Geology Through Literature

Using *Walden* by Henry David Thoreau

Science is not a new invention. People have been performing science for many thousands of years. Often they build on research of those before them and sometimes they start from scratch. The purpose of this project is to use a scientific study from the 19th century to produce a current contour map of lake depth.

The study being described is in *Walden* by Henry David Thoreau, written before 1854. The book is typically considered "philosophical" literature but in this case he performs the basis of science. He identified a problem, determined how to solve the problem, and then executed the research.

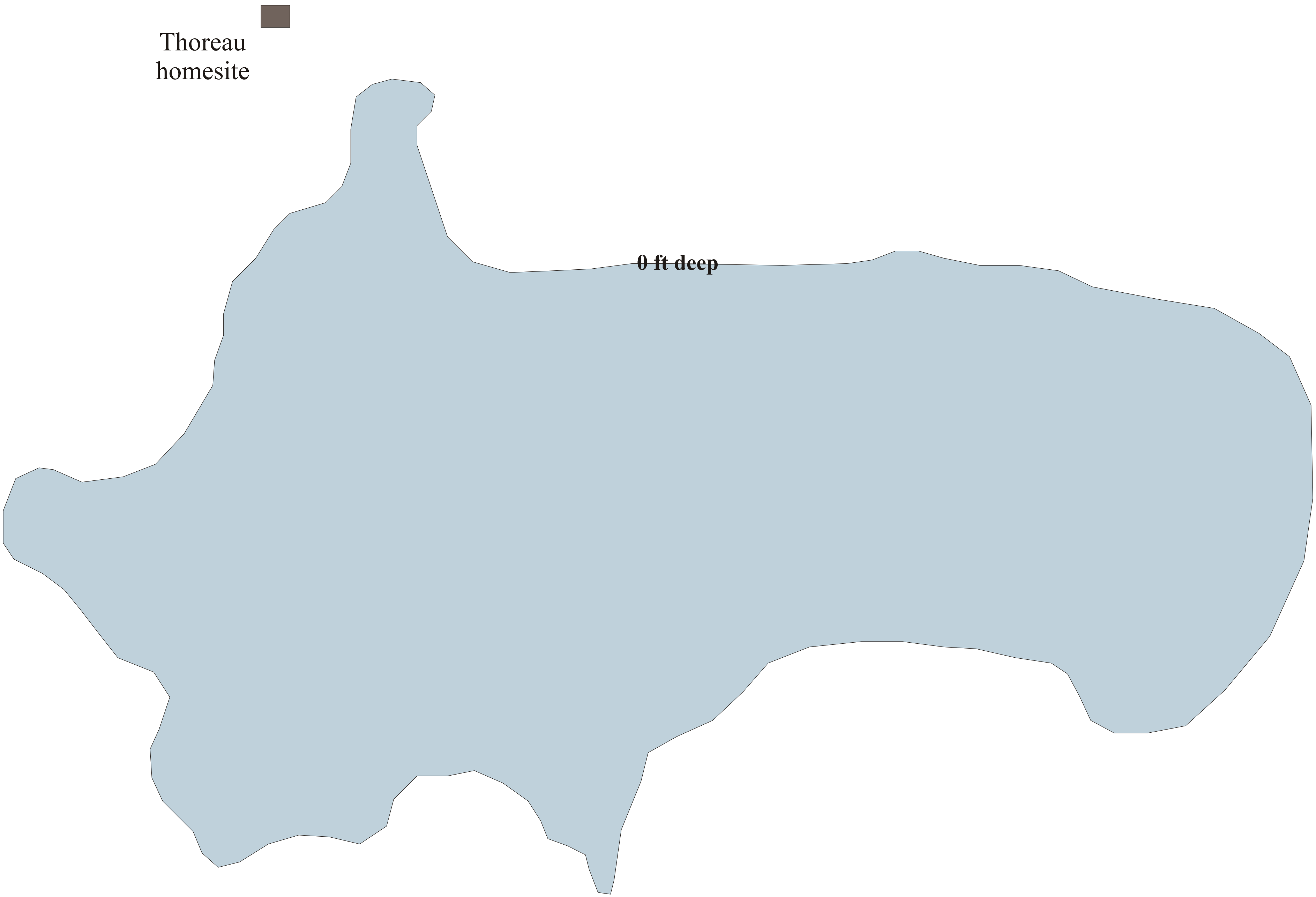
His Problem – Often people would describe the depth of Walden Pond as bottomless. He wished to prove them wrong and determine the actual depth.

His Method – To determine the actual depth of the lake he used the simple method of a rock and string.

His Solution – That's where you come in.

Project Directions

1. Read the "The Pond in winter" chapter of *Walden* by Thoreau.
2. Write down all important sentences and phrases that have to do with the depth and shape of the pond.
3. Summarize these into only the important points (like the location and depth of the deepest point.
4. Use one of the outlines of Walden Pond provided to start and outline the important features (deepest point, sand bars, etc.) in pencil.
5. Make a contour depth map with 20ft contours. The shore of the lake will be your 0 contour (provided). Then erase all of the mistakes and non-important items on the map so you just have a finalized contour map left.


Thoreau
homesite
0 ft deep


Thoreau homesite
0 ft deep

Step 2 – Solutions

Sentences and Phrases Straight from *Walden*

1. "The greatest depth was exactly one hundred and two feet; to which may be added the five feet which it has risen since, making one hundred and seven.

2. "…appears in a vertical section through its centre not deeper than a shallow plate."

3. "…I was surprised at its general regularity. In the deepest part there are several acres more level than almost any field which is exposed to the sun, wind, and plow. In one instance, on a line arbitrarily chosen, the depth did not vary more than one foot in thirty rods; and generally near the middle, I could calculate the variation for each one hundred feet in any direction beforehand within three or four inches."

4. "…the greatest depth was apparently in the centre of the map, I laid a rule on the map lengthwise, and then breadthwise, and found, to my surprise, that the line of greatest length intersected the line of greatest breadth exactly at the point of greatest depth, notwithstanding that the middle is so nearly level, the outline of the pond far from regular, and the extreme length and breadth were got by measuring into the coves."

5. "Of five coves, three, or all which had been sounded, were observed to have a bar quite across their mouths and deeper water within, so that the bay tended to be expansion of water within the land not only horizontally but vertically, and to form a basin or independent pond, the direction of the two capes showing the course of the bar."

6. "Also there is a bar across the entrance to every cove, or particular inclination; each is our harbor for a season, in which they are detained and partially landlocked.

Step 3 Solutions

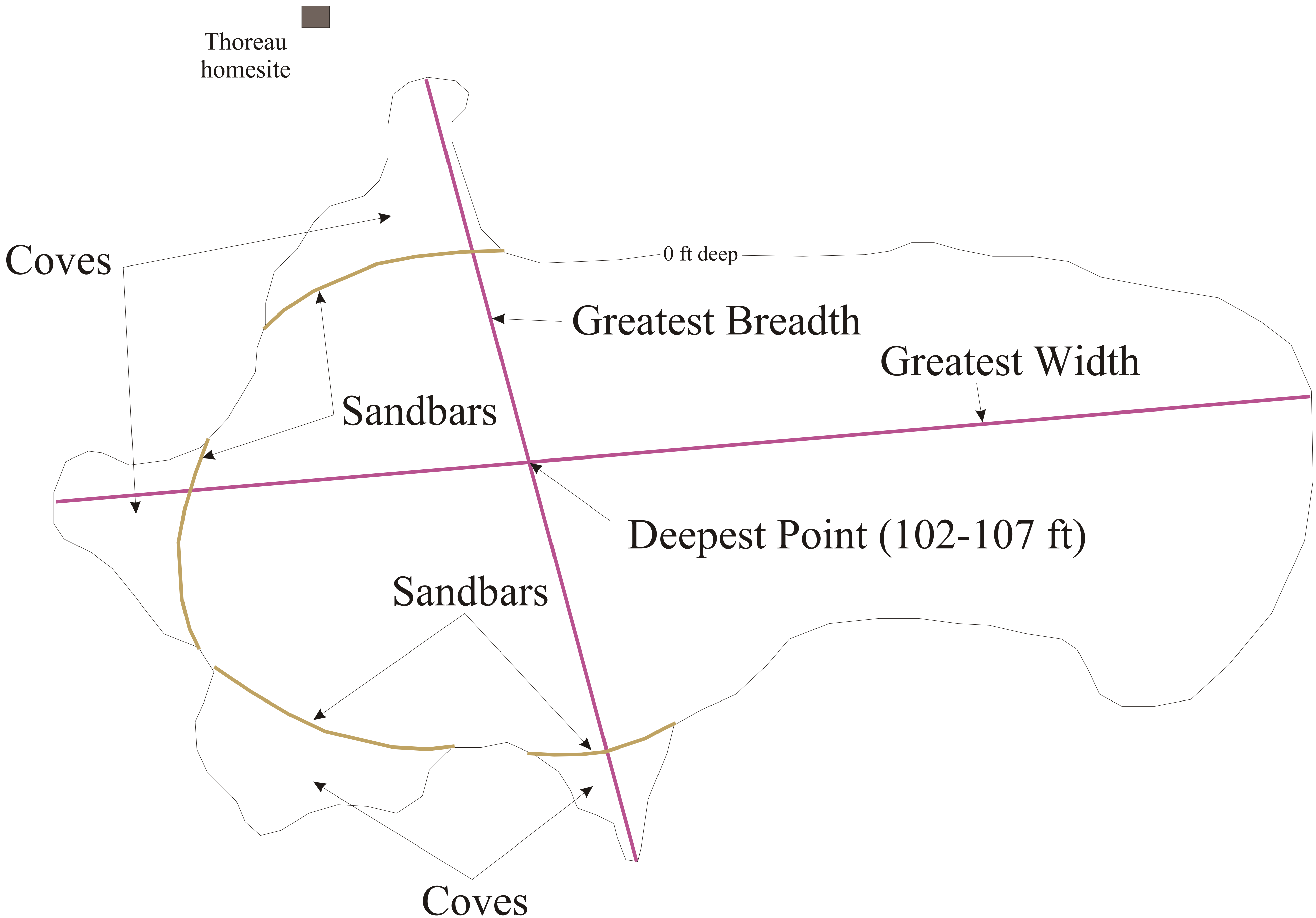
Summarization of Important Points

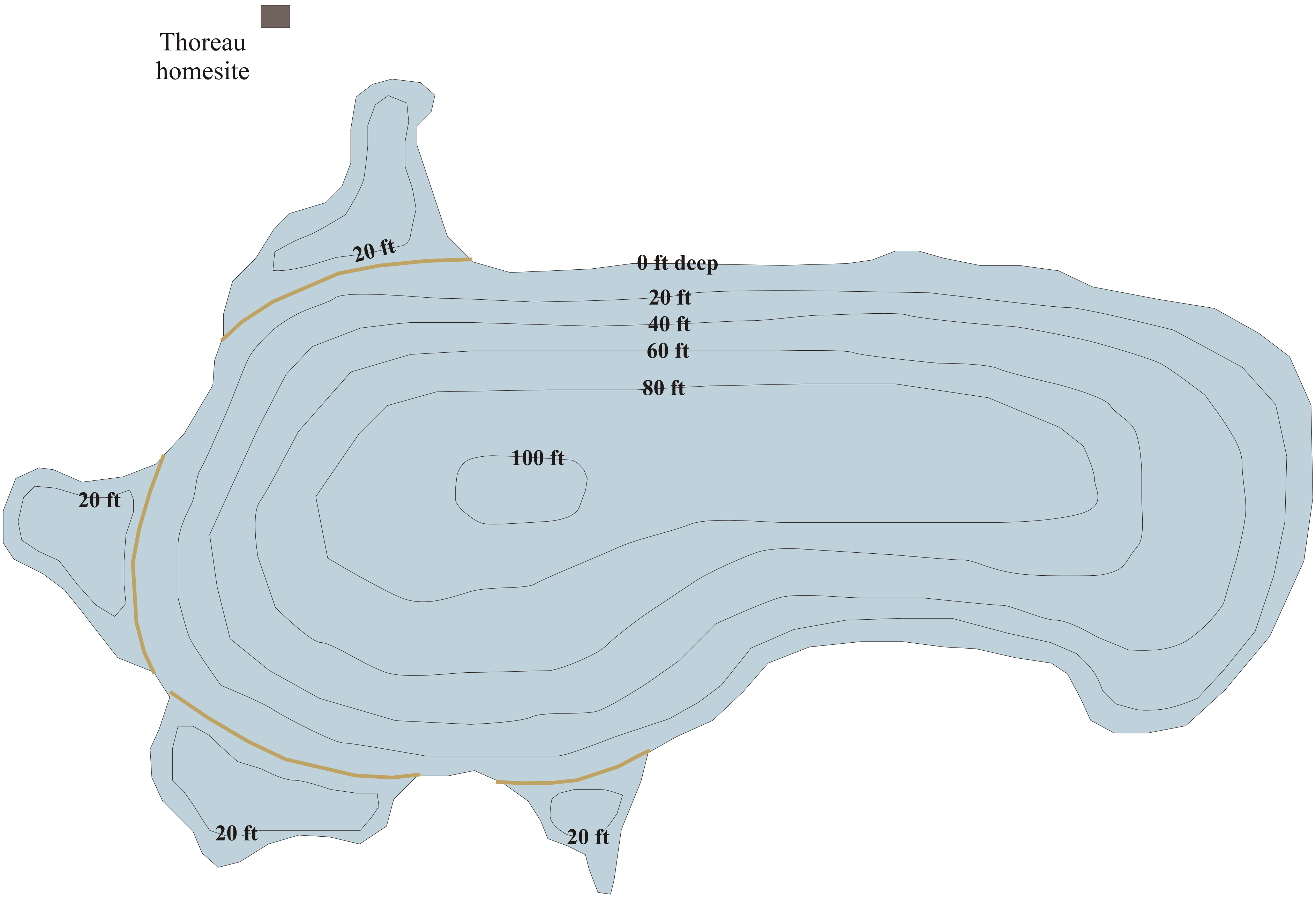
1. The deepest point of the lake is 102-107 feet deep and is located at the intersection of the greatest breadth and the greatest width lines.

2. There are sandbars that surround the coves creating mini lakes.

3. The pond is regular, meaning that the contours are evenly spaced apart.

4. The base of the pond is relatively flat.

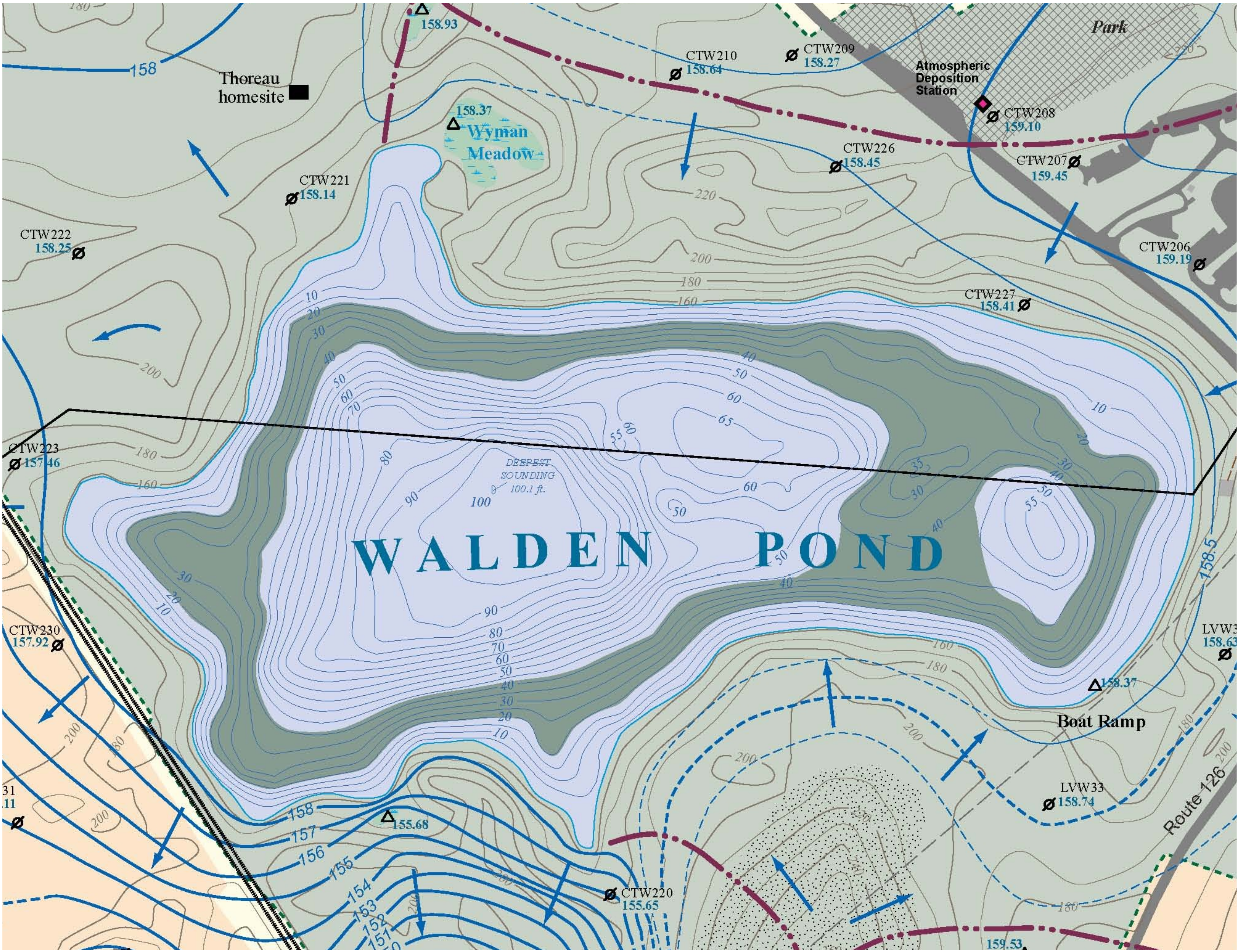

Thoreau
homesite
Coves
0 ft deep
Greatest Breadth
Greatest Width
Sandbars
Deepest Point (102-107 ft)
Sandbars
Coves


Thoreau
homesite
20 ft
0 ft deep
20 ft
40 ft
60 ft
80 ft
100 ft
20 ft
20 ft
20 ft

Walden Professional Solution

The following map can be found at http://pubs.usgs.gov/wri/wri014153/report.pdf and shows a professional contour map of Walden Pond. It is from a document called *Hydrology and Trophic Ecology of Walden Pond, Concord, Massachusetts* by Paul J. Friesz and John A. Colman, 2001.

This is what is considered to be the actual contours of the pond and is surprisingly similar to what Thoreau actually concluded with just a rock and a string. Amazing what science is able to do with just primitive tools.

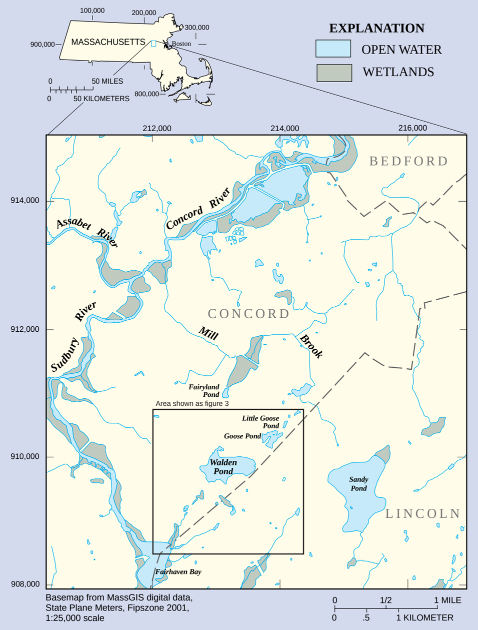


Park
Atmospheric
Deposition
Station
Thoreau
homesite
Wyman
Meadow
158.93
158.37
CTW210
158.64
CTW209
158.27
CTW208
159.10
CTW207
159.45
CTW226
158.45
CTW221
158.14
CTW222
158.25
CTW206
159.19
CTW227
158.41
CTW223
157.46
CTW230
157.92
DEEPEST
SOUNDING
100.1 ft.
WALDEN POND
158.5
LVW33
158.74
158.37
Boat Ramp
155.68
CTW220
155.65
159.53
Route 126
158
157
156
155
154
153
152
151

Prepared in Cooperation with the
MASSACHUSETTS DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

INTRODUCTION

Walden Pond, the deepest lake in Massachusetts, has great historical, naturalistic, and limnological significance as the subject of Henry David Thoreau's well-known essay "Walden: or, Life in the Woods" (Thoreau, 1854). Only 15 miles (mi) northwest of Boston, Mass. (fig. 1), Walden Pond potentially is threatened by environmental stresses common to urban lakes: a municipal landfill, septic leachate, high visitor-use rates, acid and other contaminants from atmospheric deposition, and invasion of exotic species. Walden Pond retains clear, undegraded water because of conservation efforts that protect the shore and woods surrounding the lake. Questions remain, however, regarding the extent of ecological changes that may already have occurred and the degree to which conservation efforts will preserve water quality in the future. Hydrologic and limnologic results from a cooperative investigation of Walden Pond between the U.S. Geological Survey and the Massachusetts Department of Environmental Management are summarized in this plate report, which shows Walden Pond in relation to the ground-water system and land use. Details of the investigation from data collected from 1997 to 1999 (Colman and Friesz, 2001) and basic information about limnology and Walden Pond (Colman and Waldron, 1998) also are available.



Basemap from MassGIS digital data, State Plane Meters, Fipszone 2001, 1:25,000 scale

Figure 1. Location and hydrologic setting of Walden Pond, Concord, Massachusetts.

HYDROLOGY

Walden Pond and the underlying and surrounding aquifer are bordered by the Sudbury and Concord Rivers (fig. 1). Walden Pond, a kettle-hole lake with no surface water inlet or outlet, formed at the end of the last glaciation about 15,000 years ago by the melting of a large block of ice that broke off into glacial Lake Sudbury from the retreating glacier. The ice block eventually was surrounded by sorted, stratified sediments ranging mainly from fine sand to coarse gravel deposited by glacial meltwater (fig. 2), (Koteff, 1963). Seismic reflection and fathometer data indicate that the lake and its associated fine-grained bottom sediments extend to the till and bedrock surface in the deepest areas. Three deep areas are defined in the lake (fig. 3); the middle deep area was unmapped before this investigation. The maximum measured depth of 100.1 feet (ft) was within 2 ft of that measured by Thoreau in the winter of 1846.

Knowledge of the water balance and the land-surface area contributing water to Walden Pond is needed to understand the hydrology of the lake and to derive a nutrient budget for the lake. Sources of water to Walden Pond include precipitation on the lake surface and ground water (fig. 2). Water from precipitation infiltrates the permeable surficial deposits, recharges the aquifer, then flows in the direction of decreasing water levels. Thus, ground-water flow does not necessarily follow land surface topography. Along steep shoreline areas sloping towards Walden Pond, small quantities of overland flow may occur after intense precipitation events, thereby adding small amounts of water to the lake. Water leaves Walden Pond by evaporation from the lake surface and from lake-water seepage to the aquifer (fig. 2).

Ground-Water Contributing Area

Water-table contours, surficial geology, and topography were used to delineate the area contributing ground water to Walden Pond (fig. 3). The altitude and configuration of the water table in areas of stratified glacial deposits surrounding Walden Pond were determined from water levels measured in 40 monitoring wells and 8 ponds on July 19, 1999. The direction of ground-water flow, shown by arrows on figure 3, is perpendicular to the water-table contours. In areas of bedrock highs, such as Emersons Cliff and Pine Hill, ground water flows downslope through the overlying saturated till in the direction of declining land-surface altitude because the bedrock surface is relatively impermeable. The water-table map shows that Walden Pond is a flow-through lake: ground water flows into the lake along its eastern perimeter, and lake water flows out to the aquifer along its western perimeter. The contributing area also includes Goose Pond, also a flow-through pond, and its contributing area. Some of the water that enters Goose Pond, from ground-water inflow from the Pine Hill area and from precipitation that falls directly on Goose Pond, flows west out of Goose Pond into the aquifer and towards Walden Pond.

The Walden Pond contributing area of 0.24 square miles (mi^2) is contained mainly within the Walden Pond State Reservation boundary and other conservation land, except for that area that also is part of Goose Pond and its contributing area (fig. 3). The Reservation septic leach field and the septic leach fields from residences on privately owned land in the contributing area east of Walden Pond are potential sources of nutrients to the lake. Ground water in the Reservation leach field area flows westward toward the eastern shore of Walden Pond. Leach fields from private residences are in areas where ground water flows directly toward Walden Pond or indirectly by first flowing into Goose Pond. Ground water in the southeastern part of the contributing area generally flows northwest from the till-covered bedrock highs, Emersons Cliff and Pine Hill. Most of the ground water from these till-covered areas most likely enters the stratified glacial deposits before discharging to Walden Pond. Northeast of Walden Pond, the Concord Municipal landfill and a trailer park are on the north side of a ground-water divide; ground water north of this divide flows generally in the northward direction away from Walden Pond.

Lake-derived ground water flows towards and discharges into the Sudbury and Concord Rivers or to wetlands and streams draining into these rivers. The steep water-table gradient southwest of Walden Pond is caused by large water-level differences between Walden Pond and discharging areas—Heywoods Meadow and the Andromeda Ponds.

Water-Level Fluctuations

Water levels in Walden Pond and the surrounding aquifer fluctuate because of seasonal and long-term variations in recharge from precipitation. A hydrograph from a nearby USGS long-term observation well (fig. 4*A*) indicates water levels rise, in general, from winter through early summer when recharge to the aquifer exceeds ground-water discharge; water is available to recharge the aquifer when precipitation exceeds evapotranspiration. From summer through winter, water levels decline because ground-water discharge exceeds recharge. The annual cycle of water-level rises and declines lags climatic conditions because of the transit time for precipitation to recharge the water table through the unsaturated zone and because of storage within the aquifer. Lake-water levels (fig. 4*B*) indicate a similar seasonal pattern as the ground-water levels because the lake is hydraulically connected to the surrounding aquifer. The magnitude of fluctuations in the lake is less than in the aquifer, however, because the lake has proportionally greater storage capacity than the aquifer.

Long-term variations in water levels reflect long-term storage changes in the aquifer and lake. Water levels fluctuated over a range of about 11.5 ft from 1956 to 1999. The lowest water level was measured in early 1967 after 4 successive years of below-average precipitation (fig. 4*C*) resulted in a cumulative precipitation deficiency of about 46 inches (in.). Two periods of high water-level altitudes occurred in 1956 and 1984 following periods of above-average precipitation. In the eastern half of Massachusetts, ground-water levels and streamflows generally were below normal from autumn 1998 to late summer 1999. Water levels in Walden Pond and the surrounding aquifer during this study, however, were at or above-average levels because of the large quantity of water in storage and because of the low outflow rates from the lake and aquifer.

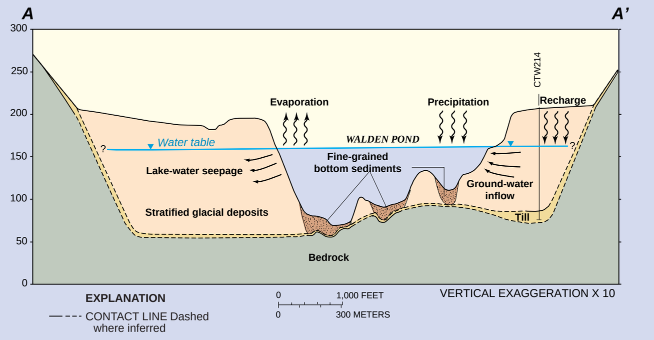


Figure 2. Walden Pond and fine-grained bottom sediments extend to the till and bedrock surface in deep areas. Stratified glacial deposits surround the lake. Water enters the lake from precipitation on the lake surface and from ground water and leaves the lake from evaporation and lake-water seepage. (Line of section shown in fig. 3.)

Water Balance

The water balance for Walden Pond without surface inflows or outflows can be expressed as

$$\Delta S = P + GW_i - E - GW_o \quad (1),$$

where ΔS is change in lake-volume storage; *P* is precipitation that falls directly on the lake surface; GW_i is ground-water inflow; *E* is evaporation from the lake surface; and GW_o is lake-water seepage to the aquifer (ground-water outflow). The water balance for Walden Pond was based on average annual conditions during the 5-year period, 1995–99. Water-balance calculations based on this time period indicate that the water-residence time of the lake is approximately 5 years; therefore, inflows and outflows to Walden Pond should reflect climatic conditions during this period. Ground-water outflow was calculated indirectly as a residual of the water-balance equation. There was no change in long-term lake storage over the 1995–99 period based on the ground-water hydrograph (fig. 4*A*). Average precipitation from 1995–99 was 47.82 in/yr, which is 2.50 in. above the 40-year average (fig. 4*C*). Average evaporation of 28 in/yr from the lake surface was estimated by using regionalized pan evaporation and pan coefficient measurements (Farnsworth and others, 1982). The ground-water inflow rate to Walden Pond was determined by contributing-area and isotope mass-balance approaches.

The contributing-area approach requires knowledge of the recharge rate and the size of the area where ground water flows directly to Walden Pond. In addition, the quantity of water entering the aquifer from Goose Pond and flowing as ground water to Walden Pond must be considered. An average recharge rate of 26.8 in. was based on regional estimates of Randall (1996) and adjusted to account for the increased average precipitation during the 1995–99 period. The ground-water contribution to Walden Pond from Goose Pond was estimated to be 20 percent of the average annual ground-water outflow because about 20 percent of the outflow perimeter of Goose Pond lies within the contributing area of Walden Pond. No upgradient ground water was assumed to flow beneath or by-pass Walden Pond because deep areas of the lake extend to the till and bedrock surface. The total average annual ground-water inflow to Walden Pond equals 53 inches per year (in/yr) (expressed as depth of water over the lake surface). The estimated contribution from Goose Pond is 6 percent of this total inflow from ground water.

The isotope mass-balance approach uses the stable isotopes of oxygen ($\delta^{18}O$) and hydrogen (δD) that naturally occur in water. Flows into and out of a lake and the lake water itself can have different isotopic signatures. These isotopic differences along with precipitation and evaporation rates can be used to determine ground-water inflow to a lake (Krabbenhoft and others, 1990)

$$GW_i = \frac{P\ (\delta_L - \delta_P) + E\ (\delta_E - \delta_L)}{\delta_{GW_i} - \delta_L} \quad , \quad (2),$$

where GW_i, *P*, and *E* have been defined previously and δ_L, δ_P, δ_E, and δ_{GW_i} are the isotopic composition of the lake, precipitation, evaporation, and ground-water inflow, respectively. Average isotope values from water samples collected from July 1998 to June 1999 represented the average isotopic values during 1995–99, except for the isotopic composition of evaporated water, which was calculated indirectly.

The isotopic compositions of precipitation, ground-water inflow, and lake water are plotted in figure 5. The isotopic composition of precipitation primarily varies because of changes in atmospheric temperature (Gat, 1980); the precipitation samples define a local meteoric water line (LMWL). The isotopic composition of ground water varied little spatially and temporally. The isotopic composition of ground water has lower $\delta^{18}O$ and δD values compared to the average annual isotopic composition of precipitation because precipitation recharges the aquifer from autumn to spring when atmospheric temperature is low. The isotopic composition of lake water also varied little seasonally, which is typical of deep surface-water bodies with relatively long water-residence times (Dincer, 1968). The lake isotopic values plot to the right of the LMWL because evaporation causes an increased enrichment of $\delta^{18}O$ relative to δD in the lake water. Ground-water inflow calculated with equation 2 results in 68 in/yr for $\delta^{18}O$ and 57 in/yr for δD, which compare favorably to the estimate based on the contributing-area approach. A ground-water inflow value of 58 in/yr, based on the average of the $\delta^{18}O$ and δD results (62 in/yr) and the contributing-area result (53 in/yr), was used in the water-balance analysis.

A summary of the water balance for Walden Pond for the 5-year period 1995–99 is shown in figure 6 partitioned on the basis of the magnitude of inflow and outflow components. Average inflow from precipitation and ground water totalled about 106 in. Precipitation on the lake surface accounted for 45 percent of the inflow, whereas ground water contributed 55 percent of the inflow. The proportion of inflows anchors the evaporation line for Walden Pond on figure 5, which extends from the average of the average isotopic compositions of precipitation and ground-water inflow through the lake samples. This evaporation line defines the isotopic evolution of lake water from its source waters (Krabbenhoft and others, 1990). Ground-water outflow (74 percent), is significantly greater than evaporation (26 percent). Results indicate that ground water is the dominant pathway into and out of the lake and that the water-residence time for the lake is 4.8 years.

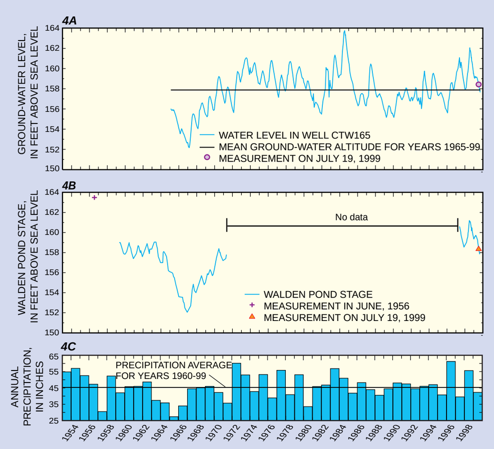


Figure 4. Measurements of water levels in well CTW165 (*A*) and Walden Pond (*B*) show the annual cycle of water-level declines and rises. Long-term trends in water levels reflect trends in annual precipitation (*C*). (Lake water levels in 1956 and from1959 to 1971 were collected by Walden Pond State Reservation staff (Walker, 1971); precipitation data are from the National Oceanic and Atmospheric Administration.)

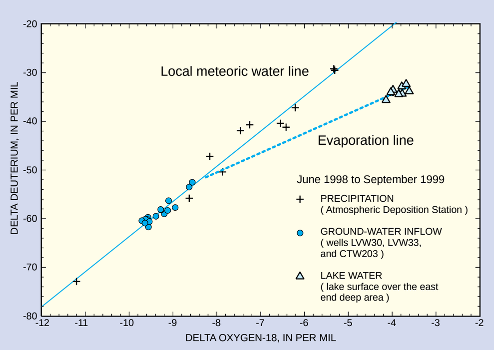


Figure 5. The isotopic composition of precipitation varied on the basis of atmospheric temperature and defined a local meteoric water line (LMWL). The isotopic composition of ground water clustered at the low end of the LMWL and reflected the cold temperature when ground water was recharged. The isotopic composition of lake water plotted to the right of the LMWL, and defined an evaporation line.

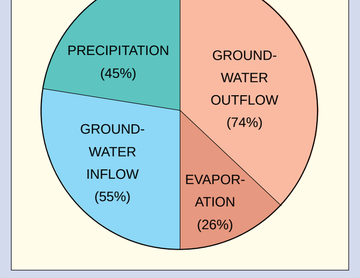
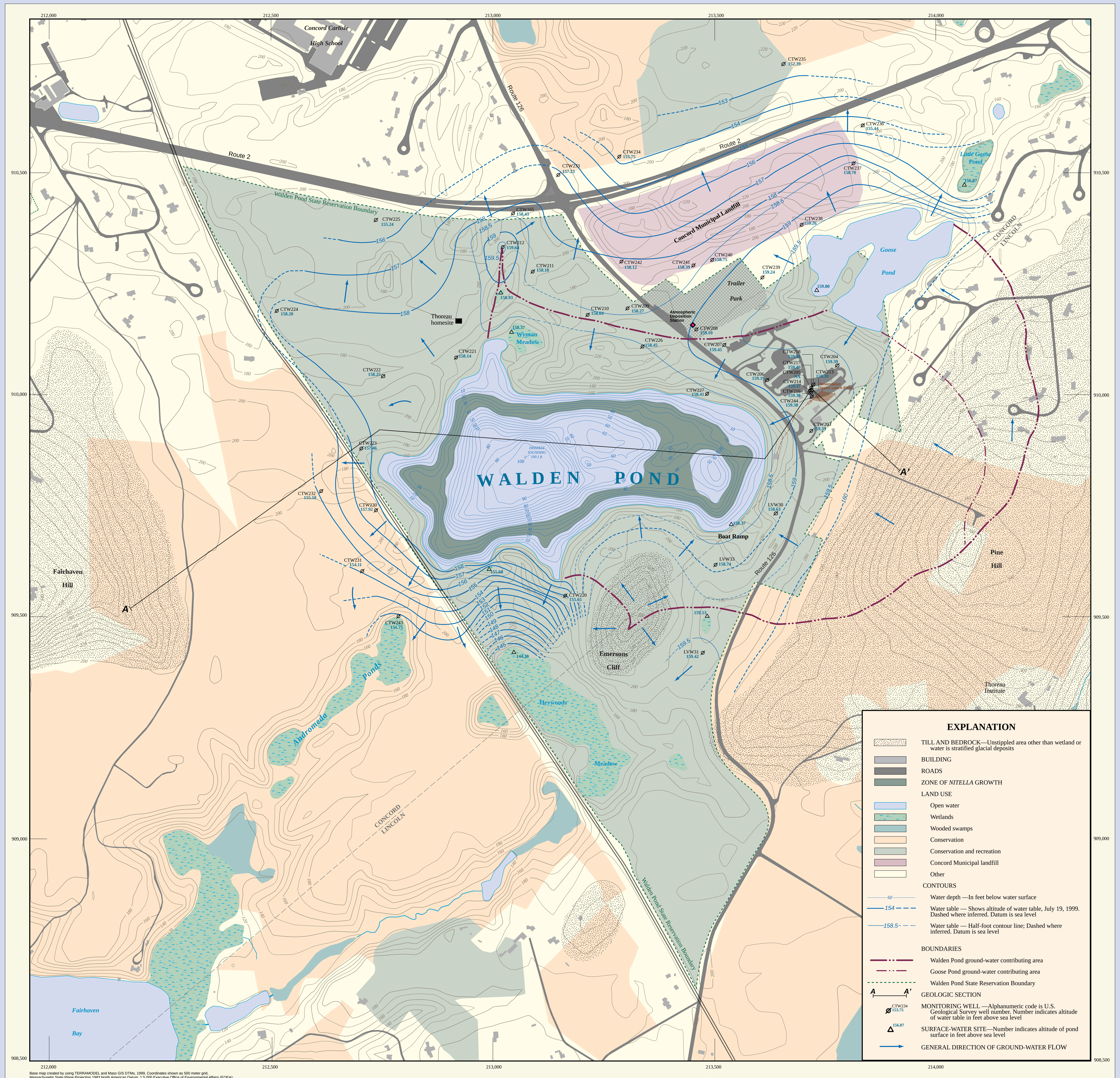


Figure 6. The average annual water balance for Walden Pond shows that ground water is the dominant pathway into and out of the lake.



Base map created by using TERRAMODEL and Mass GIS DTMs, 1999, Coordinates shown as 500 meter grid, Massachusetts State Plane Projection,1983 North American Datum; 1:5,000 Executive Office of Environmental Affairs (EOEA); Protected and Recreational Open Space data from MassGIS, 1989, Massachusetts State Plane Projection, 1983 North American Datum; 1:24,000 EOEA; Surficial Geology data from USGS,1964, Massachusetts State Plane Projection, 1983 North American Datum; 1:24,000 USGS; Building Footprints and Roads data from towns of Concord and Lincoln, 1999 State Plane Feet, Zone 5176, 1983 North American Datum; 1:5,000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 3. Walden Pond is a kettle-hole, flow-through lake. Ground water discharges into Walden Pond along its eastern perimeter and lake water discharges into the aquifer along its western perimeter. The area contributing ground water was delineated on the basis of the configuration of the water table, surficial geology, and surface topography. The bathymetric map reveals three deep areas.

TROPHIC ECOLOGY

The primary public environmental issue for Walden Pond concerns its trophic ecology—whether urban development or high visitor attendance may have altered or will alter the relation between plant-nutrient supplies and aquatic-plant growth. Nutrient supplies, especially of growth-limiting nitrogen and phosphorus, are key water-quality features of kettle-lake investigations because plant growth affects water clarity, determines the type and quantity of lake biomass production, affects the amount of summer dissolved oxygen present in the deep water, and may even affect other ecological problems, such as invasion of exotic species or cycling of bioconcentrating pollutants like polychlorinated biphenyls (PCBs) and mercury. Nutrient supply, in turn, depends on geohydrology—sources, amounts, and cycling of water and chemical constituents carried by the water.

Sources and Amounts of Plant-Nutrient Inputs

Phosphorus and nitrogen can enter Walden Pond carried by ground water, through direct dry or wet deposition from the atmosphere, from birds roosting on the lake, from parking-lot or road runoff, by fish stocking, and from swimmers. Estimated annual nutrient loads indicated that inputs were dominated by three sources; ground water (septic leach field plume for nitrogen and ambient ground water for phosphorus), atmospheric deposition, and human swimmers (table 1).

Table 1. Nutrient budget for Walden Pond

[Ground water, septic leach-field plume, and atmospheric sources measured directly; swimmer source estimated; other sources modified from Baystate Environmental Inc. (1995); kg/yr, kilograms per year; N, nitrogen; P, phosphorus; kg/3 mo, kilograms per months]

Source	Annual					Summer				
	Nitrogen		Phosphorus			Nitrogen		Phosphorus		
	Load (kg/yr)	Percentage of total load	Load (kg/yr)	Percent-age of total load	N:P ratio (atomic)	Load (kg/3 mo)	Percent-age of sum load	Load (kg/3 mo)	Percent-age of sum load	N:P ratio (atomic)
Background ground water	66	7.7	5.5	17	27	16	4	1.4	9	27
Plume ground water	260	30	--	--	--	65	15	--	--	--
Atmospheric wet	152	18	.8	3	412	38	9	.2	1	412
Atmospheric dry	75	8.7	15	47	11	19	4	3.8	23	11
Swimmers	290	34	8.7	27	74	290	67	8.7	54	74
Waterfowl	4	.5	.6	2	15	1	0	.6	4	4
Fish stocking	6	.7	.7	2	19	2	0	.7	4	5
Direct runoff	6	.7	.8	2	16	1	0	.8	5	4
Total	858	100	32	100	59	432	100	16	100	59

Computations for ground-water nutrient inputs were divided according to background and point-source contributions. Background nitrogen and phosphorus loads were determined as the product of ground-water discharge to Walden Pond and average ground-water concentrations. A ground-water plume containing nitrogen was detected in drive-point wells along the northeast shore of Walden Pond and in observation wells immediately downgradient from the Reservation leach field, the only substantial point source within the ground-water contributing area (fig. 7). Nitrogen load for the plume was computed from the product of water use, an unsaturated-zone loss factor, and nitrogen concentration in the septic tank. In contrast to nitrogen, the average concentration of phosphorus in the plume was not greater than that in background ground water. Phosphorus had been retained in the 40-ft unsaturated zone beneath the leach field and was not included in plume load. Seventeen residences on septic leach fields were in the contributing area (fig. 3). Ground-water flow direction indicated that transport from 15 residences was toward Goose Pond. These residences contribute nutrients minimally to Walden Pond, only as mediated after loss to the sediments in Goose Pond. Although nitrogen from the leach field of two residences would enter Walden Pond directly, movement of phosphorus is unlikely because of the thick unsaturated zone and long distance to the lake at their respective locations.

Atmospheric inputs were measured separately for wet and dry deposition (collector location on fig. 3). A substantial phosphorus load associated with pollen fall was measured. Swimmer inputs were estimated from known average composition of urine and assumptions about the percentage of summer Reservation visitors that are swimmers (90 percent) and percentage of swimmers that urinate in Walden Pond (50 percent). Swimmers account for 34 percent of the annual nitrogen load and 27 percent of the annual phosphorus load. The percentages increase to 67 and 54, respectively (table 1), during the summer.

The growth-limiting nutrient for Walden Pond can be determined by comparison of the nitrogen-to-phosphorus ratio for different inputs to the average atom-to-atom ratio required by algae (15:1; (Redfield and others, 1963). The overall nitrogen:phosphorus ratio in nutrient inputs of 59, which was similar to the ratio in water-column measurements, indicated that nitrogen was in excess and phosphorus input would control the amount of plant growth. Nutrient sources in which nitrogen is substantially in excess of the Redfield ratio may mitigate blooms of cyanobacteria, which have the capability to fix nitrogen from the atmosphere. A selective advantage of cyanobacteria over algae, which can not fix atmospheric nitrogen, is removed when nitrogen is in excess supply (Levine and Schindler, 1999). Cyanobacteria blooms often form nuisance surface scums on lakes and even may develop toxins; a high nitrogen to phosphorus ratio and sources that contribute to it, such as the leach-field plume, may help prevent cyanobacteria blooms.

Three lake terms used to indicate progressively greater nutrient supply and consequent plant growth are oligotrophic, mesotrophic and eutrophic. Based on phosphorus loading, Walden Pond at 0.13 g $P/m^2/yr$ is approaching a eutrophic state between "permissible and critical phosphorus loads," 0.084 and 0.17 $g/m^2/yr$, respectively (Vollenweider (1975), that apply to a lake with mean depth (42.4 ft) and hydraulic residence time (4.8 yr) of Walden Pond.

Plant-Growth Measurement and Dissolved Oxygen

Whereas nutrient budgets indicate relative importance of nutrient sources, direct measures of lake trophic state such as changes in standing crops of plants or changes in dissolved oxygen or carbon dioxide, associated with photosynthesis and respiration, indicate how inputs are processed into plant growth in a given lake. Phytoplankton biomass, determined by chlorophyll measurements, amounted to 285 kg on a dry-weight basis for Walden Pond. In addition, large stands of the deep-growing macroalga *Nitella* grow on the bed-sediment surface between depths of 20 and 42 ft (figs. 3 and 8). *Nitella* biomass determined from weight of dried samples and percent area covered was about 5,000 kg, or more than 17 times greater than the phytoplankton biomass. *Nitella* presence in lakes has been associated with clear-water conditions and later absence of *Nitella* with more turbid, eutrophic conditions.

Large stands of *Nitella* have been hypothesized to intercept phosphorus that might recycle from the sediments before it gets mixed into the water column and, through oxygen generation, to reduce phosphorus recycled from the sediments (Nygaard and Sand-Jensen, 1981).

Lake distribution of dissolved oxygen, indicative of plant growth and a determinant in internal cycling of nutrients in lakes, is a consequence of the balance among photosynthesis, respiration, and exchange with the atmosphere, as mediated during summer by thermal stratification. Vertical zonation based on thermal stratification results in temperate-zone lakes during the summer. The zones in order of increasing depth are the epilimnion (in Walden Pond 0 to 20 ft), the metalimnion (20 to 46 ft), and the hypolimnion (46 to 100 ft) (fig. 9). Restricted vertical mixing that results from thermal stratification causes zone-specific (such as metalimnetic or hypolimnetic) chemical changes, including dissolved oxygen depletion, that accrue during the entire stratified period.

During cold weather every year, water mixing in Walden Pond moved dissolved oxygen from the atmosphere into the water column resulting, by early spring, in near-saturation by dissolved oxygen throughout (fig. 10 *A* and *B*). With spring warming, the deep water was cut off from the surface by thermal stratification, and vertical transport of dissolved oxygen into or out of the metalimnion was negligible. Dissolved-oxygen concentrations measured during March and April increased in the metalimnion, indicative of substantial plant growth in this zone. After the increase, metalimnetic dissolved oxygen concentrations remained high and unchanged during the remaining six months of temperature stratification. Dissolved oxygen decreased in the hypolimnion, where respiration dominated after onset of stratification, mainly in response to decay of algal biomass, that settles from the sunlit upper zones. By late fall in Walden Pond, virtually all of the dissolved oxygen stored below the 46-ft depth has been consumed (black zones in fig. 10*A*). In winter, wind and surface cooling break up stratification, and the cycle starts over.

The complete depletion of hypolimnetic dissolved oxygen just before fall turnover likely increased the release of sediment phosphorus, which accumulates on the aerobic bed-sediment surfaces during the summer. Although cause and effect has not been established, these late stratification-period events preceded the only surface-scum-producing cyanobacteria blooms (of *Anabaena*) observed during the investigation, in late December of 1997 and 1998.

The rate of dissolved-oxygen depletion in the hypolimnion of Walden Pond can be measured by the hypolimnetic oxygen deficit (HOD). The HOD is represented by the rate of change in dissolved oxygen mass in the hypolimnion (slope of line in fig. 11). HOD is an integrative indicator for lake trophic state, because it depends on oxygen use during much of the time that the lake is stratified. Three years of biweekly dissolved oxygen monitoring, 1997–99, and two profiles from 2000 indicated that the May through July HOD values nearly were identical (0.049, 0.050, 0.051, 0.048 mg $O_2/cm^2/d$, 1997 through 2000). These results indicate that baseline trophic-state conditions as measured by HOD are relatively stable at present.

Long-term change in HOD-trophic state can be estimated from the few historical dissolved-oxygen profiles available for Walden Pond, from 1939, 1992, 1994, and 1996 (fig.11). A projected depletion line for the 1939 datum indicates that dissolved oxygen in the 1939 hypolimnion may not have been depleted if turnover occurred at the same time as in the present. The more recent historical profiles—1992, 1994, 1996—indicates that depletion in those years generally was similar to the depletion data of 1997–2000.

The early profile suggests that HOD has doubled since 1939, which implies that historical inputs of nutrients were less than present inputs. Of the principal sources of growth-limiting phosphorus (table 1), only the swimmer source is subject to anthropogenic change. Although phosphorus input in pre-recreational Walden Pond may have been low, inputs may have been high in the more recent past. One thousand swimmers were observed at the 1939 sampling (Deevey, 1942); the *Concord Herald* newspaper reported on September 5, 1935, that summer Sunday afternoon crowds reached 25,000 at Walden Pond and that total summer attendance was 485,000. The relation between this apparent long-term nutrient supply increase and plant growth is not necessarily linear, and growth may lag behind supply. The effect of initial increases in phosphorus supply would be decreased because of phosphorus sequestration by mineral forms in the bed sediments followed by a larger fraction included in internal recycling as the sediment capacity for phosphorus became filled. To the extent that dissolved oxygen in the hypolimnion became depleted, sediment-sequestered phosphorus would be released from iron-mineral forms through reductive dissolution. The first occurrence of dissolved oxygen depletion at a given level in the hypolimnion may have been associated with a substantial hypolimnetic release of phosphorus, which had accumulated with iron over the ages. If HOD could be decreased to the level present in 1939 so that dissolved oxygen was not depleted in the final weeks before turnover, then annual accumulation of phosphorus in the upper hypolimnetic sediments might begin again. Because some dissolved oxygen remains in the upper hypolimnion until nearly the end of stratification, the decrease of phosphorus input necessary to sustain aerobic conditions may not be too large.

Comparison of Walden Pond with other seepage kettle-hole lakes of eastern Massachusetts indicates the variability in dissolved oxygen regimes that can develop (fig. 12). Thickness of the oxygenated layer in these lakes is correlated inversely with nutrient inputs per area of lake surface.

Trophic Stability

Walden Pond may have become more eutrophic, but the water still is clear and remains attractive to the public (fig. 13). Does the ecological health of Walden Pond require a decrease in nutrient input in an attempt to achieve more oligotrophic conditions? The answer depends on how stable the present condition is. The consequences of eutrophication, fish kills and excessive cyanobacteria blooms, present in some eastern Massachusetts kettle-hole lakes, likely could be prevented in Walden Pond by continued maintenance of dissolved oxygen in the metalimnion. An oxygenated metalimnion decreases internal recycling of phosphorus and provides cold, oxygenated water necessary for trout. Currently (2000) , the high, constant concentration of dissolved oxygen in the metalimnion is a prominent feature of stratification in Walden Pond.

The stability of metalimnetic dissolved-oxygen concentrations of Walden Pond likely involves the ecology of the macroalga *Nitella*, which grows only in the metalimnion but in amounts that dominate plant biomass in the entire lake. Although factors presently limiting growth and areal extent of *Nitella* in the Walden Pond metalimnion are not completely understood, it is known that some species of *Nitella* can not grow in eutrophic systems, which lack light penetration below the thermocline. Substantial eutrophication has occurred since the historical dissolved oxygen data collection in 1939. The principal anthropogenic perturbation causing eutrophication is the hypothesized swimmer input of nutrients. Because of the long recreational history at Walden Pond, increased nutrient input may have occurred over a period of more than 100 years. Although there is insufficient HOD data between 1939 and the present to conclude whether the present level of eutrophication has reached a new steady state, no obvious trend is evident in HOD determined in recent years—1992-2000. Stability would be enhanced by nutrient input decrease, which would benefit the deep-growing *Nitella*.

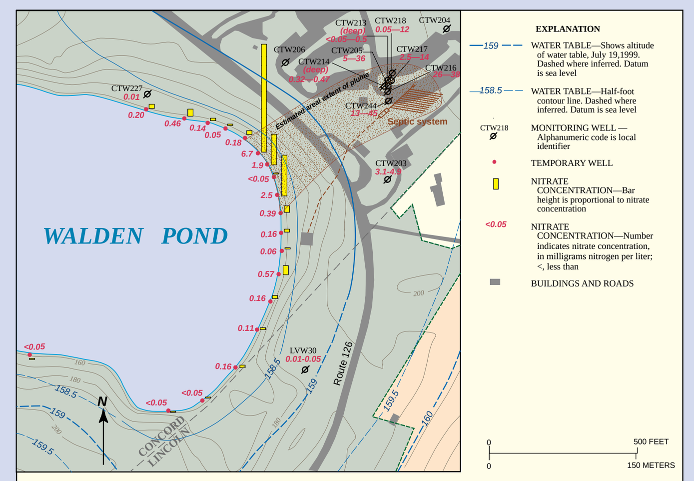


Figure 7. Nitrate concentrations in samples from observation wells near the Walden Pond State Reservation septic leach field and at temporary drive-point wells on the shore of Walden Pond. Estimated areal extent of the nitrate plume boundary is based on water-quality data and computations on ground-water flow.

Figure 8. The macroalga *Nitella* grows on the bed sediment in Walden Pond at depths between 20 and 42 feet. The *Nitella* biomass ties up nutrients and generates oxygen deep in Walden Pond.

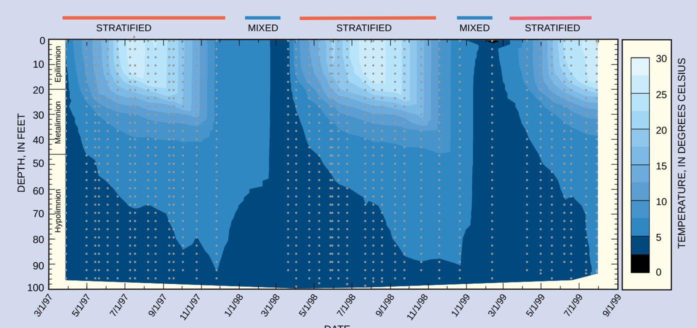


Figure 9. Distribution of temperature in Walden Pond, 1997—99, indicating thermal stratification during the summer and fall, and mixed conditions during winter and early spring. The temperature data were collected as vertical profiles, shown as lines of white dots.

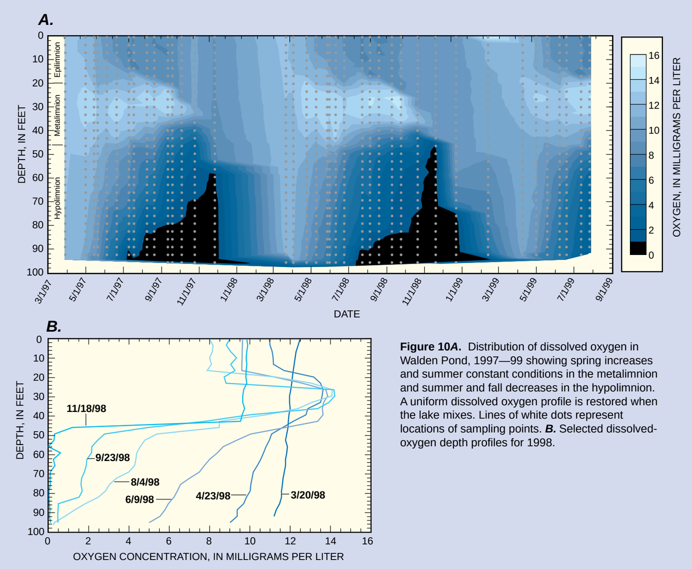


Figure 10*A*. Distribution of dissolved oxygen in Walden Pond, 1997—99 showing spring increases and summer constant conditions in the metalimnion and summer and fall decreases in the hypolimnion. A uniform dissolved oxygen profile is restored when the lake mixes. Lines of white dots represent locations of sampling points. ***B.*** Selected dissolved-oxygen depth profiles for 1998.

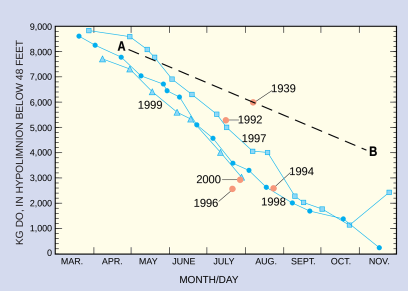


Figure 11. Dissolved oxygen (DO) content of the hypolimnion of Walden Pond, which decreases from April through lake turnover in late fall. The slope of the plot versus time represents the hypolimnetic oxygen deficit. The historical August 1939 data of Deevey (1942) define a lower deficit rate (line A-B) than that calculated from recent data. (1992 data are from Massachusetts Department of Environmental Management, written commun. (1994); 1994 data are from Baystate Environmental, Inc. (1995); and 1996 data are from this investigation.)

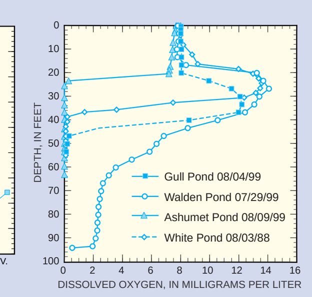


Figure 12. Comparison of dissolved-oxygen profiles for kettle-hole seepage lakes in eastern Massachusetts during summer stratification; the profiles show a range of oxygenation in the metalimnion. (Gull Pond data are from Portnoy and others, (2001); White Pond data are from Walker (1988); Ashumet Pond data are from Jacobs Engineering, Inc. (2000)).

Figure13. Walden Pond swimming beach.

SUMMARY AND CONCLUSION

The water quality of Walden Pond has been protected by land conservation and bank-stabilization efforts, and the location of its ground-water contributing area. Ground water is the dominant pathway into and out of the lake and the water-residence time for the lake is about 5 years. The contributing area excludes nearby potential sources of nutrients from the Concord Municipal landfill and a trailer park. At present, nitrogen from the Reservation septic leach field enters Walden Pond, but phosphorus is removed during transport. The net effect increases the nitrogen:phosphorus ratio of inputs, a circumstance unfavorable to growth of nuisance cyanobacteria. Walden Pond has become more eutrophic during the past 60 years, and loses deep-water dissolved oxygen. Historical and interlake comparisons of plant production indicate that the trophic level of Walden Pond could be decreased (dissolved oxygen increased) if phosphorus input were decreased, possibly through a swimmer-education program. Results of this program likely would increase the stability of the deep-growing macro alga *Nitella*, which helps maintain water quality by tying up nutrients in deep plant biomass, generating metalimnetic dissolved oxygen at the onset of stratification, and maintaining high metalimnetic dissolved-oxygen concentrations during stratification.

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By
Paul J. Friesz and John A. Colman
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