Walden Pond, Massachusetts: Environmental Setting and Current Investigations

Walden Pond, in Concord, Massachusetts, is famous among lakes because of its unique social history. Walden was the setting for American naturalist Henry David Thoreau's well-known essay "Walden; or, Life in the Woods," first published in 1854. Thoreau lived and wrote at Walden Pond from July 1845 to September 1847. In "Walden," Thoreau combined highly admired writing on Transcendental philosophy with pioneering observations of aquatic ecology and physical aspects of limnology, the study of lakes. Because Thoreau also defended so effectively the value of living close to nature in the Walden woods, the pond is considered by many to be the birthplace of the American conservation movement. Visitors come from all over the world to the pond, which has been designated a National Historic Landmark, and its fame has resulted in a major fund drive to preserve the surrounding woods.

Walden Pond has no surface-water inflow or outflow, and much of its ground-water contributing area likely is preserved within the Walden Pond Reservation area (fig. 1). Only 15 miles from Boston, the pond is unusually clear and pristine for an urban-area lake. However, point sources of nutrients near the pond, and a large annual visitor attendance, concentrated during the summer when the swimming beach (fig. 2) is open, may contribute a nutrient load sufficient to change the pond environment. The occurrence of nuisance algal species, a recent beach closing, and an awareness of water-quality problems suffered by other ponds in the region raise concerns about the risk of ecological change at Walden Pond.

Despite the role of Walden Pond as a cultural and environmental icon, little is known about the pond's ecological features, such as its internal nutrient cycling or the structure of its food web, nor have consistent measurements been made to determine whether these features are changing or are stable. Production rates of aquatic plants in lakes and ponds naturally undergo a slow increase as plant nutrients, organic matter, and soil

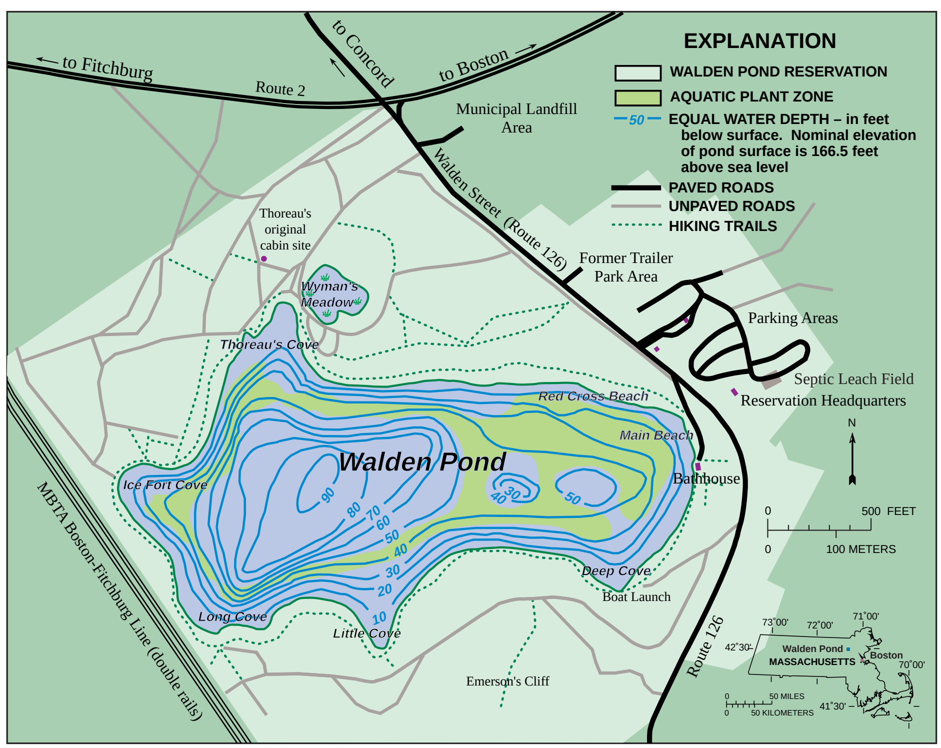

Figure 1. Walden Pond Reservation Map composed from Massachusetts Department of Environmental Management and U.S. Geological Survey sources.

Figure 2. Main swimming beach and bathhouse at the east end of Walden Pond.

are leached and eroded from the surrounding watershed. This process is known as eutrophication. The term "cultural eutrophication" refers to an accelerated form of the natural process in which extra soil and nutrients are derived from people's use of fertilizer, rerouting of surface drainage, and disposal of domestic and industrial waste. Cultural eutrophication can lead to excessive growth of aquatic plants, pond filling by decayed plants and eroded soils, reduced water clarity, and depletion of dissolved oxygen in deep water with subsequent loss of cold-water fish habitat.

In order to document the long-term ecological health of Walden Pond, the U.S. Geological Survey (USGS), working in cooperation with the Massachusetts Department of Environmental Management (MDEM), is investigating factors that could contribute to cultural eutrophication of Walden. Through measurements of mass balance of nutrients and oxygen in the pond's deep water, the investigation will establish a baseline data set on Walden's trophic state, which is a measure of the pond's ability to support plant growth. The baseline data will be used to detect trends and give early warning of trophic changes or trophic response to pond remediation projects.

This Fact Sheet provides background information on the environmental setting, limnological features, and cultural eutrophication of Walden Pond, and describes the joint USGS/MDEM study.

Environmental Setting and Limnological Features of Walden Pond

In geological terms, Walden Pond is known as a kettle lake. It was formed at the end of the last Ice Age, some 10,000 to 12,000 years ago, when a huge block of glacial ice broke off and remained behind as the glacier retreated to the north. Meltwater streams from the main glacier carried sand and gravel and deposited this coarse-grained material around the base of the ice block. When the ice block finally melted, perhaps over a period of 100-200 years, the result was a steep-sided basin, or "kettle hole," formed in the highly porous glacial outwash. The irregular shape of the pond, with its steep sides, coves along its margins, and two deep areas (fig. 1), reflects the shape of the original ice block. The maximum depth of present-day Walden Pond is 100 feet, virtually unchanged from the first accurate sounding by Thoreau 150 years ago. The pond can be described as a seepage lake, meaning that it has no surface inflows or outflows. Rather, it receives its water from direct precipitation and the inflow of ground water. Today, the pond's ground-water contributing area, in the towns of Concord and Lincoln, is largely protected. Indeed, in Thoreau's time it was one of the few wooded areas in a heavily farmed region.

As first measured and discussed by Thoreau, Walden Pond (and other temperate-zone lakes) undergoes alternating periods of thermal stratification and mixing during the year. This pattern influences many chemical and biological processes that occur in lakes (Cole, 1983). During summer, the upper water becomes warmer and slightly less dense than the deeper water. As a result, only the water in the warm top layer (the epilimnion, fig. 3) circulates in contact with the atmosphere, whereas greater density keeps the deep, colder layer of water (the hypolimnion) away from the surface. Between the two layers is a zone in which

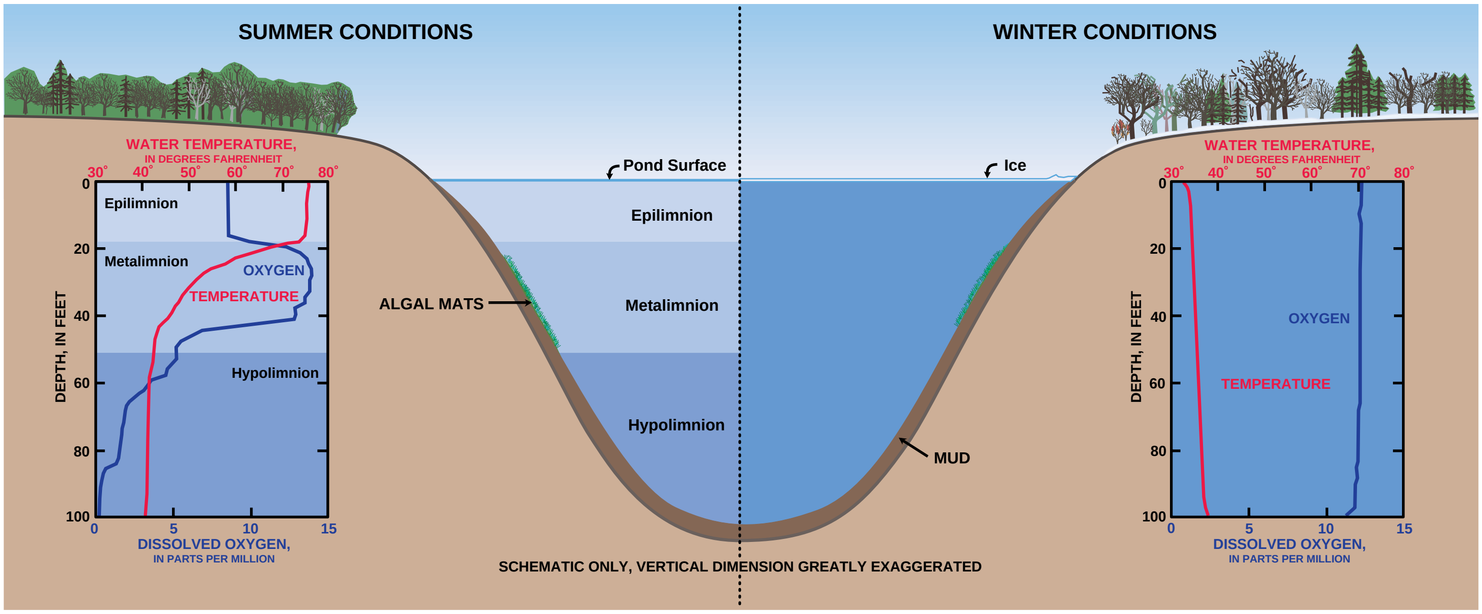

Figure 3. Temperature and oxygen changes through the year in temperate deep lakes and ponds, modified from Odum, (1971). Summer profiles are from Walden Pond, July 22, 1996; winter profiles are typical of lakes under ice cover.

water temperature decreases rapidly with depth (the metalimnion), which is a barrier to mixing. Dissolved oxygen, which is essential to many forms of aquatic life, usually is abundant in the epilimnion, where it is produced during photosynthesis by aquatic plants and exchanges with the atmosphere during wind-driven circulation. The plants, which are the base of the aquatic food web, are grazed by zooplankton (fig. 4) and transported, in part as zooplankton fecal pellets, by settling to deep water. In the absence of light sufficient for photosynthesis, oxygen that was present in the hypolimnion when the lake became thermally stratified is consumed by the respiratory activity of bacteria and other organisms that break down organic matter raining down from the upper layer.

Figure 4. Zooplankton (*Daphnia* on left and calanoid copepod on right) grazing on phytoplankton (star-shaped *Asterionella*, and others) from the epilimnion of Walden Pond. Photomicrographs magnification about 130 X.

With the onset of cool weather in fall, the temperature of the epilimnion drops until it is the same as that of the hypolimnion. At that point, the water is free to mix and cool further, drawing dissolved oxygen in from the surface to achieve a uniform distribution with depth (graph at right in fig. 3). Mixing continues until an ice cover forms, at which time the entire water body can be isolated from the atmosphere. In spring, when the ice melts, a second mixing period occurs prior to surface warming and the return of summer stratification.

Thoreau first recorded the clarity of Walden Pond, describing it and nearby White Pond as “great crystals on the surface of the earth, Lakes of Light” (Thoreau, 1854, p. 448). The extraordinary clarity of the water allows light to penetrate well into the metalimnion. Resulting photosynthesis in the metalimnion generates oxygen that can escape only slowly from the density-stratified water of that zone, causing a distinct metalimnetic bulge in the summer dissolved-oxygen profile (fig. 3). In lakes with less clear water, summer oxygen concentrations decrease with depth. Much of the plant biomass producing oxygen in the metalimnion of Walden Pond may be the bottom-dwelling macroalga *Nitella* (fig. 5). In his "Journal," Thoreau (1852) noted the presence of *Nitella gracilis* at depths below 40 feet in nearby White Pond. The plant is also present at depth in other lakes celebrated for their clarity, such as Crater Lake, Lake George, and Lake Tahoe (Stross and Rottier, 1989). In Walden Pond, *Nitella* grows in a ring in the predominately blue-wavelength light that penetrates to depths of 28 to 40 feet. Not present in less clear ponds, the alga may help preserve water clarity in Walden Pond by keeping oxygen concentrations high over large areas of the littoral sediments, which promotes binding of phosphorus by the sediments.

Figure 5. *Nitella* scraped from the bed sediment with a weed rake.

Cultural Eutrophication: Possible Causes and Consequences for Walden Pond

Many lakes surrounded by developed land receive excess sediments and plant nutrients (1) in runoff from agricultural fields, domestic lawns, and impervious surfaces, (2) by tributary and ground-water inputs of industrial and domestic waste, and (3) from precipitation and dry-fall atmospheric inputs. Although Walden Pond is in a developed area, the absence of surface-water inflow and the pond's largely protected small ground-water contributing area decrease its potential nutrient load.

Most precipitation that falls in the area that contributes ground water to Walden Pond moves through a thick unsaturated zone to the water table and then flows through the sand and gravel of the aquifer to the pond. Along this flow path, particulate nutrients are filtered out by the aquifer materials and much of the dissolved phosphorus, the nutrient that most commonly limits the growth of algae in ponds, is chemically bound to the aquifer materials. Phosphorus from point nutrient sources discharging to ground water, however, can exceed the absorption capacity of the aquifer, leaving a soluble residue that can move with the ground water. Walden receives no domestic or industrial waste directly from surface water, but the Concord landfill, a trailer park, and the septic leach field behind the Reservation headquarters are not far from the pond (fig. 1) and could conceivably contribute nutrients by way of the ground water. Direct atmospheric deposition of nutrients on Walden Pond may be substantial and should be investigated in light of recent findings that dry fall ("dust," not precipitation) can be substantial in urban areas (Caraco and others, 1992; Kortman, 1991). Direct erosion of sediments and soil from the shoreline may cause some filling of the pond, but erosion is unlikely to be an important nutrient source because the sandy soil is probably nutrient poor.

Biological sources of nutrients at Walden include wastes from waterfowl that roost on the pond surface at night, particularly during the spring and fall seasons; stocked fish; and people visiting the pond (swimmers). Nutrients from birds likely are decreasing since fill operations at the Concord Landfill ceased. The swimmer source of nutrients (urine) might be especially important because input takes place during the warm months, when thermal stratification keeps the hypolimnion from being replenished with oxygen from the surface. Walden receives about a half million visitors per year, concentrated during the summer months (fig. 6). The percentage of visitors who swim also increases on the hottest days during the summer. The swimmer source is unique in that it could conceivably be changed by management strategies, for example, through a swimmer education program.

Increased nutrient input to ponds generally stimulates plant growth and consequent oxygen depletion in deep water, but the suite of plant species stimulated and the effect on water clarity in specific cases are difficult to predict. Historical responses to

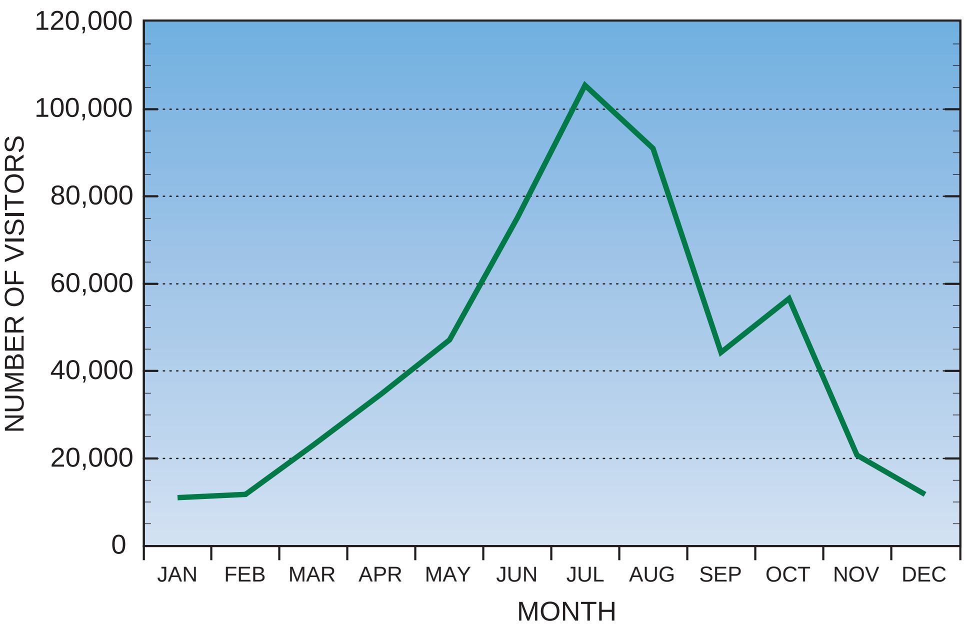

Figure 6. Average monthly visitor attendance at Walden Pond, 1994–1996 (Massachusetts Department of Environmental Management).

changed nutrient inputs can be inferred from comparison of oxygen profiles taken over time. The earliest available depth profile of dissolved oxygen concentrations in Walden Pond (fig. 7) was measured in August 1939 by Deevey (1942), a Yale University limnologist. Similar profiles were measured in 1986 by the MDEM, and in 1996 by the USGS. The average concentration of dissolved oxygen in the hypolimnion was 6.3 ppm (parts per million) in the August 1939 profile. In summer 1986, however, the average hypolimnetic dissolved oxygen concentration, 3.2 ppm, was one half of its 1939 value. The most recent depth profile shows the lowest average concentration of dissolved oxygen at 2.1 ppm. The progressive depletion rate of dissolved oxygen since 1939 is indicative of substantial eutrophication of Walden Pond, probably a consequence of increased loads of plant nutrients, particularly phosphorus. During the same period, oxygen concentrations increased in the metalimnion, probably because of increased growth of algal species such as *Nitella*. Metalimnetic algal production contributes oxygen to the deep water by vertical mixing because the water column is only weakly stratified at the bottom of the metalimnion. If nutrient inputs to Walden Pond continue to increase, the metalimnetic algal (and oxygen) production would at some point begin to decrease because of shading from increased planktonic algae in the surface water. The disappearance of oxygen from the hypolimnion after the decrease in metalimnetic production would be still more rapid because less oxygen would be contributed from the metalimnion.

Present-day nutrient load is one measure of the trophic state of a lake or pond. A recent nutrient budget computed for Walden Pond indicates that 26 kilograms of phosphorus enters the pond annually (Baystate Environmental Consultants, 1995). This phosphorus load, which is difficult to measure directly, puts Walden in a higher trophic category than do more direct indices of trophic state, such as clarity of water and chlorophyll concentration (Baystate Environmental Consultants, 1995). When trophic state is evaluated by a fourth method, loss of oxygen from the hypolimnion (Wetzel and Likens, 1979), Walden stands out as more eutrophic than other deep lakes in Massachusetts. A tentative reconciliation of these trophic indices (other than measurement error) is that Walden's substantial nutrient input causes more growth of deep macroalgae, like *Nitella*, than would occur in most lakes with less clear water. Thus, the measures of lake clarity and chlorophyll, which reflect planktonic algal abundance, are not greatly affected by the nutrient input. The high rate of oxygen depletion in summer in the hypolimnion of Walden Pond may be related to the recreational input of phosphorus. Phosphorus input from swimmers was estimated to be about 25 percent of the annual phosphorus budget (Baystate Environmental Consultants, 1995), but would represent 50 percent of the summer budget. This would explain why Walden's hypolimnetic oxygen depletion rate is higher than that of other Massachusetts lakes with fewer swimming visitors. These possible explanations need to be tested before being used to direct pond management.

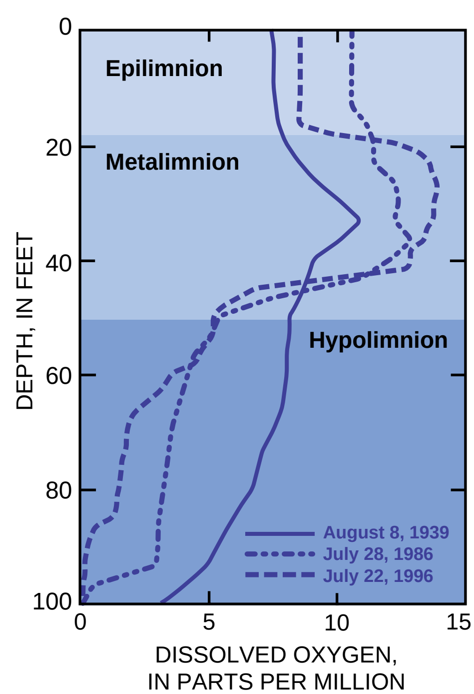

Figure 7. Oxygen profiles in Walden pond, in 1939, (Deevey, 1941), 1986 (Massachusetts Department of Environmental Protection), and 1996 (U.S. Geological Survey).

USGS/MDEM Cooperative Study

The USGS and the MDEM have begun a study of cultural eutrophication in Walden Pond. The study is designed to establish the status of ecological features of the pond: to determine whether it is in a stable or changing tropic state, to determine the dynamics of nutrient cycles in the pond, and to quantify inputs from nutrient sources. Results of the study are expected to guide management decisions for the pond. Also, because of the pond's unusual hydrologic setting—in a developed area but isolated from runoff—the data collected may be useful for assessing the effects of shoreline development, as distinct from other environmental impacts, on other ponds.

Trophic State Monitoring. A principal component of the study is to make consistent measurements of the pond's trophic state by measuring oxygen depletion in the hypolimnion. This method is sensitive for deep lakes like Walden, which have substantial hypolimnetic oxygen reserves at the beginning of the year and thus are not subject to complete oxygen depletion before October, the end of the stratified season. Oxygen and temperature profiles will be determined monthly throughout the year to document how oxygen is generated or used in the pond and replenished or lost to the atmosphere. Particular attention will be paid to the oxygen content of the pond in early spring, which fixes the value for the beginning of the summer budget, and the late summer amount, which determines depletion for the entire season. By combining oxygen and temperature measurements, vertical mixing rates and fluxes of oxygen in the pond can be determined as well as rates of oxygen generation and consumption in specific zones of the pond. This monitoring will enable a clear assessment of the present trophic state of the pond, and if continued, will indicate whether the trophic state is stable, changing, or responding to programs of remediation.

Nutrient Dynamics. The basic limnology of the pond, including determination of the dominant planktonic and benthic algae, the biogeochemical cycling of nutrients, and the chemicals that interact with nutrients, is needed to determine whether Walden Pond might respond differently than other lakes to nutrient inputs. Profiles of the concentrations of silica, nitrogen, iron, manganese, sulfide, and phosphorus will be measured at two deep-hole stations on the pond. Additional water samples will be collected at one deep station and preserved for subsequent phytoplankton identification. Benthic aquatic plants will be assessed by divers, by suspending a video camera from the surface, and by trolling with a weed rake (fig. 5).

Nutrient Sources. Refinements to the estimates made for sources of nutrients from atmospheric deposition, swimmers, and ground water would be especially useful in managing Walden Pond. Swimmers represent a potentially large but controllable source, and ground water might be affected by point sources of nutrients from the nearby Concord landfill, the trailer park, and the septage leach field for the pond bath house. Swimmer input will be determined by measuring the increase of urine constituents in the epilimnion during the swimming season when the pond is stratified. Atmospheric input will be determined from samples obtained from a wetfall-dryfall collector. Nutrient contamination in ground water will be determined by defining exactly the ground-water contributing area for the pond and by sampling water from monitoring wells in background locations and locations that intercept any plumes originating from known point sources.

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For more information:

http://www.tiac.net/users/morganti/walden.htm
http://mass1.er.usgs.gov/proj.htm

U.S. Geological Survey
MA-RI District Office
28 Lord Road, Suite 280
Marlborough, MA 01752
telephone: (508) 490-5058
facsimile: (508) 490-5068

Report by:
John A. Colman and Marcus C. Waldron
Layout and Graphics by:
Mark V. Bonito and Robert F. Breault