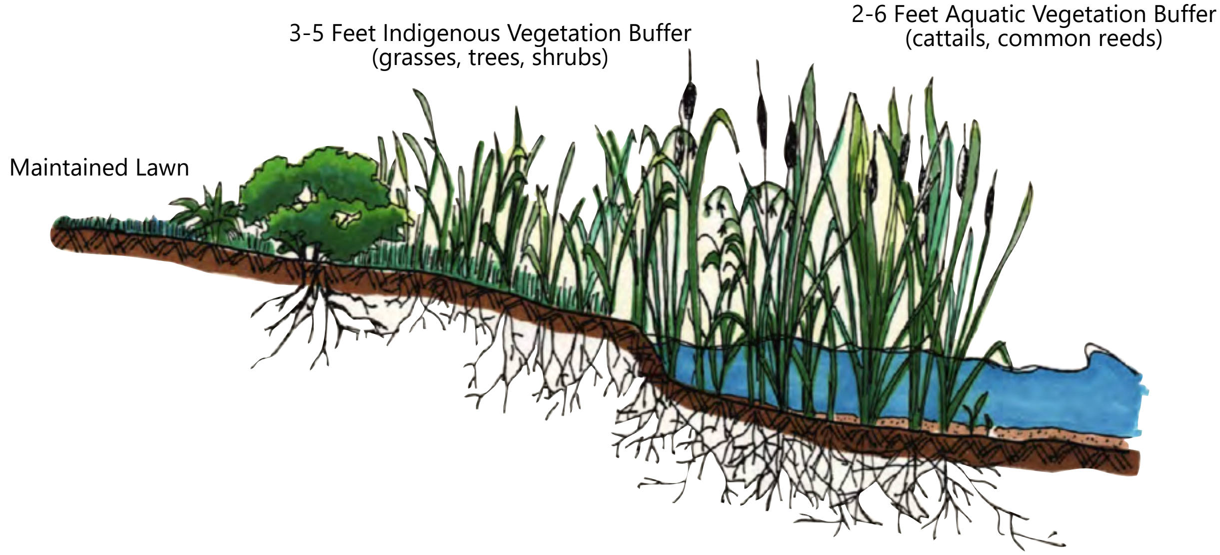
<u>Pewaukee Shoreline Conditions</u>

To help quantify the shoreline restoration and maintenance needs of Pewaukee Lake, and to help develop recommendations related to shoreline maintenance and pollution reduction, Commission staff surveyed the Lake's shoreline protection during the summer of 2015. The results of this survey are shown on Map 2.22 (with more detailed insets of this map displayed in Appendix C on page 323). As the map(s) illustrates, nearly all of Pewaukee Lake's shoreline is protected by "hard" structures of riprap or bulkhead (wooden, metal, or concrete). As previously noted, such structures are highly effective methods of shoreline

[135] *For more information on "living" shorelines, see www.habitatblueprint.noaa.gov/wp-content/uploads/2018/01/NOAA-Guidance-for-Considering-the-Use-of-Living-Shorelines_2015.pdf.*

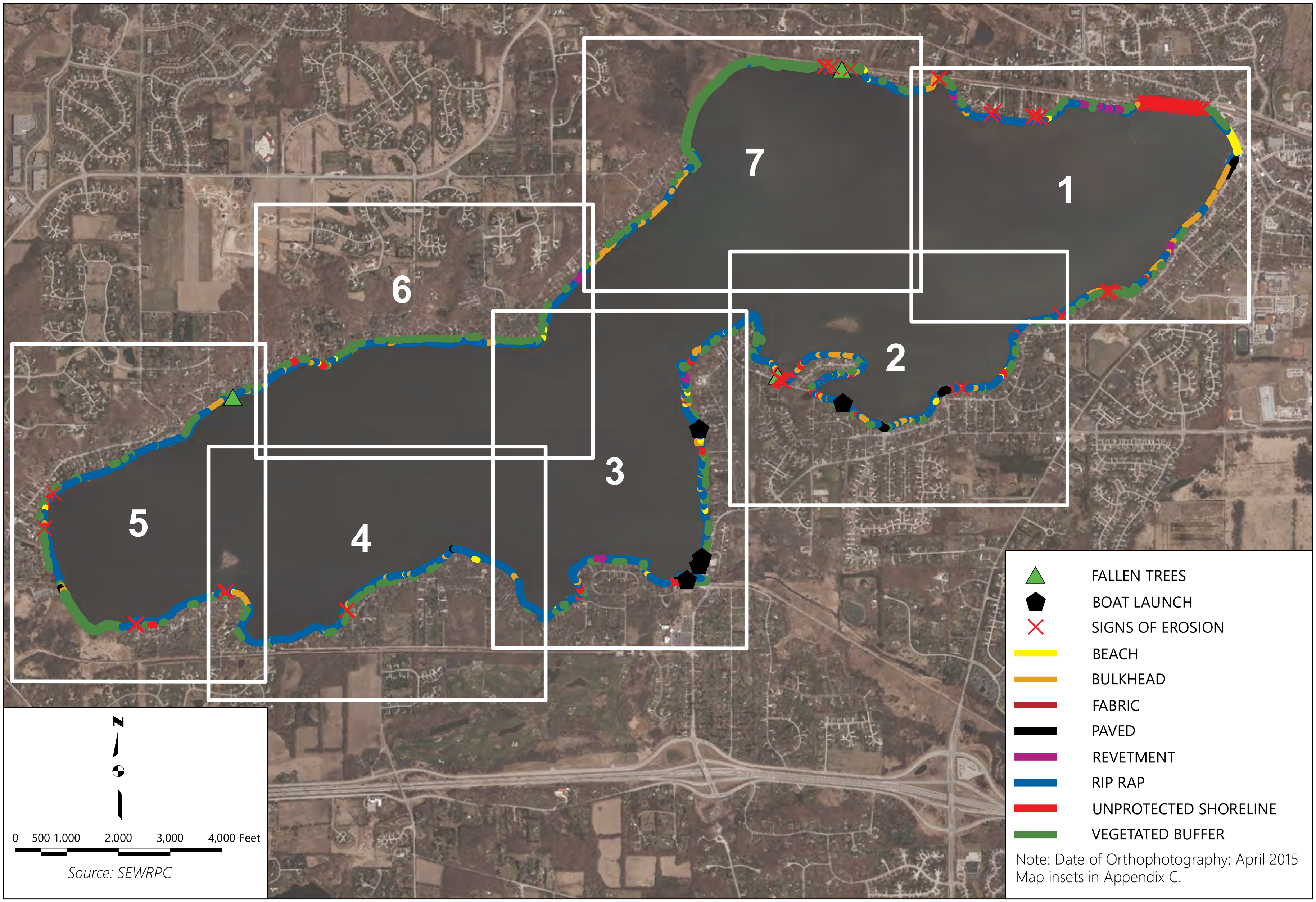
[136] *WDNR does not permit the use of sand because these materials quickly flow into a waterbody and contribute to the "fill-in" of the Lake.*

Figure 2.60
Natural Shoreline Buffers



Source: Washington County Planning and Parks Department and SEWRPC

Map 2.22
Pewaukee Lake Shoreline Conditions: 2015



erosion control, especially in areas of low banks and shallow waters. The majority of riparian properties on Pewaukee Lake that have riprap as shoreline protection have mowed lawns within the riparian zone behind the riprap protection. Although the rock placement protects against the actions of waves and ice, it does not effectively protect against nutrient and sediment runoff. Rock riprap should include natural, unmowed vegetation reinforcement on the upslope side of the riprap protection to help trap nutrients and sediment before they enter the Lake (see Figure 2.61).

Other methods of shoreline protection identified during the 2015 survey included beach, natural vegetation, and vegetated buffer strips within the riparian zone of the Lake. These are illustrated in Map 2.22 as *vegetated buffer*, which includes natural aquatic and riparian vegetation along the shoreline as well as portions of riparian land back from the immediate shoreline that utilize vegetation as a means of reducing sediment and pollution runoff.

Although the majority of the shoreline of Pewaukee Lake does have some form of protection, there were several areas around the Lake that were either unprotected (i.e., mowed lawn up to the water's edge) or exhibiting symptoms of erosion (see Appendix C). Given the desire of Lake users to promote long-term Lake health and the need to preserve recreational use and aesthetics of the Lake, priority should be given to adding natural shoreline protection to these areas that lack protection or are showing active erosion; repairing or maintaining already installed shoreline structure where feasible; and installing "soft" shoreline protection such as native vegetative shoreline protection wherever and whenever possible, as well as expanding riparian buffer. Shoreline maintenance and recommendations will be further discussed in Chapter 3.

Riparian Corridor Conditions

Healthy riparian corridors help to protect water quality, groundwater, fisheries and wildlife, and ecological resilience to invasive species, and can reduce potential flooding of structures and harmful effects of climate change.[137] The health of riparian corridors is largely dependent upon width and continuity. Therefore, efforts to protect and expand the remaining riparian corridor width and continuity are foundational elements for protecting and improving the fishery, wildlife, and recreation within the Pewaukee Lake watershed.

Riparian buffers are areas of plant growth—constructed or natural—in the *riparian zone* (those lands immediately back from the shoreline) that trap sediment and nutrients emanating from upland and nearshore erosion. The provision of buffer strips along waterways represents an important intervention that addresses anthropogenic sources of contaminants. Even relatively small buffer strips provide a degree of environmental benefit, as suggested in Table 2.21 and Figure 2.62.[138,139] The Wisconsin Buffer Initiative (WBI) further developed two key concepts that are relevant to this plan: 1) riparian buffers are very effective in protecting water resources and 2) riparian buffers need to be a part of a larger conservation system to be most effective.[140] However, it is important to note that the WBI limited its assessment and recommendations solely to the protection of water quality, and did not consider the additional values and benefits of riparian buffers. Research clearly shows that riparian buffers can have many potential benefits, such as flood mitigation, prevention of channel erosion, provision of fish and wildlife habitat, enhancement of environmental corridors, and water temperature moderation. However, the nature of the benefits and the extent to which the benefits are achieved is site-specific. Consequently, the ranges in buffer width for each of the buffer functions shown in Figure 2.62 are large. Buffer widths should be based on desired functions, as well as site conditions. For example, based upon a number of studies of sediment removal, buffer widths ranging from about 25 to nearly 200 feet achieved removal efficiencies of between 33 and 92 percent, depending upon local site differences such as soil type, slope, vegetation, contributing area, and influent

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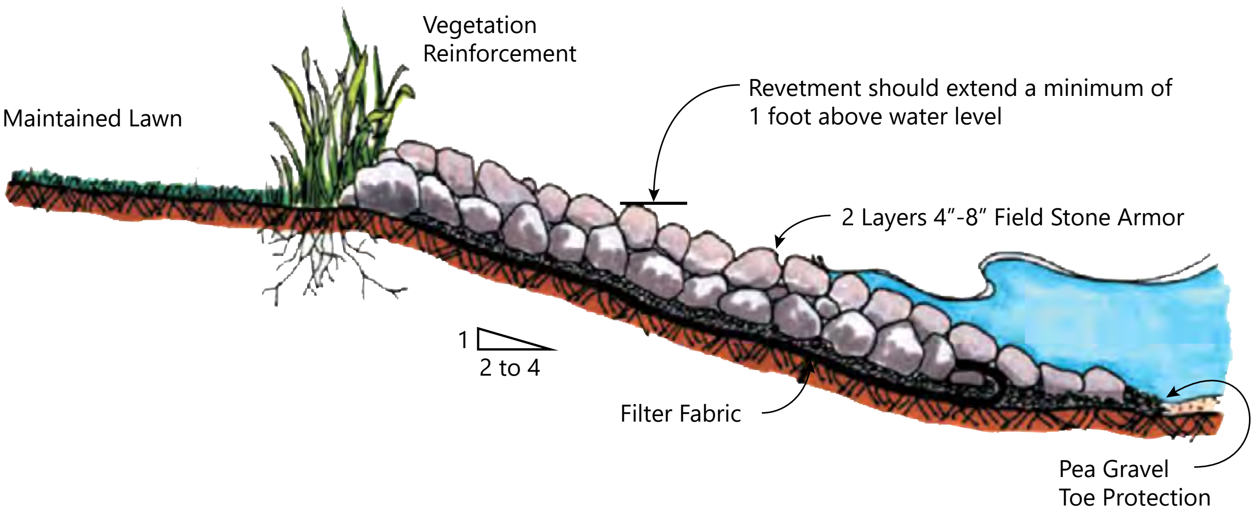
[137] *N.E. Seavy, et al., "Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research,"* Ecological Restoration*, 27(3): 330-338, 2009;* "Association of State Floodplain Managers, Natural and Beneficial Floodplain Functions: Floodplain Management—More Than Flood Loss Reduction," 2008, *www.floods.org/NewUrgent/Other.asp.*

[138] *Data were drawn from A. Desbonnet, P. Pogue, V. Lee, and N. Wolff,* Vegetated Buffers in the Coastal Zone – A Summary Review and Bibliography*, CRC Technical Report No. 2064, Coastal Resources Center, University of Rhode Island, 1994.*

[139] *See www.sewrpc.org/SEWRPCFiles/Publications/ppr/rbmg-001-managing-the-waters-edge.pdf.*

[140] *University of Wisconsin-Madison, College of Agricultural and Life Sciences,* The Wisconsin Buffer Initiative*, December 2005.*

Figure 2.61
Incorporating Vegetation into Upslope Riprap Protection



Note: Design specifications shown herein are for typical structures. The detailed design of shoreline protection structures must be based upon analysis of local conditions.

Source: SEWRPC

Table 2.21
Effect of Buffer Width on Contaminant Removal

	Contaminant Removal Efficiency (percent)[a]				
Buffer Width Categories (feet)	Sediment	Total Suspended Sediment	Nitrogen	Phosphorus	Nitrate-Nitrogen
1.5 to 25					
Mean	75	66	55	48	27
Range	37-91	31-87	0-95	2-99	0-68
Number of Studies	7	4	7	10	5
25 to 50					
Mean	78	65	48	49	23
Range	--	27-95	7-96	6-99	4-46
Number of Studies	1	6	10	10	4
50 to 75					
Mean	51	--	79	49	60
Range	45-90	--	62-97	0-99	--
Number of Studies	5	--	2	2	1
Greater than 75					
Mean	89	73	80	75	62
Range	55-99	23-97	31-99	29-99	--
Number of Studies	6	9	8	7	1

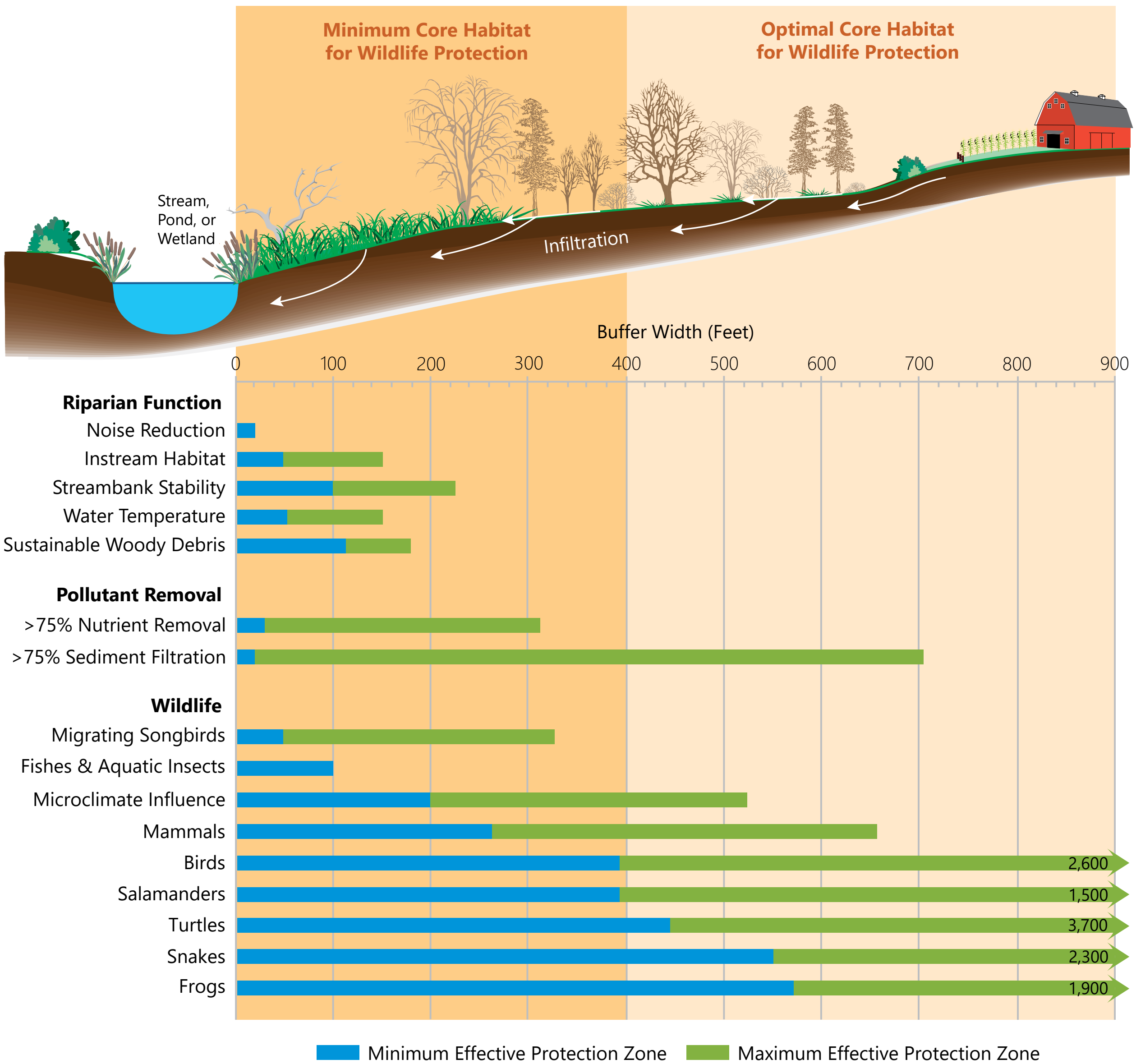
[a] *Removal efficiency measured in surface runoff.*

Source: University of Rhode Island Sea Grant Program

concentrations, to name a few. Figure 2.62 shows that for any particular buffer width, for example 75 feet, the buffer can provide multiple benefits, ranging from water temperature moderation to enhancement of wildlife species diversity. Benefits not shown in the figure include bank stabilization, which is an important concept in utilizing buffers for habitat protection.

While it is clear from the literature that wider buffers can provide a greater range of values for aquatic systems, the need to balance human access and use with the environmental benefits to be achieved suggests that a 75-foot-wide riparian buffer provides a minimum width necessary to contribute to good water quality

Figure 2.62
Buffer Widths Providing Specific Conservation Functions



Source: SEWRPC

and a healthy aquatic ecosystem. In general, most pollutants are removed within a 75-foot buffer width. However, from an ecological point of view, 75-foot-wide buffers are inadequate for the protection and preservation of groundwater recharge or wildlife species. Riparian buffer strips greater than 75 feet in width provide significant additional physical protection of streams, owing to their function in intercepting sediment and other contaminants mobilized from the land surface as a result of natural and anthropogenic activities. These wider buffers also serve to sustain groundwater recharge and discharge relationships, and biological benefit, as a result of the habitat available within the shoreline and littoral areas associated with streams and lakes.[141]

For example, the highest quality environmental corridors, natural areas, and vegetation communities are located within and adjacent to the riparian buffer network throughout the Pewaukee Lake watershed as

[141] *See, for example, B.M. Weigel, E.E. Emmons, J.S. Stewart, and R. Bannerman, Buffer Width and Continuity for Preserving Stream Health in Agricultural Landscapes*, Wisconsin Department of Natural Resources Research and Management Findings, Issue 56, *December 2005.*

shown on Map 2.20. In other words, riparian buffers are a vital conservation tool that provides connectivity among landscapes to improve the viability of wildlife populations within the habitats comprising the primary and secondary environmental corridors and isolated natural resource areas.[142]

As previously mentioned, healthy and sustained aquatic and terrestrial wildlife diversity is dependent upon adequate riparian buffer width and habitat diversity. Specifically, recent research has found that the protection of wildlife species is determined by the preservation or protection of core habitat within riparian buffers with widths ranging from a minimum of 400 feet to an optimal 900 feet or greater. These buffer areas are essential for supporting healthy populations of multiple groups of organisms, including birds, amphibians, mammals, reptiles, and insects and their various life stages. For example, some species of birds, amphibians, turtles, snakes, and frogs have been found to need buffer widths as great as 2,300 feet, 1,500 feet, 3,700 feet, 2,300 feet, and 1,900 feet, respectively, for at least part of their life histories. Hence, preservation of riparian buffers to widths of up to 1,000 feet or greater represents the optimal condition for the protection of wildlife in the Pewaukee Lake watershed.[143]

Map 2.16 shows the major natural cover types both within and outside of the existing riparian buffers distributed throughout the Pewaukee Lake watershed. This inventory shows that the riparian buffers are comprised of a variety of wetland (emergent/wet meadow, flats, forested, and scrub/shrub) and upland (brush, grassland, upland conifer, and deciduous) vegetation communities. Each of these habitats is necessary to support the life history requirements of multiple wildlife species. For example, amphibians and reptiles have been reported to utilize numerous habitat types that include seasonal (ephemeral) wetlands, permanent wetlands (lakes, ponds, and marshes), wet meadows, bogs, fens, small and large streams, springs and seeps, hardwood forest, coniferous forest, woodlands, savannahs, grasslands, and prairies.[144] Hence, it is this mosaic of habitats and the ability of organisms to travel between them at the correct times in their lives to survive, grow, and reproduce, which is essential to support an abundant and diverse wildlife community throughout this watershed.

The development patterns and infrastructure that humans create on the landscape lead to a number of obstructions that can limit both the availability of wildlife habitat as well as the ability for organisms to travel between habitats. These obstructions are primarily a result of roadways, railways, and buildings that fragment the natural landscape. Therefore, an effective management strategy to protect wildlife abundance and diversity in the Pewaukee Lake watershed would be to maximize critical linkages between habitat areas on the landscape, ensuring the ability of species to access these areas. Examples of critical linkages include the following:

- Water's edge (lake, pond, river, wetland) to terrestrial landscapes (i.e., riparian buffer width)
- Water's edge to water's edge (e.g., river to ephemeral pond, lake to ephemeral pond, permanent pond to ephemeral pond)
- Habitat complexes or embedded habitats-wetland to upland (e.g., seep to prairie) and upland to upland (e.g., grassland to woodland)

In addition, connecting the secondary environmental corridor (SEC) lands and multiple isolated natural resource areas (INRAs) throughout the Pewaukee Lake watershed to the larger primary environmental corridor (PEC) areas, as well as building and expanding upon the existing protected lands, represent sound approaches to enhancing the corridor system and wildlife areas within the watershed.

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[142] *P. Beier and R.F. Noss, "Do Habitat Corridors Provide Connectivity?,"* Conservation Biology, *12(6): 1241-1252, 1998.*

[143] *The shoreland zone is defined as extending 1,000 feet from the ordinary high water mark of lakes, ponds, and flowages and 300 feet from the ordinary high water mark of navigable streams, or to the outer limit of the floodplain, whichever is greater. To be consistent with this concept and to avoid confusion, the optimum buffer width for wildlife protection is defined as extending 1,000 feet from the ordinary high water mark on both sides of the lakes, ponds, and navigable streams in the watershed.*

[144] *B.A. Kingsbury and J. Gibson (eds.),* Habitat Management Guidelines for Amphibians and Reptiles of the Midwestern United States, *Partners in Amphibian and Reptile Conservation Technical Publication HMG-1, 2nd Edition, 2012.*

Potential Restorable Wetlands

Wetlands provide a number of benefits such as water quality improvement, wildlife habitat, and flood mitigation. According to the USEPA, a typical one-acre wetland can store about one million gallons of water.[145] Restoring wetlands in the watershed area would provide water storage and reduce sediment and phosphorus loading. Establishing restored wetlands, particularly as riparian buffers, can help reduce pollution loads from tile drains, barnyards, and upland runoff, and can be implemented in areas where frequent crop damage occurs due to flooding. Although modeling load reductions associated with wetland restorations was beyond the scope of this report, constructed wetlands have been reported to reduce median pollutant loads by 73 percent for total suspended solids, 38 percent for total phosphorus, 69 percent for particulate phosphorus, 30 percent for total nitrogen, 70 percent for metals (zinc and copper), 60 percent for bacteria, and, 80 percent for hydrocarbons.[146]

Hydric soils characteristic of wetland conditions form under settings where the ground is saturated with water for long enough periods of time to cause changes in the soil properties. These unique soils and growing conditions foster a suite of plant species that thrive in wet, oxygen-deprived soil. Hence, the majority of the wetlands remaining in the Pewaukee Lake watershed are found along the tributaries. Wetlands currently comprise a total of 8.6 percent of the Pewaukee Lake watershed. This falls below a standard of 10 percent established by Environment Canada for the minimum recommended level of wetland area needed to provide protection for a major watershed. This minimum requirement also includes meeting a level of 6 percent wetland for each subwatershed.[147] None of the sub-watersheds meet this recommended level of wetland protection. The Coco Creek watershed has the highest level of protection at 4 percent. The Audley Creek and Pewaukee Lake watersheds both have extremely low levels of protection at 0.6 percent each. Therefore, there is a good potential to restore wetlands throughout the Pewaukee Lake watershed, which could be a key component to address nonpoint source soil erosion and associated pollutant load reductions in this basin.

Potentially restorable wetland areas are also good candidate sites for constructed floodplain benches associated with re-meandering ditched reaches within the Lake tributary network network and/or opportunities to modify tile drainage to reduce pollution loads. Therefore, any potential restorable wetland areas that are located within the existing floodplain boundary would be a high priority for conversion to wetland, because their location would facilitate a higher level of protection to reduce the amount of pollutants entering Pewaukee Lake. Onsite evaluation of potential wetland restoration sites will be necessary prior to design and implementation.

Existing and Potential Riparian Buffers

Map 2.23 shows the current status of existing and potential riparian buffers at the 75-foot, 400-foot, and 1,000-foot widths along the Pewaukee Lake and its major tributary streams. Buffers were primarily developed from 2015 digital orthophotographs and the 2010 WDNR Wisconsin Wetland Inventory, and from Commission inventories of PEC, SEC, and INRA. Polygons were created using geographic information system (GIS) techniques to delineate contiguous natural lands (i.e., nonurban and nonagricultural lands) comprised of wetland, woodland, and other open lands adjacent to waterbodies. Those lands comprise a total of about 2,204 acres, or 16 percent, of the total land area (not including water area) within the Pewaukee Lake watershed.

The most extensive existing buffers were found within the Coco Creek and Meadowbrook Creek sub-basins that together comprised about 75 percent (1,649 acres) of the total buffered lands within the Pewaukee Lake watershed (see Figure 2.63). Existing buffers comprise between 18 to 27 percent of the total land area within these sub-basins. The remaining three sub-basins of Pewaukee Lake, Zion Creek, and Audley Creek contain 25 percent (555 acres) of the total buffered lands within the watershed, which ranged from a total of 9 to 11 percent of existing buffers of the total land area within each of their respective sub-basins.

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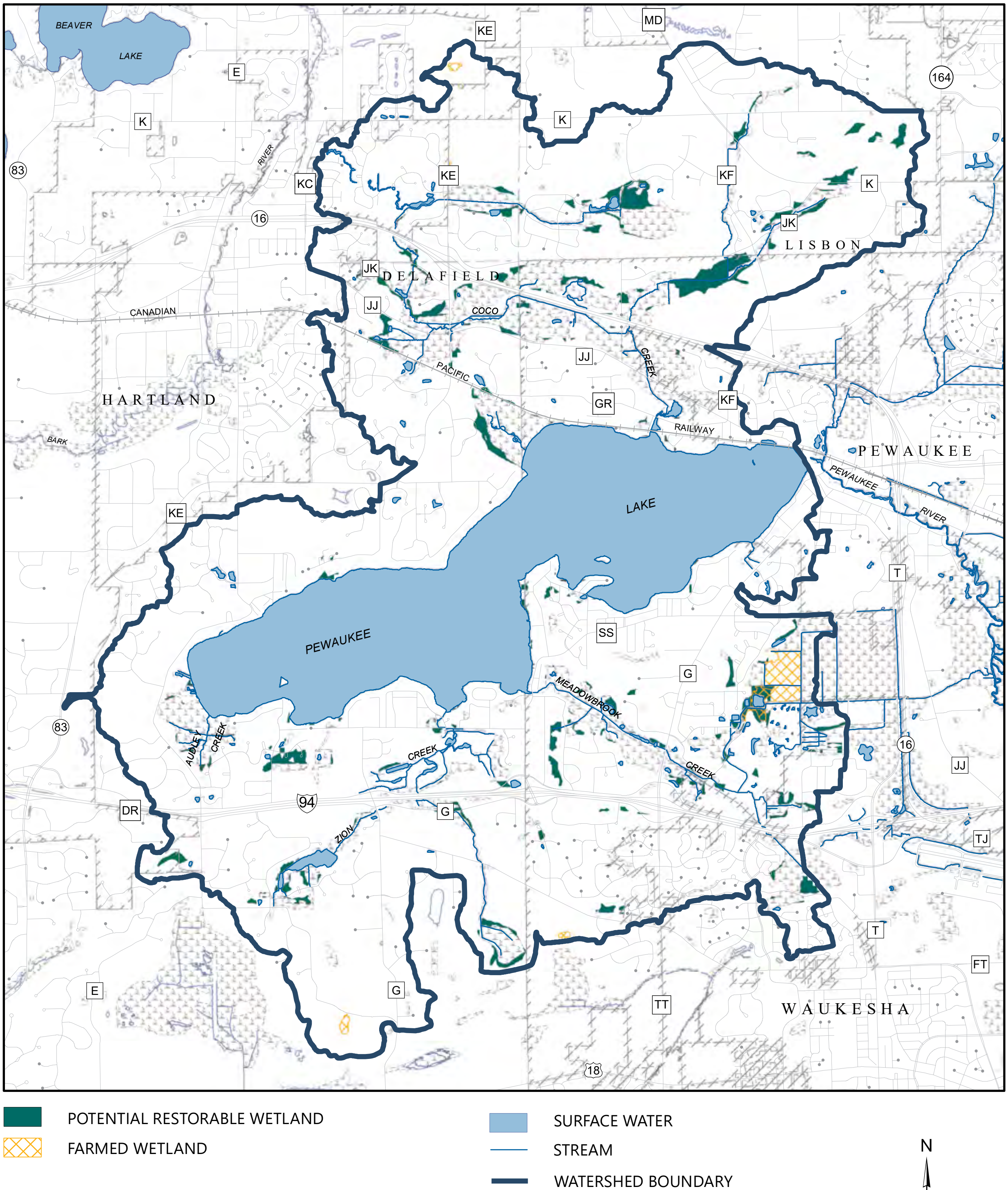
145 *U.S. Environmental Protection Agency (USEPA),* Wetlands: Protecting Life and Property from Flooding*, May 2006, USEPA843-F-06-001, Website: water.epa.gov/type/wetlands/outreach/upload/Flooding.pdf.*

146 *Minnesota Pollution Control Agency, Minnesota Stormwater Manual website, stormwater.pca.state.mn.us/index.php/Information_on_pollutant_removal_by_BMPs.*

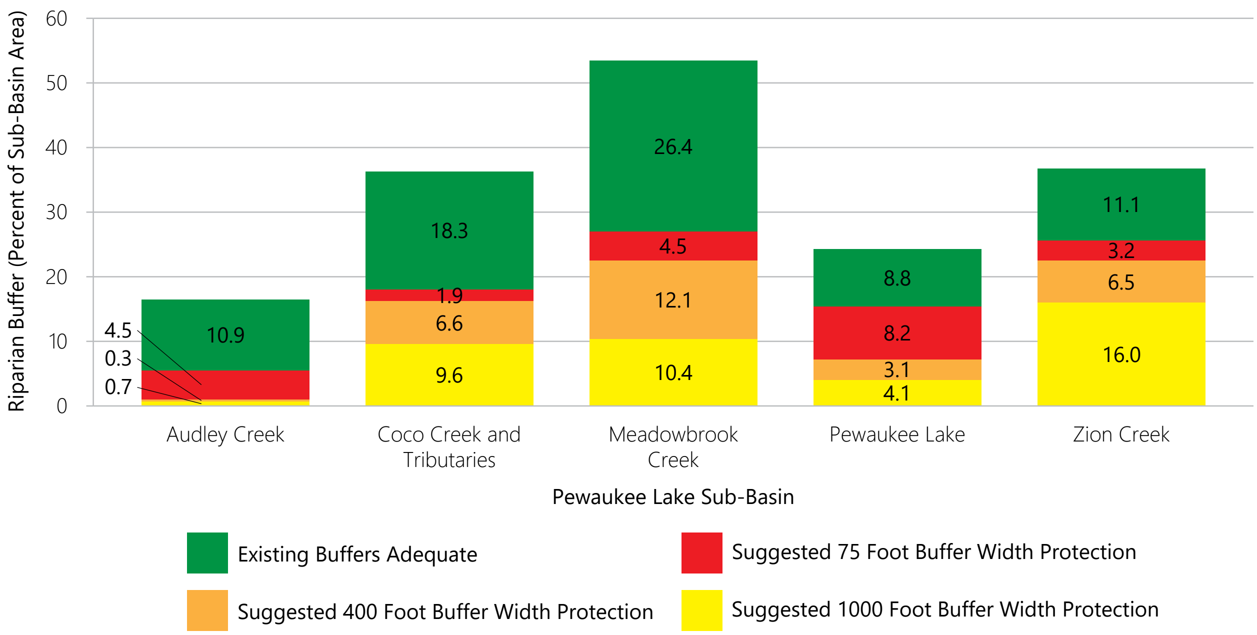
147 *Environment Canada,* How Much Habitat is Enough? Third Edition, *Environment Canada, Toronto, Ontario, 2013, www.documentcloud.org/documents/2999368-THUNDER-BAY-How-Much-Habitat-Is-Enough-3rd-Ed-2013.html.*

Map 2.23
Potentially Restorable and Farmed Wetlands Within the Pewaukee Lake Watershed



Source: Wisconsin Department of Natural Resources and SEWRPC

Figure 2.63
Existing and Suggested Riparian Buffer Width by Watershed Sub-Basin



Source: SEWRPC

Comparison between the existing buffers versus the potential buffers at the 75-foot, 400-foot, and 1,000-foot widths throughout the Pewaukee Lake watershed indicates that some areas contain existing buffers at 75-foot, 400-foot, and 1,000 feet widths from the edge of the stream, which indicates they are providing a good level of water quality and wildlife protection. However, there are multiple locations in both urban and agricultural areas throughout the watershed that show encroachments into the 75-foot and 400-foot riparian zones (see Map 2.20), including the Pewaukee Lake shoreline perimeter. It is important to note that there are about 8.8 linear miles (46,943 feet) of non-buffered riparian shoreline around Pewaukee Lake. That distance represents 63 percent of the total shoreline length. Based upon this analysis, there are many opportunities to improve the amount of riparian buffers to protect water quality and wildlife (at the 75-foot, 400-foot, and 1,000-foot widths) while reducing pollutant loading, both within the tributary network and the Pewaukee Lake shoreline.

Pollutant Loadings Summary

There are no significant point sources of pollution in the Pewaukee Lake watershed. Anticipated changes in land use between existing and planned conditions in the Lake's watershed are expected to result in an overall decrease in sediment loading to the Lake of about 400,000 pounds per year as 1,800 acres of rural lands (mainly agricultural) are converted to urban use (mostly residential). This conversion of existing rural lands to urban uses is also expected to produce an increase in the predicted amounts of metal loading to Pewaukee Lake: copper is expected to increase about 160 pounds (from 609 pounds in 2015 to 769 pounds) and zinc is expected to increase nearly 1,100 pounds (from 4,119 pounds in 2015 to 5,205 pounds). A very small net decrease in the amount of phosphorus entering the Lake is expected as well, as most of the decrease in phosphorus from a decline in rural land uses (mostly agricultural) is offset by increases in phosphorus due to an increase in urban uses (residential). While there may not be a pollution input source problem with total phosphorus in the Lake, data show that there is a great deal of phosphorus in the bottom sediments that is released under anoxic conditions (i.e., internal loading). In addition, recycling of phosphorus, while shown to be a significant part of the nutrient load in other Wisconsin lakes, has yet to be determined for Pewaukee Lake and will require a separate study. Coco Creek and Meadowbrook Creek are the two main tributary contributors of phosphorus to Pewaukee Lake, at 1,343 pounds annually and 1,209 pounds annually, respectively, followed by Zion Creek. Nuisance levels of aquatic plants in Pewaukee Lake have been managed since the 1970s using chemicals initially and then transitioning to mechanical harvesting in the 1980s. Data have shown that harvesting has played a key role in removing at least 13,000 pounds of phosphorus from Pewaukee Lake since 1988 with higher estimates in excess of over 50,000 pounds. Aquatic plant harvesting, combined with stormwater management practices, protection of wetlands, and key riparian buffered lands, are contributing to the improvement (i.e., reduced phosphorus loads) of Pewaukee Lake. Recommendations regarding management to mitigate pollutant loading are provided in Section 3.4, "Pollutant and Sediment Sourced Loads."

2.7 AQUATIC PLANTS

This section presents data from aquatic plant surveys completed on Pewaukee Lake. It should be used to gain a better understanding of the plant communities within the Lake, determine changes in the Lake's plant communities over time, and guide aquatic plant management, particularly as it relates to invasive species.

It is important to note that all healthy lakes have plants. In fact, in a nutrient-rich lake such as Pewaukee Lake, it is normal to have luxuriant plant growth in shallow areas (e.g., the east end of Pewaukee Lake, in particular). Nutrient-rich lakes are common in Southeastern Wisconsin due to nutrient-rich soil. Native aquatic plants form a foundational part of a lake ecosystem. Aquatic plants form an integral part of the aquatic food web, converting sediments and inorganic nutrients present in the water into organic compounds that are directly available as food to other aquatic organisms. In this process, known as *photosynthesis*, plants utilize energy from sunlight and release the oxygen required by many other aquatic life forms into the water. Aquatic plants also serve a number of other valuable functions in a lake ecosystem, including:

- Improving water quality by filtering excess nutrients from the water
- Providing habitat for invertebrates and fish
- Stabilizing lake bottom substrates
- Supplying food for waterfowl and various lake-dwelling animals

It is also important to note that even though aquatic plants may hinder human use and/or access to a lake, aquatic plants should not necessarily be eliminated or even significantly reduced in abundance because they often support many other beneficial functions. For example, white water lily (found commonly throughout Southeastern Wisconsin) plays a major role in providing shade, habitat, and food for fish and other important aquatic organisms. It also helps prevent damage to the lakeshore by dampening the power of waves that could otherwise erode the shoreline. Additionally, the shade that this plant provides helps reduce the growth of undesirable plants (e.g., invasive EWM) because it limits the amount of sunlight reaching the lake bottom. Given these benefits, large-scale removal of native plants that may be perceived as a nuisance (especially white water lilies) should be avoided when developing plans for aquatic plant management.

Phytoplankton and Macrophytes

Aquatic plants include microscopic algae ("phytoplankton") and larger plants ("macrophytes"). Macrophytes are often described using the terms *submerged, floating-leaf, free-floating,* and *emergent,* depending on where the plant is found in the lake ecosystem. *Submerged* plants are found in the main lake basin and, although most are rooted in the bottom substrate, some species, such as coontail (*Ceratophyllum demersum*) can become free-floating. *Floating-leaf* plants, such as water lilies, generally have large, floating leaves and are usually found in shallow water areas a few feet in depth or less that contain loose bottom sediments. *Free-floating* plants, such as duckweed (*Lemna* spp.), have small leaves, are not rooted to the sediment, and are often wind-blown around the waterbody. *Emergent* plants, which have leaves that emerge above the water, are commonly found along the shoreline areas of a lake, such as bulrushes and cattails. All four types have significant roles to play in the overall working of a lake's ecosystem.

Maintaining a rich and diverse community of native species is important for every ecosystem as this:

- Helps sustain and increase the robustness of the existing system
- Increases the ability of an ecosystem to adapt to environmental changes
- Provides a spectrum of options for future decisions regarding the management of that system

Many factors—including lake configuration, depth, water clarity, nutrient availability, bottom substrate, wave action, and type and size of fish populations—determine the distribution and abundance of aquatic macrophytes in lakes, with most waterbodies within Southeastern Wisconsin naturally supporting abundant and diverse aquatic plant communities.

Depending on their types, distribution, and abundance, aquatic macrophytes can be either beneficial or a nuisance. Plants growing in the proper locations and in reasonable densities in lakes are beneficial in maintaining lake fisheries and wildlife populations, and in providing habitat for a variety of aquatic organisms. Aquatic plants also may remove nutrients from the water that otherwise would contribute to excessive algal growth. They can become a nuisance when their densities become so great as to interfere with swimming and boating activities, when their growth forms limit habitat diversity, or when the plants reduce the aesthetic appeal of the resource.

Phytoplankton

Phytoplankton is the term for a group of microscopic organisms that includes bacteria, protists, and algae. These organisms are aquatic and can all actively photosynthesize. Maintaining a healthy community of phytoplankton is essential for lake health, as these species form the foundation of the lake's food web and create oxygen required by other organisms, such as zooplankton and fish. However, an overabundance of phytoplankton, generally caused by excessive nutrient loads, can impair lake health by decreasing water clarity and reducing hypolimnetic oxygen. Phytoplankton were most recently surveyed in the Lake during 1976 by WDNR and 2002 by Wisconsin Lutheran College. Blue-green algae were noted to be the dominant algal group in the Lake in both surveys[148].

Since phytoplankton and rooted plants compete for nutrients, an abundance of rooted aquatic plants means fewer nutrients (usually phosphorus) available to algae, in turn reducing the abundance of free-floating algae and increasing water clarity. Conversely, when rooted aquatic plants senesce or die, the subsequent return of nutrients to the water column can increase algal populations and decrease water clarity; algae blooms occur during large die-offs of aquatic plants. Thus, it is important to appreciate the balance that exists between rooted aquatic plants and algae in a Lake; the over-suppression of one can often lead to an over-abundance of the other. For example, the elimination of too many rooted plants in an attempt to achieve a "weed-free lake" can result in a condition of chronic algae blooms, supersaturated oxygen levels in night time surface waters, and summer fish kills.

Native Plants

Aquatic plants live in community with one another. They develop complex interactions and mutual dependencies that are of great significance in how these dynamic communities function within a lake. Native aquatic plant species are specifically adapted to local aquatic environments and many kinds of wildlife depend on the presence of specific native plant species for survival. For example, the seeds and tubers of Sago pondweed (*Stuckenia pectinata*) are an important food source for migratory waterfowl.

In Wisconsin, the presence of native pondweeds is generally considered to be indicative of a healthy lake with good habitat for fish and aquatic life. Pondweeds provide good habitat and serve as food and shelter for a variety of aquatic organisms and waterfowl. Of the pondweeds that occur in the Region, white-stem pondweed (*Potamogeton praelongus*) is of special importance because of its sensitivity to changes in water quality and intolerance of turbidity. It is considered a valuable water quality indicator species, since its disappearance from a lake can be due to deteriorating water quality. Conversely, its presence in a lake is an indicator of good water quality.[149] White-stem pondweed was first recorded as present in Pewaukee Lake (albeit, in small numbers) in 2000 and has also been observed (in small numbers) in surveys conducted in 2007, 2008, 2011, 2014, and 2016.

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[148] *For a greater description of the phytoplankton community, see SEWRPC Community Assistance Planning Report No. 58, 2nd Edition,* op. cit.

[149] *Wisconsin Lakes Partnership, Through the Looking Glass...A Field Guide to Aquatic Plants, University of Wisconsin-Extension.*

Community Changes Over Time

Aquatic plant communities undergo cyclical and periodic changes that reflect community responses to interannual climatic conditions as well as long-term changes in a lake's "hydroclimate." Interannual changes, occurring between three to seven years, can include surface water elevations, water temperature, as well as ice-off and ice-on dates. These factors can promote the short-term growth of certain species, such as curly-leaf pondweed (CLP) (*Potamogeton crispus*) being more abundant in years with earlier ice-off. Long-term factors affecting plant communities—those which occur over a decade or longer—can include nutrient loading, sedimentation rates, recreational use patterns, and natural stressors. Natural stressors can include biological stressors, such as herbivory and disease, as well as climatic and limnological factors, such as insulation, water temperature, and lake circulation patterns. For example, EWM populations have been observed to increase rapidly upon introduction, but decline following this explosive initial growth[150], which may be partly attributed to herbivory by native milfoil weevils. Additionally, aquatic plant management can reduce the abundance of nonnative species over time, although total eradication from the community is unlikely in many cases. Examining changes in aquatic plant communities over time can reveal the factors promoting or inhibiting the growth of specific species, informing management options to control the abundance of those species in the Lake.

Aquatic Nonnative and Invasive Species (AIS)

The terms "nonnative" and "invasive" are often confused and incorrectly assumed to be synonymous. *Nonnative* is an overarching term describing living organisms introduced to new areas beyond their native range with intentional or unintentional human help. Nonnative species may not necessarily harm ecological function or human use values in their new environments. *Invasive* species, on the other hand, are the subset of nonnative species that have damaging impacts on the ecological health of their new environments and/or are considered a nuisance to human use values. In summary, invasive species are non-native but not all non-native species are invasive.

Introducing invasive species, either plants or animals, can severely disrupt both terrestrial and aquatic natural systems. Since invasive species often have no natural predators to control their growth, they are often able to reproduce prolifically and outcompete native species for space and other necessary resources. This can have devastating effects on native species that have well developed dependencies on the availability of native plants and animals**.**

The most common and destructive invasive species in Wisconsin lakes are EWM and CLP; both are declared nuisance species identified in Chapters NR 40 and NR 109 of the *Wisconsin Administrative Code* and both species have been recorded as present in Pewaukee Lake since at least 1967. Invasive species of high concern are continuously changing due to new introductions and successful management of past invasions. Waukesha County recently adopted a strategic aquatic invasive species (AIS) plan with the goals of monitoring AIS populations, educating water users about AIS, preventing the spread of AIS, and managing existing AIS populations.[151] As part of this effort, the County is maintaining an updated, online database of recorded AIS populations.[152]

The WDNR officially lists three invasive aquatic plant species as having been verified and vouchered in Pewaukee Lake: EWM, CLP, and starry stonewort (*Nitellopsis obtusa*). Another species, yellow floating heart (*Nymphoides peltata*) was listed as verified in 2011, with observations in two ponds adjacent to Coco Creek. The LPSD completed an AIS early detection and response project in 2011 to eradicate the population; no new observations have been recorded since completion of this project. Hybrid Eurasian/northern watermilfoil, commonly found in nearby lakes, may also be present but the WDNR does not currently list it as verified in the Lake.[153]

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[150] *S.R. Carpenter, "The Decline of* Myriophyllum spicatum *in a Eutrophic Wisconsin (USA) Lake,"* Canadian Journal of Botany, *58(5): 527-535, 1980.*

[151] *For more information, see SEWRPC Community Assistance Planning Report No. 333,* Waukesha County Aquatic Invasive Species Strategic Plan*, February 2018.*

[152] *See www.waukeshacounty.gov/AISStrategicPlan.*

[153] *See dnr.wi.gov/lakes/invasives/AISLists.aspx?species=MILFOIL_HYBRID&location=68.*

Eurasian Watermilfoil

While eight milfoil species are found in Wisconsin, EWM (see Figure 2.64) is the only nonnative, or *exotic*. EWM was first observed in Pewaukee Lake in 1966. As an exotic species, EMW has few natural enemies that can inhibit its growth. Thus, EWM can grow abundantly in suitable conditions, particularly in mesotrophic or eutrophic hard-water lakes or where the lake bottom has been disturbed, such as following dredging. Unless its growth is anticipated and controlled, EWM populations can displace native plant species and interfere with the aesthetic and recreational use of waterbodies; this plant has been known to cause severe ecological and recreational problems within Southeastern Wisconsin lakes.

EWM can quickly reproduce through the rooting of plant fragments, which can unintentionally be created during lake recreational activities. For example, boat propellers can fragment EWM plants, which are able to generate new root systems from fragments, causing the plant to become more widespread within the lake. Additionally, these fragments allow EWM to disperse to new lakes, as they cling to boats, trailers, motors, and/or bait buckets and can stay alive for weeks. As EWM can become a dominant plant species within two years of arriving in a new waterbody, it is very important to remove all vegetation from boats, trailers, and other equipment after removing them from the water and prior to launching in other waterbodies.

Curly-Leaf Pondweed

CLP (see Figure 2.64) is the only non-native pondweed (*Potamogeton* spp.) found within Wisconsin. This species is predominantly found in disturbed, eutrophic lakes, where it exhibits a peculiar split-season growth cycle that provides a competitive advantage over native plants and makes management of this species difficult. This species reproduces using turions, a type of plant bud utilized by some aquatic plants. The turions are produced in late summer and lie dormant in lake sediment until cooler fall water temperatures trigger the turions to germinate. Over the winter, the turions produce winter foliage that thrives under the ice. In spring, when water temperatures begin to rise again, the plant has a head start on the growth of native plants and quickly grows to full size, producing flowers and fruit earlier than its native competitors. CLP begins to die-off in midsummer, releasing phosphorus that reduces lake water quality. It can grow in more turbid waters than many native plants, so protecting or improving water quality is an effective method of control of this species, as clearer waters in a Lake can help native plants compete more effectively.

Starry Stonewort

A new potentially invasive macrophytic algal species, starry stonewort (see Figure 2.64), was identified in Pewaukee Lake in 2019. This species can form extremely dense mats, which may affect the species richness of the aquatic plant community and cause recreational use impediments. Overgrowth of starry stonewort can also reduce the movement of fish and other animals, as well as reduce fish spawning.[154] Starry stonewort is indigenous to Eurasia and first appeared in the United States in 1978 along the St. Lawrence River. As of the writing of this report, starry stonewort has been found in Indiana, Michigan, Minnesota, New York, Pennsylvania, Vermont, and Wisconsin.[155] The first observation of this species in Wisconsin was during 2014 in Little Muskego Lake. Subsequently, starry stonewort has been observed in Big Muskego Lake, Bass Bay, Lower Nemahbin Lake, and Okauchee Lake in Waukesha County; Green Lake, Little Cedar Lake, Pike Lake and Silver Lake in Washington County; Long Lake and Wind Lake in Racine County; and Geneva Lake in Walworth County. No methods have yet been found to successfully manage its growth.

Pewaukee Lake Surveys

Nuisance levels of aquatic plants, especially in the east basin of Pewaukee Lake, have long been a part of the Lake. Beginning with the construction of the first dam in 1838 that flooded the wetland at the east end, the Lake has experienced abundant aquatic plant growth. Abundance levels of plant growth in the Lake were viewed mainly within the context of their impact on commerce by competing ice companies who depended on clear lake waters for the production of contact-grade ice. Not until the 1960s were attempts

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[154] "Aquatic Invasive Species Quick Guide: Starry Stonewort (*Nitellopsis obtusa L.*)", *Golden Sands Resource Conservation and Development Council, Inc. This Quick Guide is part of a series on aquatic invasive species, and may be reproduced for educational purposes. Visit uwsp.edu/cnr/uwexlakes/clmn or goldensandsrcd.org/our-work/water to download this series of handouts. Developed by Golden Sands Resource Conservation & Development Council, Inc. as part of an AIS education program, supported by a grant from the Wisconsin Department of Natural Resources. Maintained and updated by the Wisconsin Citizen Lake Monitoring Network.*

[155] USGS Nonindigenous Aquatic Species Database, Gainesville, FL. *nas.er.usgs.gov/queries/FactSheet.aspx?SpeciesID=1688*.

Figure 2.64
Invasive Aquatic Plants Verified and Vouchered in Pewaukee Lake: 2019

Eurasian watermilfoil (*Myriophyllum spicatum*)

Curly-leaf pondweed (*Potamogeton crispus*)

Starry Stonewort (*Nitellopsis obtusa*)

Starry stonewort bulbil

Source: Paul Skawinski and SEWRPC

made to produce meaningful aquatic plant surveys, but even then these surveys relied mainly on subjective anecdotal descriptions rather than objective quantifications (see Table 2.22). It wasn't until the 1980s that aquatic plant surveys in Pewaukee Lake began to utilize more objective and scientific survey protocols to accurately describe, quantify, and document aquatic plant communities (see Table 2.23).

Aerial photography has been a useful tool for documenting abundant plant growth in Pewaukee Lake. Beginning in the early 1970s, aerial views of the Lake were taken as part of the US Department of Agriculture Farm Service Agency program. These aerial photographs indicate Lake areas that have historically had abundant plant growth, as shown on Map 2.24. In addition, Map 2.24 lists the years corresponding to times of peak abundances in those areas as shown by aerial photographs. These aerial surveys reinforce the ground-level observations and in-lake surveys documenting areas of greatest aquatic plant abundance in the Lake.

Aquatic plant surveys on Pewaukee Lake have been conducted by various agencies over a number of years, including 1967, 1976, 1986, 1988, 1991-92, 1994, 1997, 2000-02, 2004-11, and 2013-16. In 2000, it was observed that Pewaukee Lake was experiencing the greatest level of aquatic plant growth since 1990. According to LPSD records, from 1985 to 2004, native aquatic plant populations in Pewaukee Lake increased as milfoil density decreased. In 2016, species richness in the Lake was the highest observed in the past 25 years, associated with a decline in abundance of EWM and an increased abundance of native species.

Table 2.22
Aquatic Plant Species Present in Pewaukee Lake: 1967 and 1976

Area	Common Name	Scientific Name	Relative Abundance	
			1967 (lakewide)	1976 (area)
1	Stonewort	*Chara* sp.	Sparse	Moderate
	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Moderate
	Large-Leaf Pondweed	*Potamogeton amplifolius*	None	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Sparse
	Soft-Stem Bulrush	*Scirpus validus*	Very sparse	Very sparse
	Bur Reed	*Sparganium eurycarpum*	Very sparse	Very sparse
	Broadleaf Cattail	*Typha latifolia*	Very sparse	Very sparse
	Purple Bladderwort	*Utricularia purpurea*	Very sparse	Sparse
2	Stonewort	*Chara* sp.	Sparse	Abundant
	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Clasping-Leaf Pondweed	*Potamogeton richardsonii*	None	Very sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Very sparse
3	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Very sparse
4	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
5	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Yellow Water Lily	*Nuphar* sp.	Very sparse	Very sparse
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Moderate
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
6	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Very sparse
7	Water Weed	*Elodea canadensis*	Very sparse	Very sparse
	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
8	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Moderate
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Very sparse
9	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Moderate
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Very sparse
10	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Curly-Leaf Pondweed	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
11	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
	Sheathed Pondweed	*Stuckenia vaginata*	None	Sparse
12	Stonewort	*Chara* sp.	Sparse	Very sparse
	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Moderate
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse

Table continued on next page.

Table 2.22 (Continued)

Area	Common Name	Scientific Name	Relative Abundance	
			1967 (lakewide)	1976 (area)
13	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Yellow Water Lily	*Nuphar* sp.	Very sparse	Very sparse
	Water Lily	*Nymphaea* sp.	Sparse	Very sparse
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Moderate
	Sheathed Pondweed	*Stuckenia vaginata*	None	Sparse
	Soft-Stem Bulrush	*Scirpus validus*	Very sparse	Very sparse
	Bur Reed	*Sparganium eurycarpum*	Very sparse	Very sparse
	Broadleaf Cat-Tail	*Typha latifolia*	Very sparse	Very sparse
14	Water Weed	*Elodea canadensis*	Very sparse	Very sparse
	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
15	Eurasian Watermilfoil[a]	*Myriophyllum spicatum*	Abundant	Very abundant
	Slender Naiad	*Najas flexilis*	None	Very sparse
	Curly-Leaf Pondweed[a]	*Potamogeton crispus*	Sparse	Very sparse
	Sago Pondweed	*Stuckenia pectinata*	Sparse	Very sparse
	Soft-Stem Bulrush	*Scirpus validus*	Very sparse	Very sparse
	Bur Reed	*Sparganium eurycarpum*	Very sparse	Very sparse
	Broadleaf Cattail	*Typha latifolia*	Very sparse	Very sparse

[a] *Nonnative or alien species.*

Source: Wisconsin Department of Natural Resources and SEWRPC

Aquatic Plant Survey Methods

There have also been several different methods of sampling the types, distribution, and relative abundance of aquatic macrophytes in Pewaukee Lake over the years, which complicates empirical comparisons from one year to another. For example, the WDNR aquatic plant survey in 1967 was conducted "lake wide", while the 1976 survey divided the shoreline areas of the Lake into "areas". In the absence of a consistent, objective measuring method, these two surveys relied on descriptors such as "abundant" or "sparse" to describe the abundance of each plant species (see Table 2.22).

Transect Methodology

Starting in 1986, most aquatic plant surveys of Pewaukee Lake were conducted utilizing the modified Jesson and Lound method. This methodology is based on a series of numbered transect lines located at regular intervals around the shoreline of the lake (see Figure 2.65). Along each transect line extending directly out from shore, a series of four sampling points are located based on pre-determined water depths of 1.5, 5, 9 and 11 feet. At each sampling point, four rake hauls are made and a record is made of each species observed in each haul, with no consideration for the relative abundance of each species: the species is identified as either *present* or *absent* in each haul. For example, if a species is present in three of the rake hauls, it is assigned a density rating of "3" and described as "moderate" in abundance.[156] This approach can be quantified so that empirical comparisons can be made between successive surveys over time.

Figure 2.65 shows the locations of the 24 transect lines utilized during surveys conducted by the WDNR during 1988, 1991, 1994, and 1997. A survey conducted in 2000 by the Commission utilized 48 transects created by inserting an additional transect line approximately halfway between the 24 lines previously used (see Map 2.25). Table 2.23 shows the results of these surveys.

[156] *Wisconsin Lutheran College, Biology Department Technical Bulletin 013,* Southeast Wisconsin's Pewaukee Lake Aquatic Plant Survey 2010, *April 2011.*

Table 2.23
Aquatic Plant Mean Species Density in Pewaukee Lake: 1988-2000

Aquatic Plant Species	Mean Species Density				
	1988[a,b]	1991[a,b]	1994[a,b]	1997[a,b]	2000[b]
Ceratophyllum demersum (coontail)	2.75	2.97	2.22	2.40	2.57
Chara vulgaris (muskgrass)	1.77	1.03	1.50	1.13	2.15
Elodea canadensis (waterweed)	0.56	0.65	1.25	1.65	1.86
Heteranthera dubia (water stargrass)	0.75	0.75	0.63	0.67	2.00
Myriophyllum sp. (native watermilfoil)	--	--	1.20	1.91	1.00
Myriophyllum spicatum (Eurasian watermilfoil)[c]	3.62	2.96	2.76	2.47	3.27
Najas flexilis (slender naiad)	2.07	1.47	1.79	0.63	2.61
Najas guadalupensis (southern naiad)	--	--	--	1.72	--
Potamogeton amplifolius (large-leaf pondweed)[d]	1.50	0.50	0.40	1.17	1.50
Potamogeton crispus (curly-leaf pondweed)[c]	1.82	1.58	0.88	--	1.00
Potamogeton filiformis (thread-leaf pondweed)	--	0.75	--	--	--
Potamogeton illinoensis (Illinois pondweed)[d]	--	--	--	--	0.60
Potamogeton natans (floating-leaf pondweed)	--	--	--	--	0.60
Potamogeton praelongus (white-stem pondweed)[d]	--	--	--	--	1.20
Potamogeton richardsonii (clasping-leaf pondweed)[d]	--	0.42	0.25	--	1.00
Potamogeton zosteriformis (flat-stemmed pondweed)	0.75	0.80	1.05	1.48	1.60
Potamogeton spp. (pondweed)	1.90	0.25	0.25	0.63	--
Stuckenia pectinata (Sago pondweed)[d]	0.94	1.56	1.24	1.13	1.56
Utricularia sp. (bladderwort)	0.25	--	0.88	0.75	1.00
Vallisneria americana (water celery)[d]	0.77	0.79	1.16	1.50	2.51

Note: Species mean density for all sample points including sample points where a particular species did not occur in Pewaukee Lake: Abundant (density rating equals 4 to 5), Common (density rating equals 2 to 3), Scarce (density rating equals 1), and Absent (density rating equals 0).

[a] *Survey conducted by Wisconsin Department of Natural Resources as part of the Long-Term Trend Monitoring Program.*

[b] *Maximum density equals 5.0.*

[c] *Designated as invasive and nonnative aquatic plant species pursuant to section NR 109.07 of the* Wisconsin Administrative Code.

[d] *Considered a high-value aquatic plant species known to offer important values in specific aquatic ecosystems under Section NR 107.08 (4) of the* Wisconsin Administrative Code.

Source: Wisconsin Department of Natural Resources and SEWRPC

In 2001 and 2002, aquatic plant *reconnaissance* surveys were also conducted in which only a smaller subset of the original 24 transects were used; these reconnaissance surveys were intended only to provide abbreviated follow-ups to the comprehensive 2000 survey. To avoid confusion, and because these data were not collected as part of a comprehensive survey, the resultant data and a map of these transect lines was not included in this report.

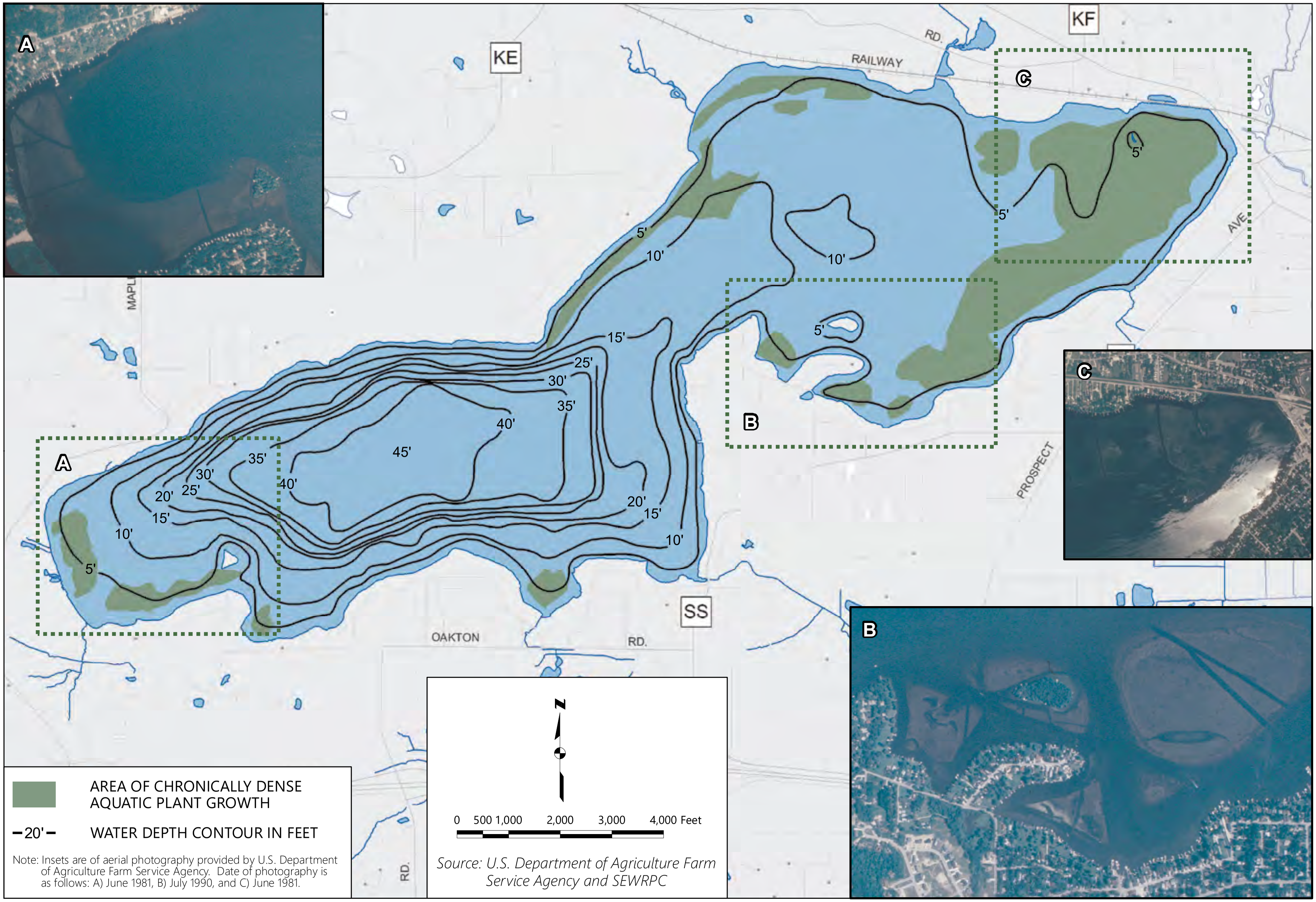
Transect methodology was continued by Wisconsin Lutheran College during aquatic plant surveys conducted by the college from 2000 through 2014 (see Table 2.24 for results). Map 2.26 shows approximate locations of the transects used for the 2000 - 2009 Wisconsin Lutheran College surveys, while Map 2.27 shows locations of the transects used during the 2010, 2013, and 2014 surveys; note that both are based on the transect locations and numbering system of the 48-transect map used during the 2000 Commission survey. The 2011 and 2016 survey data shown in Table 2.25 were the result of surveys conducted using point-intercept methodology.

Point-Intercept Methodology

In 2010, the WDNR adopted a grid-based point-intercept approach for conducting aquatic plant surveys.[157] In this method, sampling sites are based on predetermined global positioning system (GPS) location points that are arranged in a grid pattern across the entire surface of a lake (see Map 2.28). At each grid point sampling site, a single rake haul is taken and a qualitative assessment of the rake fullness, on a scale of zero

[157] *Wisconsin Department of Natural Resources, Publication No. PUB-SS-1068 2010,* Recommended Baseline Monitoring of Aquatic Plants in Wisconsin: Sampling Design, Field and Laboratory Procedures, Data Entry and Analysis, and Applications*, 2010.*

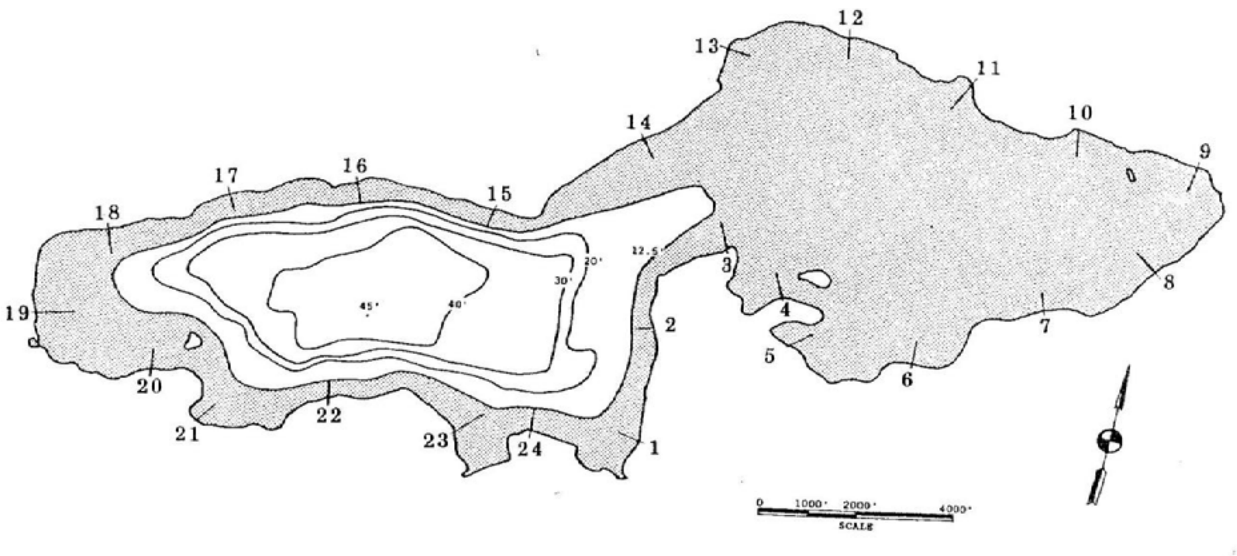
Map 2.24
Extent of Chronically Dense Plant Growth, Pewaukee Lake: 1972-2006



Note: Insets are of aerial photography provided by U.S. Department of Agriculture Farm Service Agency. Date of photography is as follows: A) June 1981, B) July 1990, and C) June 1981.

Source: U.S. Department of Agriculture Farm Service Agency and SEWRPC

Figure 2.65
Wisconsin Department of Natural Resources Aquatic Plant Transects on Pewaukee Lake: 1988, 1991, 1994, and1997



Source: Wisconsin Department of Natural Resources and SEWRPC

to three, is made for each species identified. The 2011 and 2016 Wisconsin Lutheran college aquatic plant surveys of Pewaukee Lake were conducted using the grid-based point-intercept method.

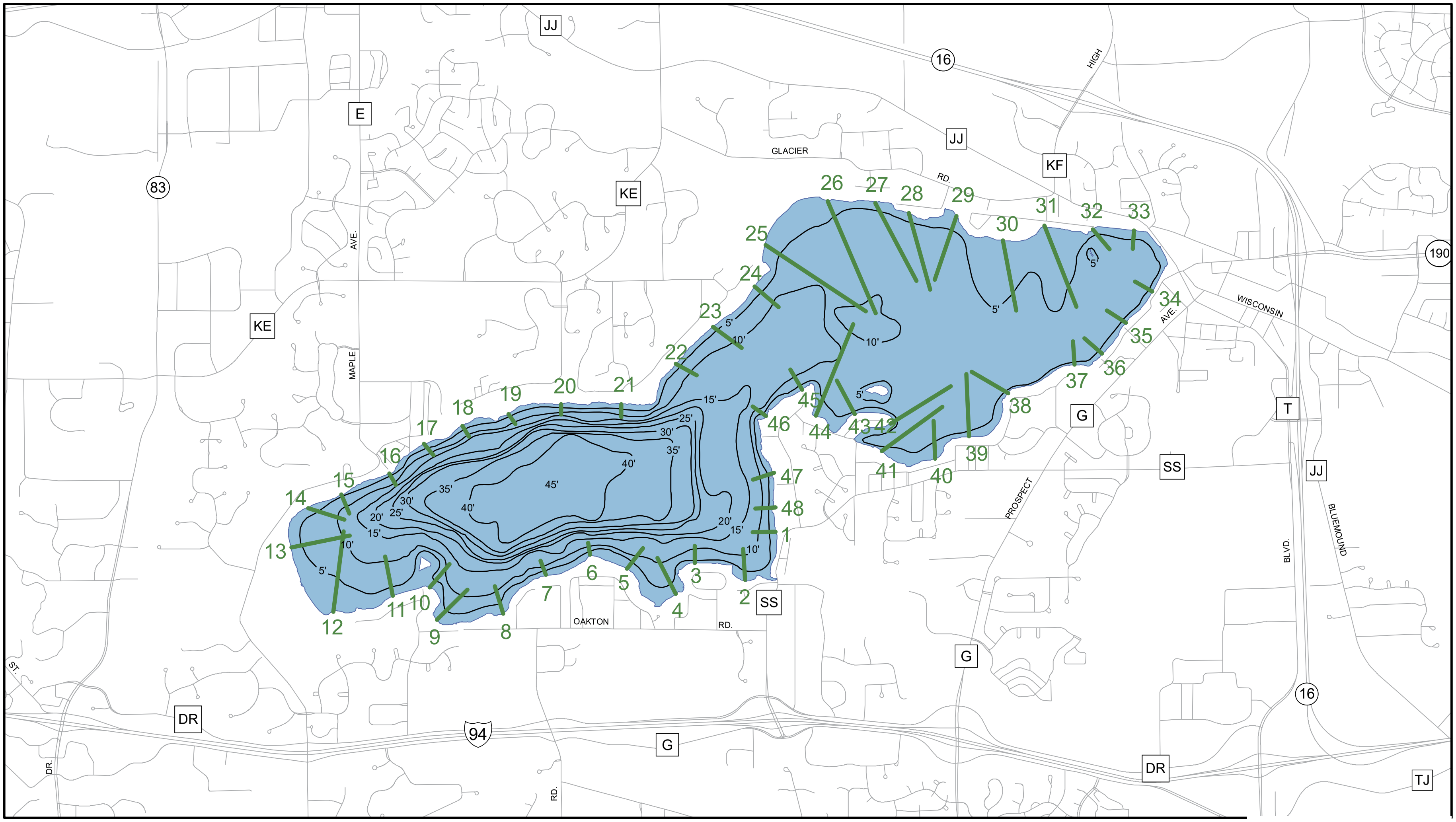
1967-2016 Transect Surveys

Table 2.22 presents a comparison of the macrophyte communities surveyed during 1976 with those noted to have been present within the Lake during 1967 based on 15 different sampling areas in the Lake. As described above, rather than use objective quantitative data to indicate the abundance of the various plant species observed, narrative descriptors were used. Notwithstanding, it is clear that the dominant plant species in Pewaukee Lake at the time of both the 1967 and 1976 plant surveys was EWM. Indeed, this plant was the dominant species in every area of the Lake during both the 1967 and 1976 surveys. So dominant was EWM that in nearly every area observed during the 1967 survey, it was described as either "abundant" or "very abundant." Every other plant species was assessed as either "sparse" or "very sparse" by comparison. This pattern of dominance was mostly the same during the 1976 survey as well. Other macrophytes observed during both the 1967 and 1976 surveys (albeit in small numbers compared to EWM) included: muskgrass (*Chara vulgaris*), waterweed (*Elodea canadensis*), CLP, and Sago pondweed.

Aquatic plant surveys conducted by the WDNR from 1988 through 1997 and by Commission staff in 2000 are summarized in Table 2.23 and illustrated in Figure 2.66. Throughout this period, the relative densities of EWM and CLP appeared to be steadily declining. With this decline, some native species, particularly waterweed, watermilfoil (*Myriophyllum* sp.), water celery or eelgrass (*Vallisneria americana*), and flat-stemmed pondweed (*Potamogeton zosteriformis*), increased in abundance with decreased competitive pressure from EWM. However, other native species did not indicate a clear trend, fluctuating in abundance between years.

In 2000, it was observed that Pewaukee Lake was experiencing the greatest level of aquatic plant growth since 1990. Indeed, the amount of plant material harvested by the LPSD during 2000 was surpassed only one time during the previous 15 years. Aquatic plant surveys were conducted by Commission staff, in association with staff from the LPSD, during July to August 2000 and in August 2001. During these surveys, plant growth occurred throughout most of the Lake where the water depth was less than 15 feet. Seventeen species of submergent aquatic plants were identified. EWM and CLP continued to be present in the Lake, while EWM, coontail, wild celery (*Vallisneria americana*), and muskgrass (*Chara* spp.) appeared to be the dominant species. At the same time, healthy populations of pondweeds (*Potamogeton* spp.) appeared to be scattered throughout the Lake. They were most commonly found at depths of between five and 10 feet.

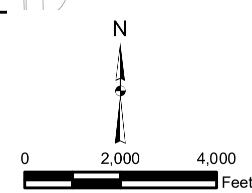
Map 2.25
Pewaukee Lake Aquatic Plant Survey Transect Locations: SEWRPC 2000



12 — TRANSECT SURVEY LINE AND IDENTIFICATION NUMBER

— 20' — WATER DEPTH CONTOUR IN FEET

NOTE: A subset of these transects was used for the 2001 and 2002 reconnaissance surveys conducted by SEWRPC staff.



Source: SEWRPC

Table 2.24
Frequency of Occurrence for Aquatic Plant Species in Pewaukee Lake: 2000-2016

Aquatic Plant Species	2000	2002	2004	2006	2007	2008	2009	2010	2011	2013	2014	2016
Ceratophyllum demersum (coontail)	49.4	54.2	17.4	13.7	7.8	13.7	21.7	63.0	29.3	71.4	8.2	24.5
Chara sp. (muskgrasses)	--	--	--	--	--	--	--	--	--	--	--	28.3
Chara vulgaris (muskgrass)	23.5	22.9	4.3	21.6	9.8	11.8	13.0	39.0	10.1	6.1	3.8	0.0
Elodea canadensis (waterweed)	13.3	18.8	1.9	2.0	--	2.0	10.9	54.0	8.4	--	0.9	7.2
Heteranthera dubia (water stargrass)	14.5	12.5	5.6	--	--	--	--	48.0	0.0	26.5	0.9	18.5
Myriophyllum heterophyllum (various-leaved watermilfoil)	--	--	--	--	--	--	--	--	--	--	--	2.3
Myriophyllum sibiricum (northern water milfoil)	--	--	--	--	--	--	--	--	--	--	--	15.7
Myriophyllum sp. (native watermilfoil)	0.6	--	--	21.6	19.6	3.9	--	74.0	13.5	79.6	34.6	--
Myriophyllum spicatum (Eurasian watermilfoil)[a]	82.5	91.7	53.4	80.4	84.3	78.4	73.9	85.0	78.1	75.5	28.3	60.4
Najas flexilis (slender naiad)	43.4	50.0	4.3	9.8	--	3.9	23.9	7.0	8.1	--	0.9	--
Najas guadalupensis (southern naiad)	--	--	--	--	--	--	--	--	--	--	--	3.9
Najas marina (spiny naiad)[a]	--	--	--	--	--	--	--	4.0	--	--	--	--
Nitella flexilis (nitella)	--	--	--	--	--	--	--	2.0	--	--	--	--
Nymphaea odorata (White water lily)	--	--	--	--	--	--	--	0.0	--	--	--	0.4
Potamogeton amplifolius (large-leaf pondweed)[b]	4.8	8.3	1.9	7.8	13.7	17.6	17.4	9.0	2.7	--	0.2	3.0
Potamogeton crispus (curly-leaf pondweed)[a]	2.4	6.3	1.9	5.9	2.0	2.0	6.5	46.0	10.9	10.2	0.3	22.5
Potamogeton diversifolius (water-thread pondweed)	--	--	--	--	--	--	--	7.0	--	--	--	--
Potamogeton foliosus leafy pondweed)	--	--	--	--	--	--	--	--	1.3	--	--	--
Potamogeton friesii (Fries' pondweed)	--	--	--	--	--	--	--	2.0	--	--	--	--
Potamogeton gramineus (variable-leaf pondweed)[b]	--	--	6.2	--	--	--	--	7.0	0.4	2.0	--	--
Potamogeton hillii (Hill's pondweed)	--	--	--	--	--	--	--	2.0	--	--	--	--
Potamogeton illinoensis (Illinois pondweed)[b]	--	--	--	2.0	--	7.8	--	9.0	--	12.2	--	0.7
Potamogeton natans (floating-leaf pondweed)	--	--	--	--	--	--	--	2.0	--	2.0	--	0.5
Potamogeton nodosus (long-leaf pondweed)	--	--	--	--	--	--	--	2.0	--	--	--	0.2
Potamogeton praelongus (white-stem pondweed)[b]	3.0	--	--	--	2.0	2.0	--	--	1.8	--	1.3	7.0
Potamogeton pusillus (small pondweed)	--	--	--	--	--	--	--	2.0	5.8	2.0	0.4	1.4
Potamogeton richardsonii (clasping-leaf pondweed)[b]	0.6	2.1	--	--	--	--	--	--	4.1	--	--	5.1
Potamogeton robbinsii (Robbin's pondweed)	--	--	--	--	--	--	--	--	0.2	4.1	--	1.9
Potamogeton zosteriformis (flat-stemmed pondweed)	9.0	16.7	2.5	3.9	11.8	9.8	13.0	30.0	7.9	2.0	3.7	38.7
Potamogeton sp. (pondweed)	--	--	--	--	--	--	--	--	--	--	--	--
Ranunculus longirostris (stiff water crowfoot)	--	--	--	--	--	--	--	--	--	--	--	1.8
Stuckenia pectinata (Sago pondweed)[b]	20.5	22.9	15.5	13.7	5.9	7.8	19.6	7.0	1.9	22.4	2.4	44.0
Utricularia sp. (bladderwort)	1.2	--	--	--	--	--	--	9.0	0.5	--	--	--
Utricularia vulgaris (common bladderwort)	--	--	--	--	--	--	--	--	--	--	--	0.7
Vallisneria americana (water celery)[b]	25.9	33.3	--	13.7	15.7	13.7	19.6	33.0	6.8	48.9	12.7	21.0
Wolffia borealis (northern watermeal)	--	--	--	--	--	--	--	--	--	--	--	0.5
Zannichellia palustris (horned pondweed)	--	--	8.1	--	--	--	--	--	--	--	--	--

Table continued on next page.