Monitoring to Evaluate the Restoration of Devil's Lake via Hypolimnetic Withdrawal

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Introduction

Devil's Lake – the centerpiece to Wisconsin's most popular state park – has been intensively studied since 1986 in response to park staff concerns that water clarity had noticeably declined (especially in late summer) concomitant with the increasing development of blue-green algal blooms in a lake renowned for its exceptional clarity. As part of an initial 2-year fact finding study by the DNR Bureau of Research to address these and other water management issues, an extensive lake water quality monitoring and research program was initiated under the continued direction of DNR limnologist Richard Lathrop. Due to budgetary cutbacks, Lathrop has personally conducted the monitoring with volunteer help (including high school students in many summers) since 2003; after retiring in late 2010, he has done the sampling as a part-time LTE supported by DNR lake section monies requiring annual approvals.

One of the principle findings of the studies was that internal loading/recycling of phosphorus (P) from very high concentrations of legacy P in the deep-water sediments was causing the lake's water quality problems. While Devil's Lake is an inherently infertile seepage lake with a relatively small undeveloped watershed located in a quartzite outcropping, historical sources of P pollution to the lake were significant. These sources were: (1) septic leachate and "gray water" from as many as 4 resorts and later over 60 cottages that were once around the lake in various periods from the late 1800's through the 1960's, (2) wastewater from a sanitary sewer pipe connecting the park's south and north shore facilities after the pipe broke sometime in the 1970s until it was fixed in 1982, and (3) runoff from farm fields on the southwest bluff prior to the park's purchase and eventual conversion of the land to prairie during the 1980s. Even though these sources of pollution no longer enter Devil's Lake, internal P recycling has maintained high lake fertility because the lake has no outlet for dilutional flushing.

This P recycling is linked to the classic "ferrous wheel" process where a large mass of legacy P is bound to insoluble hydrous iron (Fe^{+3}) oxides in the upper few centimeters of the deep-water sediments during periods when the overlying water is oxygenated. Later in the summer stratification period when the bottom water becomes anoxic, the Fe is reduced to Fe^{+2}, which causes the Fe compounds to dissolve with the concomitant release and build-up of dissolved P (and Fe) in the hypolimnion. P and Fe concentrations continue to increase in the deeper water depths as the lake undergoes destratification in late summer and early fall, with entrained P from the upper hypolimnetic waters stimulating algae growth in surface waters. At the time of complete lake mixis (fall turnover) beginning around mid-October, the entire water column is oxygenated causing Fe to reoxidize and form small insoluble Fe compounds. These compounds scavenge (via co-precipitation or adsorption) a significant portion of the P from the water column as the flocculating particles settle back to the sediments – a process that is completed when water currents become quiescent after the lake freezes over.

Other water management problems in Devil's Lake were also linked to the lake's high fertility. One study determined that high mercury (Hg) concentrations in the lake's walleye resulted from the bioaccumulation of large amounts of methyl-Hg produced by sulfate-reducing bacteria in the anoxic hypolimnion, with the extent and duration of hypolimnetic anoxia dictated by the lake's productivity. The large decline of sulfate concentrations in the anoxic hypolimnion observed over many study years confirmed that bacterial sulfate reduction was extensive with the bacteria consuming organic matter produced in the lake. (A UW-Madison microbiology graduate student recently found very high concentrations of purple sulfur bacteria in the anoxic hypolimnion of Devil's Lake.) Another study showed the vexing summer outbreaks of swimmer's itch in the lake were due to the presence of extremely dense populations of parasite-host snails that feed on periphyton algae; sampling confirmed periphyton growth rates were high in the lake.

Lake restoration by hypolimnetic withdrawal

Hypolimnetic withdrawal was proposed and extensively evaluated as the lake restoration technique to reduce the high rates of internal P loading causing the water quality and management problems in Devil's Lake. This technique was deemed the most appropriate given: (1) major external P inputs to the lake had been eliminated, (2) the technique's cost was relatively inexpensive especially with the pipe system being a siphon with no annual maintenance or energy costs to run a pump, and (3) public aversion to adding P-binding chemicals (aluminum compounds) to an "Outstanding Resource Water" lake.

Following many meetings to garner agency and public acceptance of the proposed lake restoration project, permits were obtained and funding was procured that ultimately led to the installation of the hypolimnetic withdrawal siphon system in the summer of 2002. Since that year, the withdrawal system has been operated by Lathrop in 13 out of the past 16 years (through 2017) during late summer/early fall when bottom water P reaches its highest concentrations. Late summer withdrawals were not conducted in 3 years when lake levels were low. During the periods of pipe operation, frequent sampling of the withdrawn water was conducted to determine the mass of P removed. Regular sampling of Fe and occasional sampling of Hg (both methyl and total) was also done along with additional monitoring required for the discharge permit.

In addition to the withdrawals removing legacy P from the lake, the pipe has been operated other months (mostly spring and early summer) in 9 years during 2002-2017 to alleviate/prevent flooding problems in the park.[1] During periods of withdrawals for flood control, much less P was removed as P concentrations are typically low in the lake's bottom waters prior to the onset of hypolimnetic anoxia around early July, or after lake turnover in fall.

While a large amount of P has been removed from the lake to date, the massive amounts of legacy P contained in the lake's deep-water sediments will require running the pipe for many years (even decades) as a hypolimnetic withdrawal system until certain water quality targets are

[1] This function was greatly enhanced after the pipe was retrenched deeper on land in October 2009 so that the siphon pipe could be efficiently self-primed and degassed with lake water filling the pipe by gravity feed. Now the pipe system can be operated with little maintenance other than occasional degassing. Previously, filling or degassing the pipe was done using a liquid ring vacuum pump that could not be operated when the park's water system was shut down from early October to mid-April.

met, or conditions occur (discussed later). Devil's Lake is showing signs of improving – blue-green algal blooms in late summer are no longer prevalent, and snail densities have visibly crashed concomitant with a reduction in the incidence of swimmer itch. However, changes in other limnological indicators are more subtle and will require extended monitoring to detect improving trends in water quality. The proposed monitoring program described in the following sections, while streamlined from earlier monitoring, is designed to detect these changes.

Lake monitoring description

Lake monitoring has continued in order to evaluate the effectiveness of the hypolimnetic withdrawals to reduce the lake's water quality problems and to return the lake to its historically infertile trophic status. This monitoring has been done in the deeper regions of the lake in years prior to the hypolimnetic withdrawal pipe being installed in summer 2002. However, the lake's true "deep hole" was first determined the previous winter by extensive soundings and then located by GPS. Using GPS as a guide, sampling has been conducted in subsequent years at this deep-hole location (Latitude 43.41552; Longitude -89.73143) where the pipe intake was positioned. Because lake depths change gradually throughout the middle of the lake, it is likely many earlier samplings were conducted somewhat to the north of the true deep-hole location.[2]

Each sampling entailed not only collecting vertical profiles of temperature and dissolved oxygen data along with traditional trophic state indicator data (i.e., Secchi disc readings; epilimnetic P and Chlorophyll-a concentrations) throughout the open water season, but also extensive sampling of the lake's hypolimnion on multiple dates from summer through early fall. Sampling was generally conducted biweekly from April through early November during 1986-2002; sampling was reduced to about 12 dates during 2003-2016. Beginning in 2017, eight samplings were conducted in response to budgetary cutbacks; aside from spring and fall turnover samplings, sampling was conducted approximately every three weeks during summer through early fall when hypolimnetic P processes change the most.

The hypolimnetic sampling entailed collecting water samples for "bottom-up" profiles of P, Fe, and sulfate concentrations needed to detect changes in the lake's internal P loading/recycling rates, Fe scavenging potential of P, and sulfate reduction rates, respectively. Because of widely fluctuating water levels in Devil's Lake, hypolimnetic sampling has been conducted at standardized depths from the bottom up since 1986. Depths sampled included 0.5 m, 1.0 m, 2.0 m, and so on upwards through the anoxic zone (<1.0 mg/L dissolved oxygen determined from vertical profile measurements) plus the next whole meter above that zone. Thus, hypolimnetic sampling during the period of greatest anoxia in late summer usually was done at discrete depths 5-6 meters above the bottom. Prior to 2011, hypolimnetic sampling was conducted using a peristaltic pump; a Van Dorn sampler has been used subsequently.

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[2] This could potentially introduce a bias in the historical hypolimnetic chemistry data analyses as three different transect profile samplings of redox-sensitive solutes during periods of hypolimnetic anoxia had lateral concentration gradients in the near-bottom waters extending away from the deep hole. To indicate a possible bias, data on daily lake levels and each sampling date's maximum recorded water depth can be used to estimate how far away from the deep hole each sampling was conducted.

Other monitoring has also been conducted to evaluate lake responses to the withdrawals. Extensive sampling of the profundal sediments to detect changes in P (and other elements including Fe) has been conducted in many years (1993, 1995, 2002, 2007, 2012, and 2016) before and after the withdrawals commenced. Total Hg concentrations in mimic shiners (a common short-lived forage fish in Devil's Lake) collected by beach seining along the north shoreline were tested in most years during May of 1994-2014 as indicators of Hg bioaccumulation rates. Periphyton Chl-a and biomass sampling was also conducted during June 1999-2016 using Wildco® Periphyton Sampler traps (holding 8 microscope slides) suspended for 14 days in about 1-meter water depths below the surface at two western near-shore locations (NW: 43.4220, -89.7354; SW: 43.4182, -89.7361). Both the fish and periphyton monitoring were discontinued in recent years due to time and budget constraints; the periphyton traps also had occasional disturbance/vandalism problems probably from boat anglers as the sampling locations were fairly inaccessible from shore. The sediment, fish and periphyton monitoring can be conducted in future years if desired to compare with historical data.

Finally, because of the extensive open water vertical profile sampling of water temperatures in Devil's Lake, the temperature data have been used as part of a larger project to evaluate changes in epilimnetic temperatures in a suite of lakes in southern and northern Wisconsin, northeast Germany, and Finland. Water temperature data for Devil's Lake can help detect changes in suitable habitat for trout that have been regularly stocked in the lake. However, detecting water temperature trends for different seasons in future years may be compromised (especially for spring warming trends) with the cutback from 12 to 8 open-water samplings.

Lake monitoring schedule and objectives

The following schedule summarizes arguably the most important eight (8) lake water sampling periods and the main objectives for monitoring during those periods in Devil's Lake each year:

1. Last half of April. This sampling, which is consistent with the DNR's Long-term Trend Lake (LTT) monitoring, is important for determining trends in spring turnover P concentrations as a long-term trophic state indicator.

2. Mid-June. This sampling is important for determining the start of hypolimnetic anoxia and for calculating hypolimnetic trends in rates of sediment P and Fe release as well as rates of sulfate reduction and dissolved oxygen depletion throughout each year's stratified period. The sampling is also used to determine trends in water clarity during the early summer stratification period.

3. Early July. This sampling is a continuation of #2 objectives pertaining to hypolimnetic rates of sediment P and Fe release and sulfate reduction and dissolved oxygen depletion. The sampling is used to determine water clarity conditions, and TP and Chlorophyll-*a* concentrations as long-term summer trophic state indicators.

4. Late July/early August. This sampling is a continuation of #3 objectives and is consistent with LTT's summer monitoring schedule.

5. Late August. This sampling is a continuation of #4 objectives. The sampling also indicates the presence of suitable habitat for stocked trout in the upper hypolimnion and thermocline at a time when temperature/oxygen stress is most likely to occur in Devil's Lake being managed for both warm and cold water fisheries.

6. Mid-September. This sampling is needed to determine the lake's maximum hypolimnetic P and Fe masses, and sulfate reduction loss, as well as to calculate seasonal P and Fe release rates and sulfate reduction rates. The sampling is also needed to determine Fe:P molar ratios indicating whether the lake's Fe scavenging potential for P is being maintained in response to the withdrawals. The sampling is also important for detecting trends in water clarity during the period of historically lowest seasonal Secchi readings in the lake.

7. Late September/Early October. This sampling is used to indicate long-term trends in maximum P and Fe concentrations in the deepest bottom waters prior to fall turnover.

8. Early November. This sampling is important for determining trends in early fall turnover P concentrations as a long-term indicator of the P status of the lake. The sampling is also needed to calculate the sulfate mass lost from sulfate reduction processes in the anoxic hypolimnion. The sulfate lake mass at turnover can then be compared to the whole-lake mass calculated from vertical-profile sulfate concentration data obtained in mid- to late September. The difference in sulfate masses can also be used as a conservative tracer to indicate the magnitude of lateral concentration gradients of P and Fe in the hypolimnion.

Summary

The eight recommended samplings outlined in this report cover the seasonal periods deemed most useful for evaluating if and when the sustained hypolimnetic withdrawals of P-rich water have returned Devil's Lake to its inherently infertile trophic state as indicated by various indices. Other than spring and fall turnover samplings, the six remaining open-water samplings are scheduled to be done approximately every three weeks beginning around mid-June. These samplings are when water clarity declines and blue-green algal blooms have historically occurred in the lake, and span the period of important processes in the anoxic hypolimnion.

Of particular importance is the continued measurement of Fe:P ratios in the anoxic hypolimnion around mid-September until the time when hypolimnetic withdrawals end. This Fe:P ratio should be maintained appreciably above a molar ratio of 2:1 to indicate that Fe is not being depleted by the withdrawals in amounts that would reduce the important natural mechanism of Fe scavenging of P. Fe deficiencies are not anticipated because the lake has naturally high levels of Fe due to the surrounding bluffs being pink quartzite rich in Fe oxides subject to weathering. However, if the Fe:P ratio and hypolimnetic Fe concentrations start declining due to a loss of Fe reserves in the sediments, then the pipe intake should be moved to shallower water depths where the pipe system would be used in perpetuity solely as a lake outlet to prevent flooding in the park. This intake location has advantages for flood control as flow rates would increase due to less frictional losses in the long submerged pipe. The degassing of hypolimnetic water in the pipe would also be eliminated. Once water quality objectives for the lake are obtained, moving the intake (or cutting holes in the pipe in shallow water) should be considered.