The Pond Primeval: Phosphorous and Oxygen in Walden Pond

John M. Nevison
New Leaf Project Management
500 Thoreau Street
Concord, MA 01742 USA
+978.369.9009
jmn@newleafpm.com

Abstract
A 2001 U.S. Geological Survey collected and organized a huge amount of data about the chemistry of Walden Pond between the years 1995-1999 (inclusive). Among the data were details on two elements that play major roles in the limnology of many ponds: phosphorous and oxygen. This report will show how a simple model can tie together the data on input phosphorous and consumed oxygen. When the modern high levels of phosphorous are removed, the model reveals the probable pattern of the Pond's primeval function in earlier times. The surprising finding is that, even in the late autumn of 1846 when Thoreau lived beside it, Walden Pond, at its deepest points, probably ran out of oxygen.

Keywords
Thoreau, Walden, Limnology, Dissolved Oxygen, Phosphorous, Hypolimnotic Oxygen Deficit, (HOD)

Introduction

> The water is so transparent that the bottom can easily
> be discerned at the depth of twenty-five or thirty feet.
> *Henry David Thoreau*

In 2001, the U.S. Geological Survey published a scientific report entitled "Geohydrology and Limnology of Walden Pond, Concord, Massachusetts" by John A. Colman and Paul J. Friesz (C&F). The report collected and organized a huge amount of data about the chemistry of the Pond between the years 1995-1999 (inclusive). Among the data were details on two elements that play major roles in the limnology of many ponds: phosphorous and oxygen.

This report will show how a simple model can tie together the data on input phosphorous and consumed oxygen. When the modern high levels of phosphorous are removed, the model reveals the probable pattern of the Pond's primeval function in earlier times. The surprising finding is that, even in the late autumn of 1846 when Thoreau lived beside it, Walden Pond, at its deepest points, probably ran out of oxygen.

Background data

Walden Pond's waters are thoroughly mixed from December 1 until March 30. As the waters warm during April, the Pond "stratifies" into three distinct layers: the top, the epilimnion, from the surface to a depth of 6 meters; the middle, the metalimnion, from 6 to 13.5 meters; and the bottom, the hypolimnion, from 13.5 meters to the bottom, a little below 30 meters. These stratifications last about 6.5 months, from May 1 until November 15. Each of these warm-weather stratifications, as well as the cold-weather mixed Pond, has its own distinct chemistry, which will be discussed below.

NOTE: Measurements in this article are in meters and in degrees Celsius. An Imperial System reader may substitute the word "yard" for the word "meter."

To build an annual model of the Pond, the first and broadest stretch of time to consider is the 6.5-month duration of the stratified layers. While the exact dates of the Pond's stratification vary a little from year to year, during the 1990s a good first approximation was that the layers were established during the four weeks of April and dissolved during the last two weeks of November.

An idealized annual calendar might look like this:

- December 1−March 31: Mixed period
- April 1−April 30: Transition to stratified layers
- May 1−November 15: Stratified layers
- November 16−November 30: Transition to mixed period

Chemical background

The major chemical reactions of Pond plant life are photosynthesis and respiration. C&F suggest the broad governing equation is:

$$106\ CO_2 + 16\ NO_3 + HPO_4^{2-} + 122\ H_2O + 18\ H^+ + \text{trace elements and energy}$$
$$= (C_{106}H_{263}O_{110}N_{16}P) + 138\ O_2$$

Where the formula going forward defines photosynthesis and going backward defines respiration.

Photosynthesis combines many nutrients with energy from the sun to produce plant life and oxygen. Even though the ratio of nitrogen (N) to phosphorous (P) is 16 to 1, C&F's data shows that in Walden Pond, there is **a surplus of every element but P**. Because P is the scarce resource, it controls the amount of photosynthesis and the amount of plant growth.

Going the other way, plant and animal respiration consumes oxygen and releases some energy and a variety of simple ingredients. The oxygen dissolved in the Pond is referred to as dissolved oxygen (DO). If DO runs out in a stratification of the Pond where it's too dark for photosynthesis, aerobic respiration ceases, plants and animals die, and different, anaerobic reactions begin to occur.

The Pond year

Walden Pond on January 1 is covered with ice. It is dark and cold. The temperature ranges between 0 degrees Celsius (32 degrees Fahrenheit) just below the ice to 4 degrees C (39.2 F) (water at its densest) near the bottom. The water in the Pond is thoroughly mixed and 100% saturated with DO at 12mg/L. The underground aquifer steadily feeds nutrients into the Pond, including .5 kg/month of P.

As the rising temperature melts the ice and the wind stirs the surface of the Pond, the top part of the Pond begins to warm. In March and April phytoplankton photosynthesis uses up any available P dissolved in the water. The patterns of rising temperature divide the Pond into three layers by May 1. The top layer circulates with the air-warmed surface and grows warmer and lighter. The bottom layer holds its steady, cold state. In between, a third layer makes the temperature transition from the seasonally warmed top to the persistently cold bottom. C&F data show that the thermal boundaries at 6 and 13.5 meters seal each layer into a distinct ecological system.

In the light top layer, all monthly nutrients supplied by the aquifer enter the Pond and any new P is captured by photosynthesis in phytoplankton growth. Because cold water dissolves more oxygen than warm water, the 12mg/L level of DO in the epiliminion dips down to 8 mg/L as the summer water temperature heats up and then returns to 12 mg/L as the autumn water temperature cools.

The dimly illuminated mid-level layer recycles the P that was contained in its plants on 1 May and maintains a balance of photosynthesis and respiration that results in a steady high level of 13.5 mg/L of DO in solution. The metalimnion's balance lasts until November 15, when stratification begins to break down.

In the pitch-black bottom layer where no photosynthesis occurs, the hypolimnion's bacterial respiration begins with 12 mg/L of DO (9484 kg) on April 1. That DO must last through April and the entire stratified 6.5 months. In the 1990s, that DO level usually fell to close to 0 mg/L (0 kg) by mid-November.

By November 15, the water temperature near the surface of the Pond has fallen to 4 C (39.2 F). At this temperature water is at its densest and an internal waterfall of 4-degree water begins to cascade to the bottom of the Pond. This internal waterfall mixes the whole Pond. As it does, the disintegrating hypolimnion with its huge DO deficit temporarily lowers the whole Pond's DO to 9 mg/L. As the waters continue to mix, the Pond oxygenates and by the December freeze the Pond's DO is heading back to 12 mg/L.

Mid-summer activity

Within the 6.5-month stratified period, a second interesting period to consider is the three-month, mid-summer activity of June, July, and August. During these three months the Pond entertains most of its swimmers, as well as many boaters and fishermen. C&F collected distinct data on nutrients input to the Pond for these three months, in addition to data for the entire year.

Figure 1 shows the various sources of the nutrient P. *Background ground water* is P from the inflowing year-round underground aquifer. *Atmospheric wet* is P dissolved in precipitation. *Atmospheric dry* is P in dust and pollen that falls into the Pond.

Figure 1. *Data on Walden Pond's Phosphorous Sources (derived from C&F)*

	Phosphorous kg/mth		
	Win-Spr 1-5	**Summer 6-8**	**Fall 9-12**
Background ground water	0.5	0.5	0.5
Atmospheric wet	0.1	0.1	0.1
Atmospheric dry	1.2	1.3	1.2
Swimmers	0.0	2.9	0.0
Waterfowl	0.0	0.2	0.0
Fish stocking	0.0	0.2	0.0
Direct runoff	0.0	0.3	0.0
Total	1.8	5.4	1.8

In the mid-summer, the amount of P gets a boost from *waterfowl, fish stocking, direct runoff,* and *swimmers*. The *waterfowl* are mostly ducks and geese that sleep on the pond at night. Walden is stocked with *trout* every year. A small amount of *direct runoff* from rain on the roads gets washed directly into the Pond. Finally, *swimmers* urinate in the Pond.
Over the course of one year, P enters the Pond each month at a steady rate of 1.8 kg/month, jumps up to 5.4 kg/month for June, July and August, then drops back down in September to 1.8 kg/month for the rest of the year. How does this mid-summer jump in P affect the Pond?

The P enters the Pond's epilimnion and causes a photosynthetic bloom of short-lived phytoplankton. These phytoplankton die and their dead forms fall down through the metalimnion and land on the sediment and the hungry bacteria at the bottom of the hypolimnion. The dead phytoplankton are digested by respiring bacteria (using DO) in the sediment. Phosphorous binds with iron (Fe) in the sediment.

So an increase of P in the epiliminion causes a proportional increase of the DO consumed by the bacteria in the hypolimnion. Figure 2 shows that, in the 1990s, this accelerated increase in DO consumption pointed towards the DO running out just as the stratified period ended in November. Figure 2 is a reproduction of C&F Figure 23.

Model notes
The simple model of this process begins in Figure 3 with a *Strat Factor* to turn on and off the stratification of the Pond by going from 0 to 1 in the month of April and from 1 to 0 in the last two weeks of November. Next, the *KgPhosPerMth* variable traces the mid-summer jump of the phosphorous source.

Figure 2. *C&F Figure 23. Dissolved Oxygen at Walden Pond*

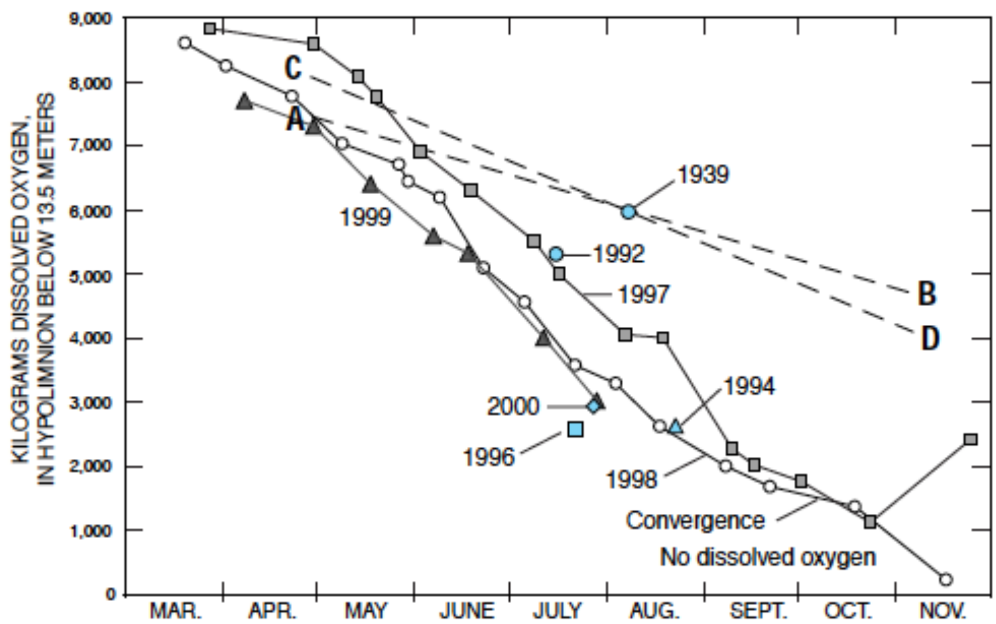


Figure 23. Dissolved oxygen content of the hypolimnion of Walden Pond, Concord, Massachusetts, during summers of 1997, 1998, and 1999 (lines); dissolved oxygen content from single profiles in 1939, 1992, 1994, 1996, and 2000 (blue symbols); and lines projecting dissolved oxygen content for summer of 1939 (A-B and C-D).

Figure 3. *Stratification Period and Mid-Summer Phosphorous Source*

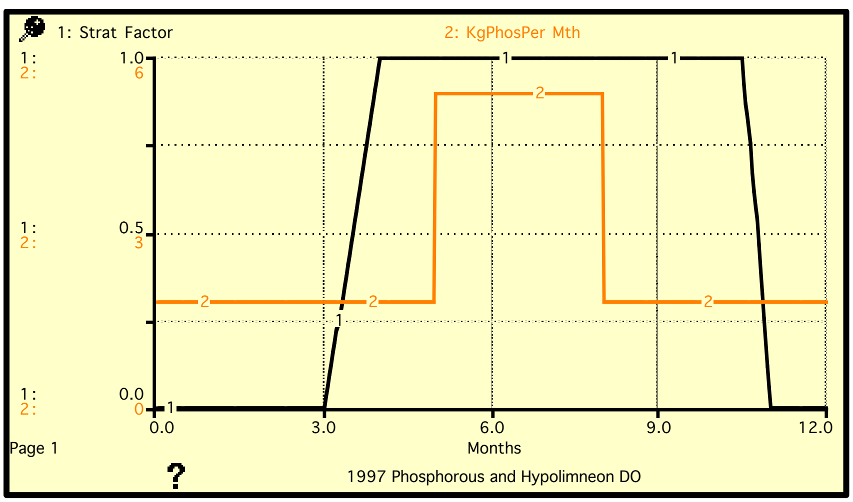


Figure 4. *Mid-Summer Phosphorous Input, DO Use and DO Decline*

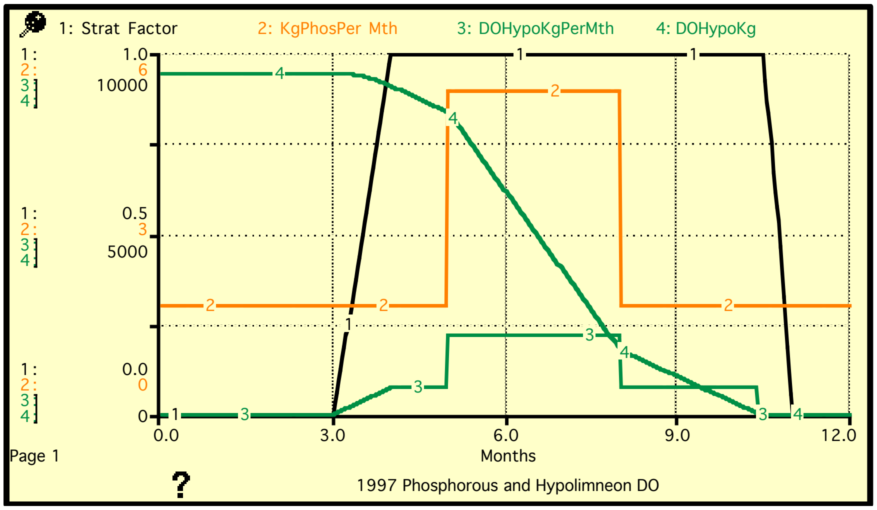


Figure 4 shows how *DOHypoKgPerMth*, the hypolimnion DO consumption rate, follows *KgPhosPerMth*, the epilimnion's phosphorous supply rate, with a proportionate mid-summer jump.

For an initial level for DO as the hypolimnion begins to form on April 1, the C&F data in Figure 2 suggest a value near 9000 kg. Other information in C&F suggests the theoretical initial value of 9484 kg that the model uses:

12 mg/L of DO x 790,329,000 L of the hypolimnion x 1 kg/1,000,000 mg = 9484 kg of DO.

Beginning with the 9484 initial value for the total DO, model experimentation found that a basic monthly depletion rate of 735 kg/mth would shrink the DO to 0 kg in mid-November.

The monthly depletion rate rose through the April stratification, was constant in May, jumped up to a high level for June, July, and August, dropped back down to its constant rate for September, October and the first half of November when destratification began. Figure 4 shows how the model's April 1 total *DOHypoKg* declines as bacterial respiration consumes DO in the hypolimnion until it's completely used up on November 15.

The monthly DO use and the declining total of DO are shown in Figure 4 on a vertical scale from 0 to 10,000 kg.

Figure 5 shows the model values superimposed on the actual data in Figure 23 of C&G. The horizontal axis goes from March through November. The mid-summer three months are visible as the steep declining straight line in the middle of the curve. The beginning and the end of the curve reflect the formation and break up of the hypolimnion stratification.

The Pond Primeval

After the Pond has been modeled to fit its 1997-98 data, the questions arise, "What would the Pond look like without all the swimmers? What would the 'Pond primeval' look like?" Removing the 2.9 kg/mth P of mid-summer swimmer input to the pond leaves a mid-summer step value of 2.5 kg/mth P. Figures 6 and 7 reveal the Pond primeval. With less P input and less DO consumed, Walden Pond preserves about 3577 kg of DO in the hypolimnion on November 15 [1].

Figure 5. *Hypolimnion DO Depletion. C&F Data and Model Values*

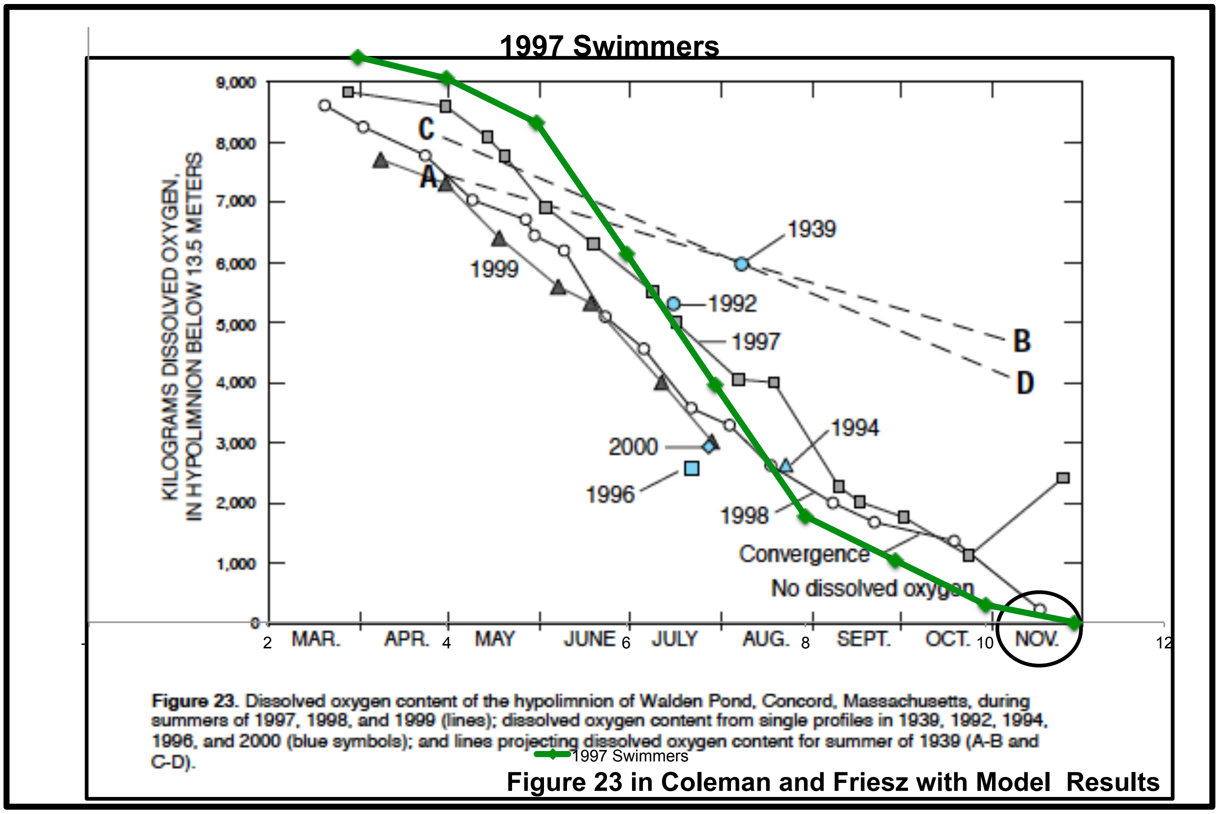


Figure 6. *Primeval Mid-Summer Phosphorous Input, DO Use and DO Decline*

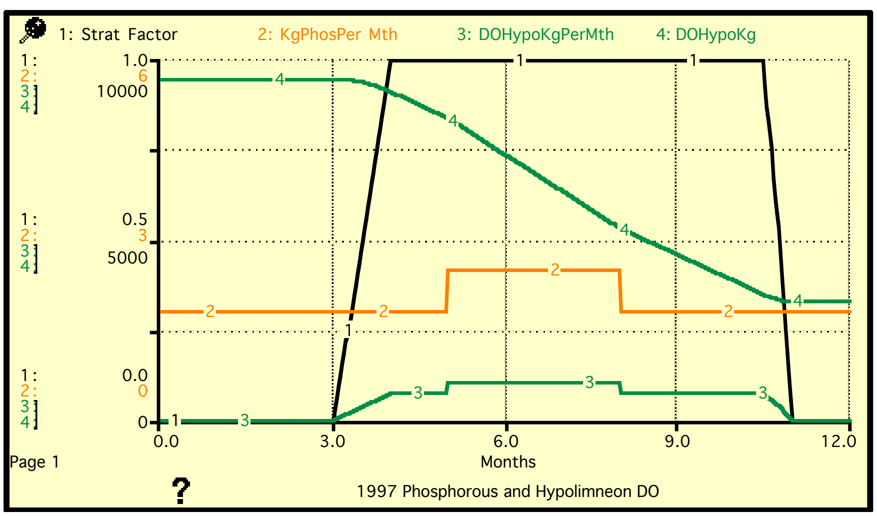
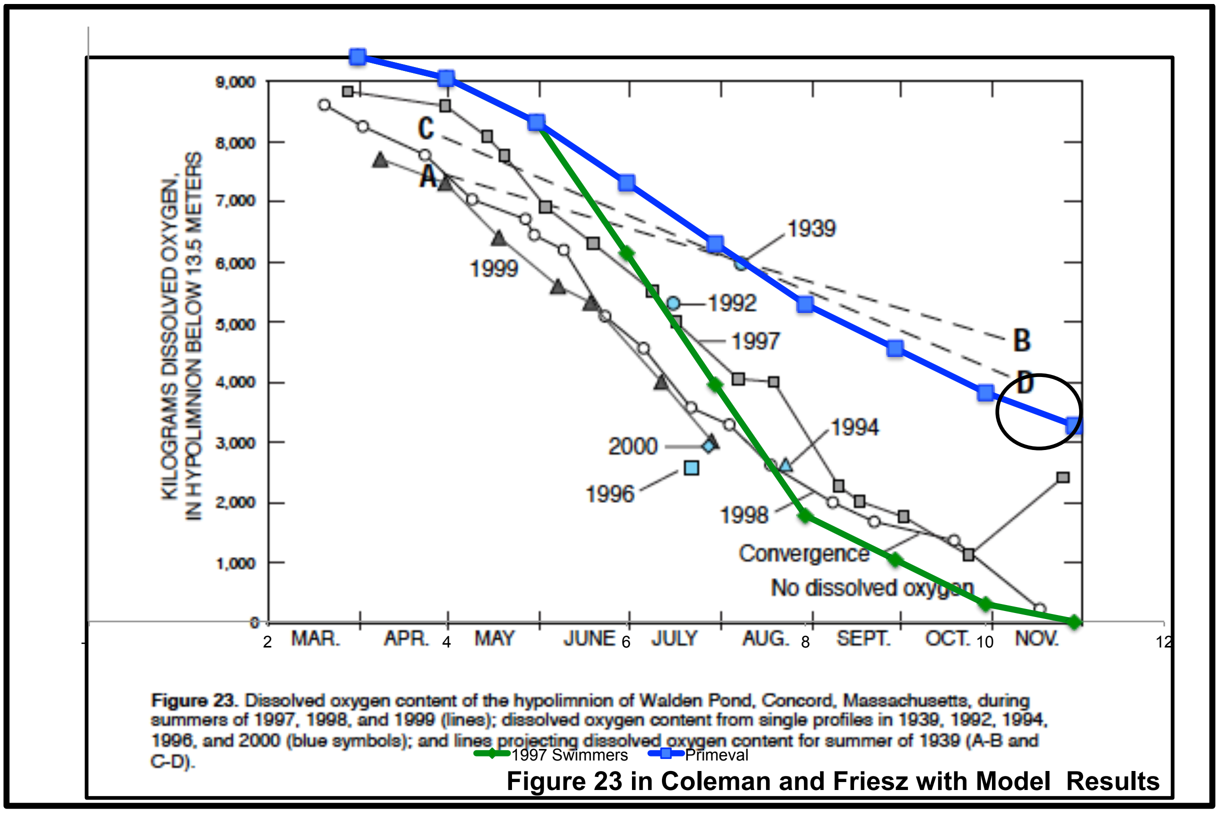


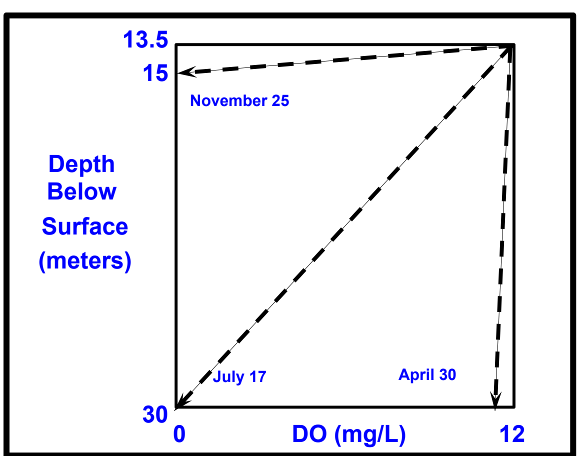
Figure 7. *Primeval Hypolimnion DO Depletion. C&F Data and Model Values*



Depletion pattern details

Does the lower input of P prevent the bottom sediments of the primeval Pond from turning anaerobic? Unfortunately no, because of *the pattern of how* the DO declines in the actual Pond. Figure 8 is a simplified diagram of the 1997 hypolimnion's progressive DO depletion on three dates, April 30, July 17, and November 25. As you can see, by July 17 the DO at the very bottom of the Pond has gone to 0 and by the end of the stratified period in November, the 81% of the hypolimnion that is below a depth of 15 meters is anaerobic [2]!

Figure 8. *Progressive Depletion of Hypolimnion DO in 1997 Walden Pond (After C&F Figure 18)*



This hypolimnion's pattern of progressive DO depletion shows that in order for the 30-meter bottom of Walden to remain aerobic, the hypolimnion must preserve **more than about 50%** of its original supply of DO. That is, 0.50 x 9484 kg = 4742 kg of DO must still be present when the hypolimnion begins to break up on November 15.

Model lessons

Figure 9 model values of the "1997 Swimmers" Pond show a bottom that stays anaerobic for four months, from about July 17 through November 15, and "Primeval" values that turn anaerobic about September 24 and remain anaerobic for approximately two months, until November 15.

Figure 9. *Model Values for Remaining Hypolimnion DO (kg)*

	Kg of Remaining DO	
End of Mth #	**1997 Swimmers**	**Primeval**
3	9484	9484
4	9128	9128
5	8393	8393
6	<u>6187</u>	7372
7	3982	6350
8	1776	<u>5329</u>
9	1041	4594
10	306	3859
11	0	3294

<u>Line</u> indicates 4742 kg, approximate beginning of anaerobic period.

1846 Walden

Finally, C&F estimate that because of global warming, the length of the stratified period at Walden Pond has increased 18 days between 1846 and 1995. The Walden Pond of 1846 would get colder earlier. Using Figure 9's "primeval" values, 18 days earlier would correspond to the stratification ending October 28th with 3930 kg DO (close to Oct 31 with 3859 kg) [3]. So in 1846, the bottom would have been anaerobic for only a little more than a month, from September 24 to October 28 [4].

Conclusion

The C&F data combined with the model of phosphorous and dissolved oxygen in Walden Pond together suggest that even in the late autumn of 1846 when Thoreau lived beside it, Walden Pond, at its deepest points, probably ran out of oxygen. The Pond has been dealing with a regular anaerobic period for a long time [5].

Notes

1. November 15's 3711 kg. is the interpolated model value between the end of October's 3987 and the end of November's 3435 in Figure 9:

   3859 – (3859 - 3294) x (15/30) = 3577 Kg.
2. The November 15 depth of the anaerobic hypolimnion differs slightly for different years (for 1997, 18 meters in C&F Figure 18; for 1998, 14 meters in C&F Figure 17B). The authors summarize their 5-year study, "By late fall, virtually all of the DO stored below a depth of 15 m in Walden Pond has been consumed" (C&F p. 44). 81% of the hypolimnion rests below the 15 m depth.
3. The actual interpolation is:

   4594 – (4594 – 3859) x (28/31) = 3930 kg
4. The "Primeval" column gives the correct values for the end of each month *of length* of an 1846 shortened period. But because the true 18-day shortening would remove 9 days from each end of the stratification, the true anaerobic period calendar *dates* would be October 3 to November 6.
5. It's good to remember that in 1846 people had been farming in Concord for 210 years, so even Thoreau's Walden may not represent the Pond "primeval."

References

1. Colman, JA, Friesz PJ. 2001. *Geohydrology and Limnology of Walden Pond Concord, Massachusetts.* U.S. Geological Survey Water-Resources Investigation Report 01-4137.
2. Colman, JA, Waldron MC. June, 1998. *'Walden Pond' Massachusetts: Environmental Setting and Current Investigations.* U.S. Geological Survey Fact Sheet FS-064-98.
3. Thoreau, HD. 1971. *Walden.* Princeton, New Jersey: Princeton University Press.
4. Diagrams are from the simulation tool, *iThink* of isee systems.

About the Author

John M. (Jack) Nevison is President of New Leaf Project Management and lives within a half-mile of Walden Pond. He is the author of six books and numerous articles on computing and management. His first simulation model, about a watershed ecosystem, was published in 1974. His most recent white paper features a dynamic model of how increased staffing can recover a troubled project.

During the course of his business career, Nevison has built and sold two businesses, managed projects, managed project managers, and served as both an internal and external consultant to Fortune 100 companies. He is a past president of the Mass Bay Chapter of the Project Management Institute (PMI®) and a past president of the Greater Boston Chapter of the Association for Computing Machinery (ACM). For more information, visit the website at www.newleafpm.com, or contact Nevison at info@newleafpm.com or 978-369-9009.