Relation of Lake-Floor Characteristics to the Distribution of Variable Leaf Water-Milfoil in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, 2005

By Denise M. Argue, Richard G. Kiah, Jane F. Denny, Jeffrey R. Deacon,
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Conversion Factors, Water-Quality Units, and Datums

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)

Temperature: Temperature is given in degrees Celsius (°C) and may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Abbreviated water- and sediment-quality units used in this report: Chemical concentrations in water and sediment samples are reported in milligrams per liter (mg/L), milligrams per kilogram (mg/kg), and percent (%). Milligrams per liter is a unit expressing the concentration of chemical constituents as mass (milligrams) of chemical per unit volume (liter) of water. Milligrams per kilogram is a unit expressing the concentration of chemical constituents as mass (milligrams) of chemical per unit mass (kilogram) of sediment. Percent is the fraction of a sample divided by the whole sample and multiplied by 100.

Abbreviated energy and time units used in this report: Energy is reported in decibels (dB) and kilohertz (kHz), and time is reported in milliseconds (ms) and seconds (s). Boat velocity is reported in knots. Underwater sound velocity is reported in meters per second (m/s).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Relation of Lake-Floor Characteristics to the Distribution of Variable Leaf Water-Milfoil in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, 2005

By Denise M. Argue[1], Richard G. Kiah[1], Jane F. Denny[2], Jeffrey R. Deacon[1], William W. Danforth[2], Craig M. Johnston[1], and Amy P. Smagula[3]

Abstract

Geophysical, water, and sediment surveys were done to characterize the effects of surficial geology, water and sediment chemistry, and surficial-sediment composition on the distribution of variable leaf water-milfoil in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. Geophysical surveys were conducted in a 180-square-kilometer area, and water-quality and sediment samples were collected from 24 sites in the survey area during July 2005.

Swath-bathymetric data revealed that Moultonborough Bay ranged in depth from less than 1 meter (m) to about 15 m and contained three embayments. Seismic-reflection profiles revealed erosion of the underlying bedrock and subsequent deposition of glaciolacustrine and Holocene lacustrine sediments within the survey area. Sediment thickness ranged from 5 m along the shoreward margins to more than 15 m in the embayments. Data from sidescan sonar, surficial-sediment samples, bottom photographs, and video revealed three distinct lake-floor environments: rocky nearshore, mixed nearshore, and muddy basin. Rocky nearshore environments were found in shallow water (less than 5 m deep) and contained sediments ranging from coarse silt to very coarse sand. Mixed nearshore environments also were found in shallow water and contained sediments ranging from silt to coarse sand with different densities of aquatic vegetation. Muddy basin environments contained the finest-grained sediments, ranging from fine to medium silt, and were in the deepest waters of the bay.

Acoustic Ground Discrimination Systems (AGDS) survey data revealed that 86 percent of the littoral zone (the area along the margins of the bay and islands that extends from 0 to 4.3 m in water depth) contained submerged aquatic vegetation (SAV) in varying densities: approximately 36 percent contained SAV bottom cover of 25 percent or less, 43 percent contained SAV bottom cover of more than 25 and less than 75 percent, and approximately 7 percent contained SAV bottom cover of more than 75 percent. SAV included variable leaf water-milfoil, native milfoil, bassweed, pipewort, and other species, which were predominantly found near shoreward margins and at depths ranging from less than 1 to 4 m.

AGDS data were used in a Geographic Information System to generate an interpolated map that distinguished variable leaf water-milfoil from other SAV. Furthermore, these data were used to isolate areas susceptible to variable leaf water-milfoil growth. Approximately 21 percent of the littoral zone contained dense beds (more than 59 percent bottom cover) of variable leaf water-milfoil, and an additional 44 percent was determined to be susceptible to variable leaf water-milfoil infestation.

Depths differed significantly between sites with variable leaf water-milfoil and sites with other SAV ($p = 0.04$). Variable leaf water-milfoil was found at depths that ranged from 1 to 4 m, and other SAV had a depth range of 1 to 2 m. Although variable leaf water-milfoil was observed at greater depths than other SAV, it was not observed below the photic zone.

Analysis of constituent concentrations from the water column, interstitial pore water, and sediment showed little correlation with the presence of variable leaf water-milfoil, with two exceptions. Iron concentrations were significantly lower at variable leaf water-milfoil sites than at other sampling sites ($p = 0.04$). Similarly, the percentage of total organic carbon also was significantly lower at the variable leaf water-milfoil sites than at other sampling sites ($p = 0.04$).

Surficial-sediment-grain size had the greatest correlation to the presence of variable leaf water-milfoil. Variable leaf water-milfoil was predominantly growing in areas of coarse sand (median grain-size 0.62 millimeters). Surficial-sediment-grain size was also correlated with total ammonia plus organic nitrogen ($Rho = 0.47$; $p = 0.02$) and with total phosphorus ($Rho = 0.44$; $p = 0.05$) concentrations in interstitial pore-water samples.

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Introduction

In freshwater bodies of New Hampshire, the most problematic aquatic invasive plant species is *Myriophyllum heterophyllum* or variable leaf water-milfoil (fig. 1) (A.P. Smagula, New Hampshire Department of Environmental Services, written commun., 2006). Once established, variable leaf water-milfoil forms dense beds that can alter the limnologic characteristics of a waterbody. The dense beds commonly clog the water and reduce circulation in shallow areas; as a result, temperatures increase throughout the water column in summer, which may lower dissolved oxygen concentrations (Smith and Barko, 1990; Keast, 1983). These types of changes may decrease the habitat quality for fish. In addition to the effect on natural lacustrine communities and their habitats, variable leaf water-milfoil infestations disrupt recreational uses of waterbodies. The lakes and ponds of New Hampshire are an important economic resource and are highly regarded for their inherent beauty and recreational uses. Invasive aquatic plants such as variable leaf water-milfoil have negatively affected swimming, boating, fishing, and property values in and around several lakes and ponds in New Hampshire (Crow and others, 2000; Halstead and others, 2003).

Lake Winnipesaukee, the subject of this study, is in the east-central part of New Hampshire (fig. 2). Moultonborough Bay is in the northern section of Lake Winnipesaukee (fig. 2).

Despite its oligotrophic status, Moultonborough Bay supports the most extensive rooted aquatic plant growth in Lake Winnipesaukee (A.P. Smagula, New Hampshire Department of Environmental Services, written commun., 2006). Several species of aquatic plants native to New Hampshire waterbodies live in Moultonborough Bay; a native species of water milfoil, bassweed, pipewort, and at least eight additional native submerged aquatic plants (which are present at low densities and occurrences) have been documented in the bay (table 1) (A.P. Smagula, New Hampshire Department of Environmental Services, written commun., 2006). In 1965, Moultonborough Bay became the first waterbody in New Hampshire where variable leaf water-milfoil (*Myriophyllum heterophyllum*) was observed (A.P. Smagula, New Hampshire Department of Environmental Services, written commun., 2006). Variable leaf water-milfoil is native to the Southeastern and Midwestern areas of the United States. In its native range, the more alkaline waters appear to limit the growth of this plant. Outside its native range, however, it adapts well to the relatively acidic, low-alkalinity, and nutrient-poor conditions of oligotrophic lakes and bays (Crow and others, 2000; Kimball and Baker, 1983) similar to Moultonborough Bay.

Since the first documented case of variable leaf water-milfoil infestation in Moultonborough Bay, the plant has been observed in 56 other waterbodies in New Hampshire (New Hampshire Department of Environmental Services, 2006). Once the plant is well established, eradication becomes complicated and expensive. Studies of Eurasian watermilfoil have noted that eradication attempts in areas where this plant is detected early have the highest rates of success (Eichler and others, 2001). These results emphasize the importance of early detection in the prevention of further infestation of invasive aquatic plants.

Figure 1. Variable leaf water-milfoil. (Photograph courtesy of A.P. Smagula, New Hampshire Department of Environmental Services.)

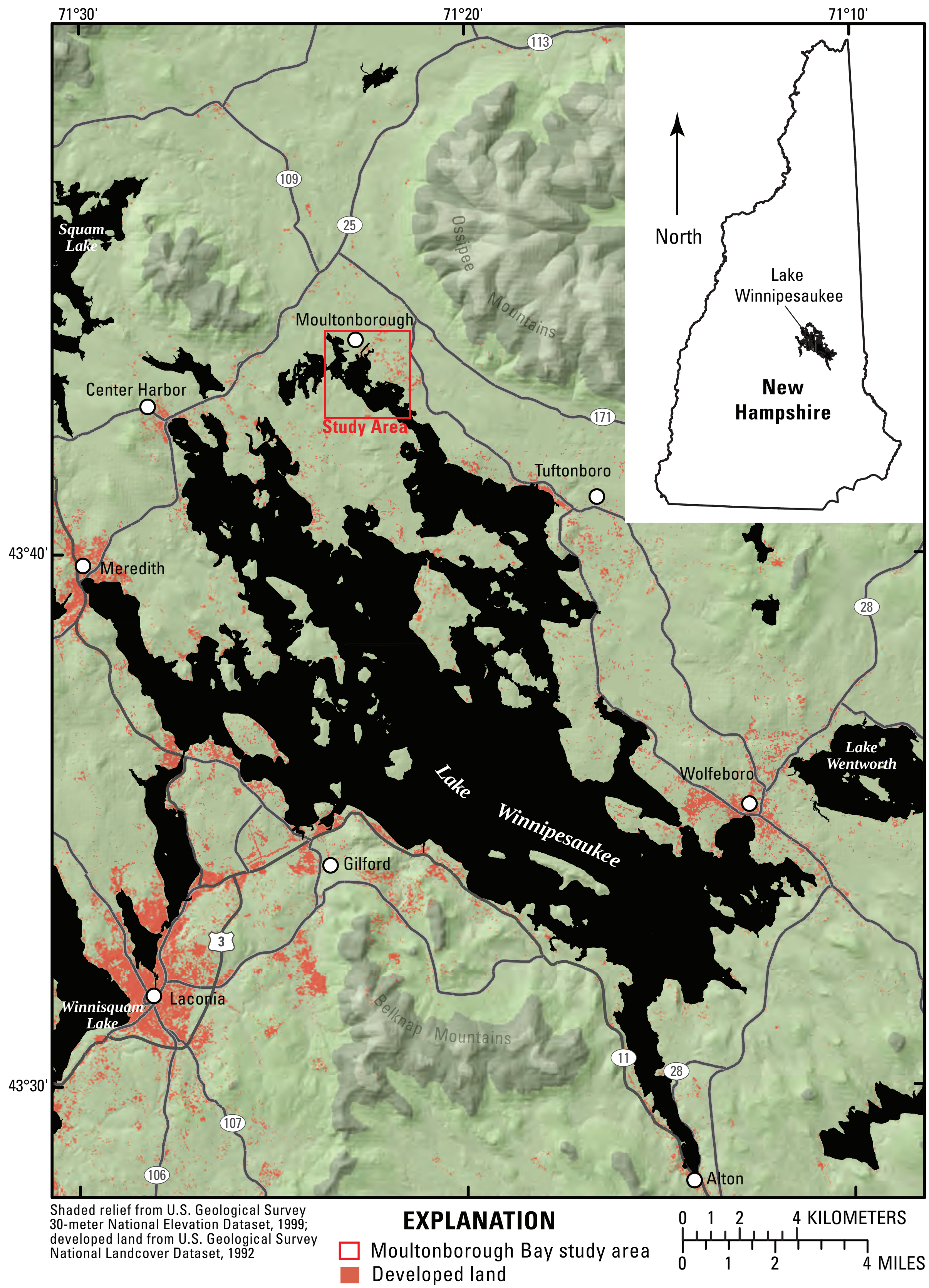


Figure 2. Study area for Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

Table 1. Family, genus, species, and common name of the most common submerged aquatic plants in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

Family	Genus and species	Common name
Haloragaceae	*Myriophyllum heterophyllum*	Variable leaf water-milfoil
Haloragaceae	*Myriophyllum humile*	Native milfoil
Potamogetonaceae	*Potamogeton amplifolius*	Bassweed
Eriocaulaceae	*Eriocaulon septangulare*	Pipewort

Effective management strategies for invasive aquatic plants are continually being investigated and developed by federal, state, and local agencies, as well as private volunteer organizations. A priority of the U.S. Geological Survey (USGS) Invasive Species Program (Lovich and others, 2003) and the 1999 Federal Executive Order on Invasive Species is to document and monitor invasions and develop methods that resource managers can use to evaluate management strategies. In 2005, the New Hampshire Department of Environmental Services (NHDES) cooperated with five research entities to develop six projects that focused on characterizing the habitats of variable leaf water-milfoil, methods of long-term control, and methods of eradication. For one of these projects, the USGS cooperated with the NHDES to investigate the distribution (presence and density) of variable leaf water-milfoil in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, in May through July of 2005. This study utilized geophysical and conventional water-quality measurements to identify lake environments that may provide suitable habitat for the establishment and growth of variable leaf water-milfoil. The results of the study are intended to assist resource managers in federal and state agencies by providing methods for detecting variable leaf water-milfoil and for identifying areas susceptible to infestation. Ultimately, this information may lead to early detection, prevention, and more effective mitigation strategies.

Purpose and Scope

This report (1) describes geophysical methods used to assess limnological characteristics; (2) describes the lake-floor environment and the distribution of submerged aquatic vegetation (SAV); and (3) correlates lake-floor environments, and water and sediment chemistry with the presence and density of variable leaf water-milfoil.

This report describes the suite of geophysical surveys done in a 180-km^2 area to characterize lake-floor environments, the surficial-sediment distribution, and the underlying geology. Acoustic ground discrimination systems (AGDS) surveys were conducted to assess the spatial distribution of SAV and to determine surficial-sediment characteristics. The results of water and sediment samples collected from 24 sites are described in this report. Three categories were used to differentiate the 24 sampling sites for analysis: variable leaf water-milfoil (sampling sites where all SAV present was variable leaf water-milfoil), other SAV (sampling sites where little to none of the SAV present was variable leaf water-milfoil), and no SAV (sampling sites where there was no SAV present).

Previous Studies

High-resolution geophysical systems are routinely used in the geologic mapping of sea- and lake-floor environments; this mapping is effective in the management of lacustrine and marine resources, habitat and environmental monitoring, and in providing baseline information for long-term limnologic and oceanographic research (Shaw and others, 1997; Butman and others, 2000; Gardner and others, 2000; Schwab and others, 2000; Twichell and others, 2000; Denny and Colman, 2003; Baldwin and others, 2004; Collier and Brown, 2005; Colman, 2005; Barnhardt and others, 2006). Technological advances in surficial (sidescan-sonar and swath bathymetry) and sub-bottom (seismic) systems now enable detailed (meter to submeter) mapping of sea- and lake-floor environments. When these data are integrated with physical sampling, the morphology, surficial-sediment distribution, and subsurface geology of the lake floor can be defined at fine scales.

Many studies have compared the use of surficial geophysical-mapping systems such as sidescan-sonar and swath bathymetric systems (Brown and others, 2002; Kenny and others, 2003; Brown and others, 2004) to narrow-swath or single-beam systems used in AGDS, to define benthic environments (Foster-Smith and Sotheran, 2003; Brown and others, 2005). Kenny and others (2003) recognized the effectiveness of AGDS in demarcating changes in bottom characteristics when accompanied by sufficient ground-truth data and in defining small-scale habitats (smaller than 1 km^2). Brown and others (2005) suggest the complementary use of sidescan-sonar and AGDS data to provide a robust approach that uses the strength of each system for benthic mapping. Sidescan-sonar surveys provide complete imagery of the sea or lake floor and can be used to broadly define benthic environments and boundaries, and high-resolution point data from the AGDS can be used to characterize these environments further.

Other investigations have used AGDS survey data to describe the distribution and density of SAV (Maceina and Shireman, 1980; Duarte, 1987; Thomas and others, 1990; Valley and Drake, 2005). Valley and others (2004) used AGDS data to measure the accuracy and precision of SAV estimates of percent bottom coverage and percent biovolume. Because results of ground-truth surveys did not differ significantly from estimates determined from AGDS, AGDS vegetation surveys were considered effective. Lubniewski and Stepnowski (1997) reported that they successfully used AGDS data to characterize sea-bottom sediment characteristics and composition.

Currently (2007), limited research has been done on the effects of water and sediment quality on the distribution of variable leaf water-milfoil. A detailed study of selected mineral concentrations measured in the submersed apical shoots of variable leaf water-milfoil in Lake Winnipesaukee and Lee's Pond, New Hampshire, related these concentrations to site and season (Kimball and Baker, 1982) and to temporal and morphological factors (Kimball and Baker, 1983). Kimball and Baker (1982) compared the changes in magnitudes of variation in apical mineral concentrations at a site for each season and determined that these variations did not significantly differ in magnitude from the variations among different sites during the same season. Kimball and Baker (1983) reported that variable leaf water-milfoil is a perennial submerged aquatic plant, that it maintains a considerable amount of green biomass through the winter season, and that plant structure and season influence the mineral concentrations in its apical shoots.

Much work has been documented on Eurasian watermilfoil, another problematic invasive species in the Myriophyllum genus. Nichols (1994) reported that Eurasian watermilfoil was growing at greater depths and in areas with less organic matter than other SAV in a lake in Wisconsin. Smith and Barko (1990) summarized literature describing Eurasian watermilfoil and reported general characteristics about its habitats: it grows in depths that range from 1 to 4 m; plants are essentially evergreen; photosynthesis occurs in cool (15ºC) waters; and it grows best in fine-textured inorganic sediments. In addition, they reported that uptake through the roots is the primary source of phosphorus and that ammonium is preferred over nitrate as a nitrogen source. Keast (1983) investigated the introduction of Eurasian watermilfoil as habitat for fish in a lake in Canada. Keast observed Eurasian watermilfoil growing at depths that ranged from 2 to 3.5 m in previously open water and concluded that Eurasian watermilfoil was not replacing native species but occupying another niche in the environment. Madsen (1998) indicated that the best predictors of Eurasian watermilfoil were water-column total phosphorus and Carlson's Trophic State Index, which is a method for characterizing a lake's trophic state.

Barko and others (1986) investigated a variety of environmental factors affecting the distribution and species composition of SAV and reported that light, water temperature, sediment composition, and inorganic carbon availability were the most important. Barko and Smart (2006) investigated the effects of sediment-related mechanisms on the growth of SAV and determined that correlations between SAV growth and nutrient concentrations in the interstitial water or total sediment were weak; moreover, correlations between SAV growth and total or extractable sediment nutrients were generally unsuccessful. Loeb and Hackley (1988) studied the sparse occurrence of macrophytes in oligotrophic lakes and examined the potential growth-regulating factors among supporting and nonsupporting habitats for macrophytes. They concluded that ground-water inflows may affect the distribution of SAV. Results from Lodge and others (1989) indicated a positive correlation between ground-water inflows and SAV. Lodge and others (1989) suggested that ground-water inflow may contribute to SAV growth by contributing an additional source of nutrients and maintaining higher winter temperatures in sediments, thus enhancing winter survival of perennial SAV.

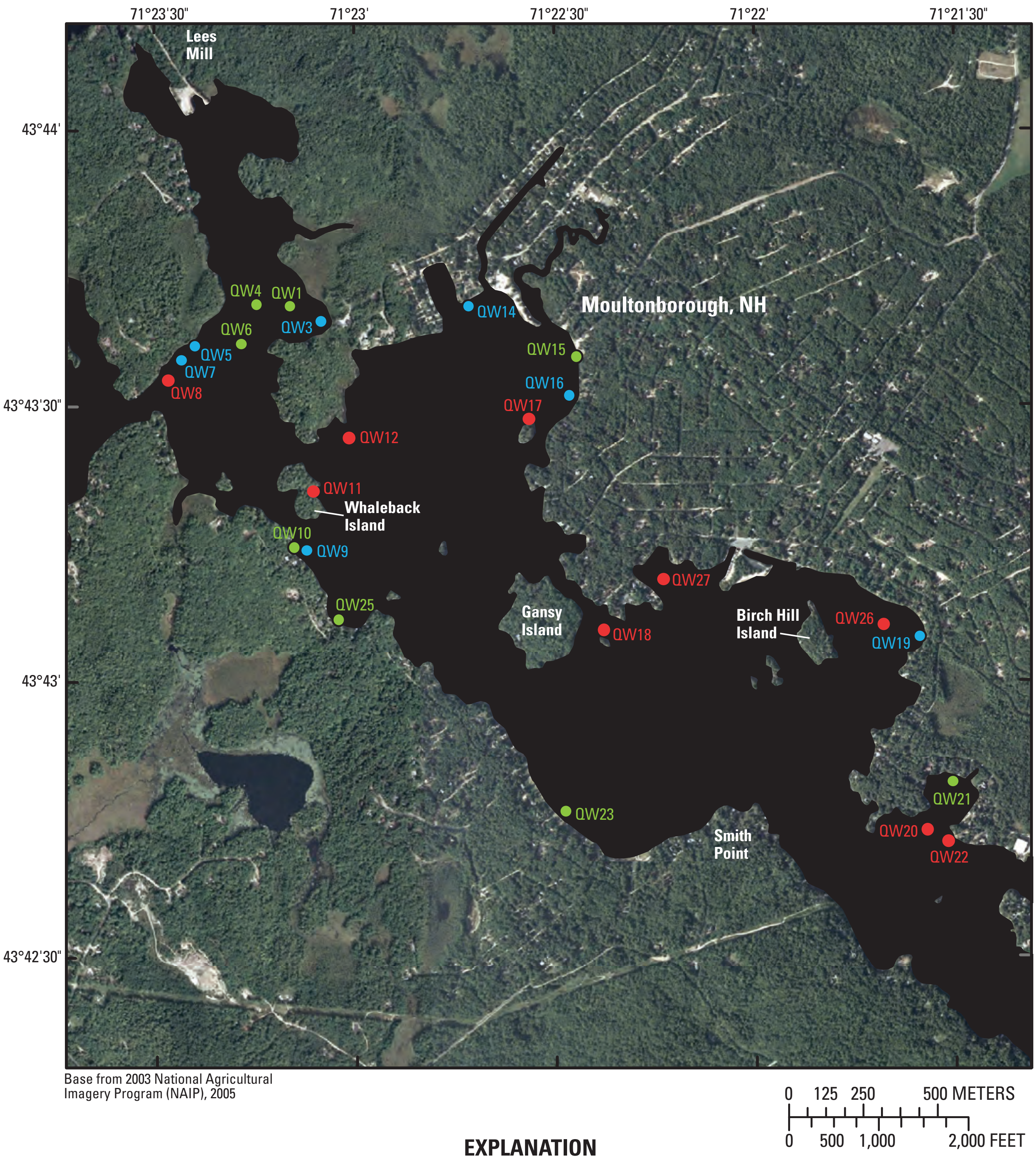
Methods of Data Collection and Analysis

Geophysical and sediment-sampling surveys were used to characterize the surficial lake-floor environment [lake-floor morphology (depth), surficial-sediment distribution, and the underlying geology] and the presence and density of SAV. Water-column, interstitial pore-water, and sediment sampling were designed to determine the concentrations of nutrients and inorganic constituents and the characteristics of surficial sediments.

A preliminary AGDS survey was conducted in May 2005 to collect data on the distribution of SAV and surficial sediment. Ground-truth data were collected to provide visual confirmation of variable leaf water-milfoil presence, sediment type, and depth. On the basis of these data, 24 sites for water and sediment sampling were selected (fig. 3). These sites were spatially distributed throughout the study area and represent a wide range of habitat conditions.

Geophysical Mapping of the Lake Floor

The characteristics of the surficial sediments on the lake floor, the underlying sediments, and the bedrock surface were mapped using the following suite of geophysical instruments: interferometric sonar (swath bathymetry), sidescan sonar, and seismic-reflection profiler (fig. 4). Sediment samples, bottom photographs, and video also were obtained (fig. 4). For all surveys, the ship's position was determined through the use of differential global positioning system (DGPS) navigation. Surveyed depths within Moultonborough Bay ranged from approximately 1.5 to 15 m. Water depths less than 1.5 m were not accessible because of the limited draft of the vessel.



EXPLANATION

- QW22 Variable leaf water-milfoil site and identifier
- QW19 Other-SAV site and identifier
- QW23 No-SAV site and identifier

Figure 3. Water- and sediment-sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. (SAV, submerged aquatic vegetation.)

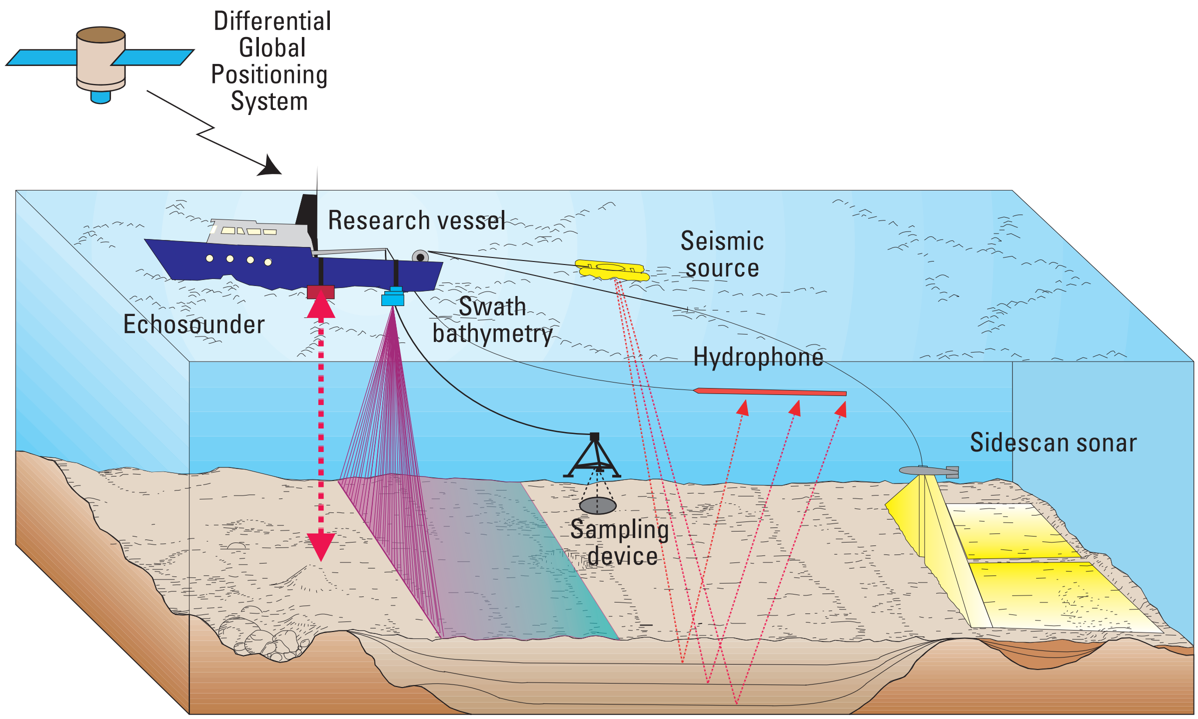


Figure 4. Geophysical and sampling tools used to map lake-floor environments.

Swath-bathymetric systems acquire depth information in a swath to either side of the survey vessel and provide continuous coverage of the lake floor (fig. 4). These data were acquired with an SEA Ltd. Submetrix 2000 series interferometric sonar (234 kiloHertz (kHz)). Swath width was a function of depth, but was generally 7 to 10 times the water depth, yielding a 7 to 100-m swath. A motion reference unit mounted directly above the sonar head recorded vessel motion (heave, pitch, roll, and yaw); this attitude information was used to rectify bathymetric measurements. A sound-velocity profiler was used to determine the sound-velocity structure of the water column to correct for variations in the speed of sound. The vertical resolution of the depth measurements was approximately 1 percent of the water depth. The processed bathymetric grid was mapped at a 1 m/pixel resolution and incorporated into a geographic information system (GIS).

Sidescan-sonar systems record the intensity of sound reflected from the lake floor (fig. 4). This backscatter reveals information about the physical characteristics of the lake-floor sediments. These data were acquired with a Klein 3000 dual-frequency (100/500 kHz) sidescan-sonar system. Data were digitally recorded at a 2-kHz sampling rate, yielding approximately a 0.2-m pixel resolution by following the methodology of Danforth and others (1991). A 50-m trackline spacing was used to ensure complete sidescan-sonar coverage of the lake floor. Data were processed and used to create a composite image of the lake floor at a 1 m/pixel resolution (Danforth and others 1991; Paskevich, 1992; Danforth, 1997). This imagery was then incorporated into a GIS.

Seismic-reflection systems are used to map the subsurface geology, such as the thickness and geometry of the underlying strata (fig. 4). These data were acquired with an Edgetech SB-424 chirp sub-bottom profiler. Data were recorded at a 75-millisecond (ms) record length and a 4-24 kHz sweep and were logged by using Triton-Elics Delph seismic acquisition software. Seismic-reflection data were converted to single-channel SEG-Y by using the Scripps Institution of Oceanography’s SIOSEIS seismic-processing software (Henkart, 2005). Automatic gains were applied to the data through the use of the Colorado School of Mines’ Seismic Unix seismic-processing software (Cohen and Stockwell, 2001). The processed SEG-Y and navigation data were then imported into Seisworks (Landmark Graphics Corporation, Inc.), an integrated seismic-interpretation package, for digital interpretation. Selected horizons were digitized to calculate the depths to reflectors. An average sound velocity of 1,500 meters per second (m/s) was used to determine the depth to bedrock and sediment thickness.

On the basis of variations in the backscatter patterns observed in the sidescan-sonar data, 40 locations on the lake floor were selected for the collection of sediment samples and for bottom photography and video. The sediment samples were collected with a mini-SeaBOSS (SeaBed Observation and Sampling System), from the upper 10 cm and were used to provide ground truth for the sidescan-sonar and seismic-reflection data (figs. 4 and 5). Grain-size analyses were done by the USGS by following the methodology of Poppe and others (1985) and Poppe and Polloni (2000).

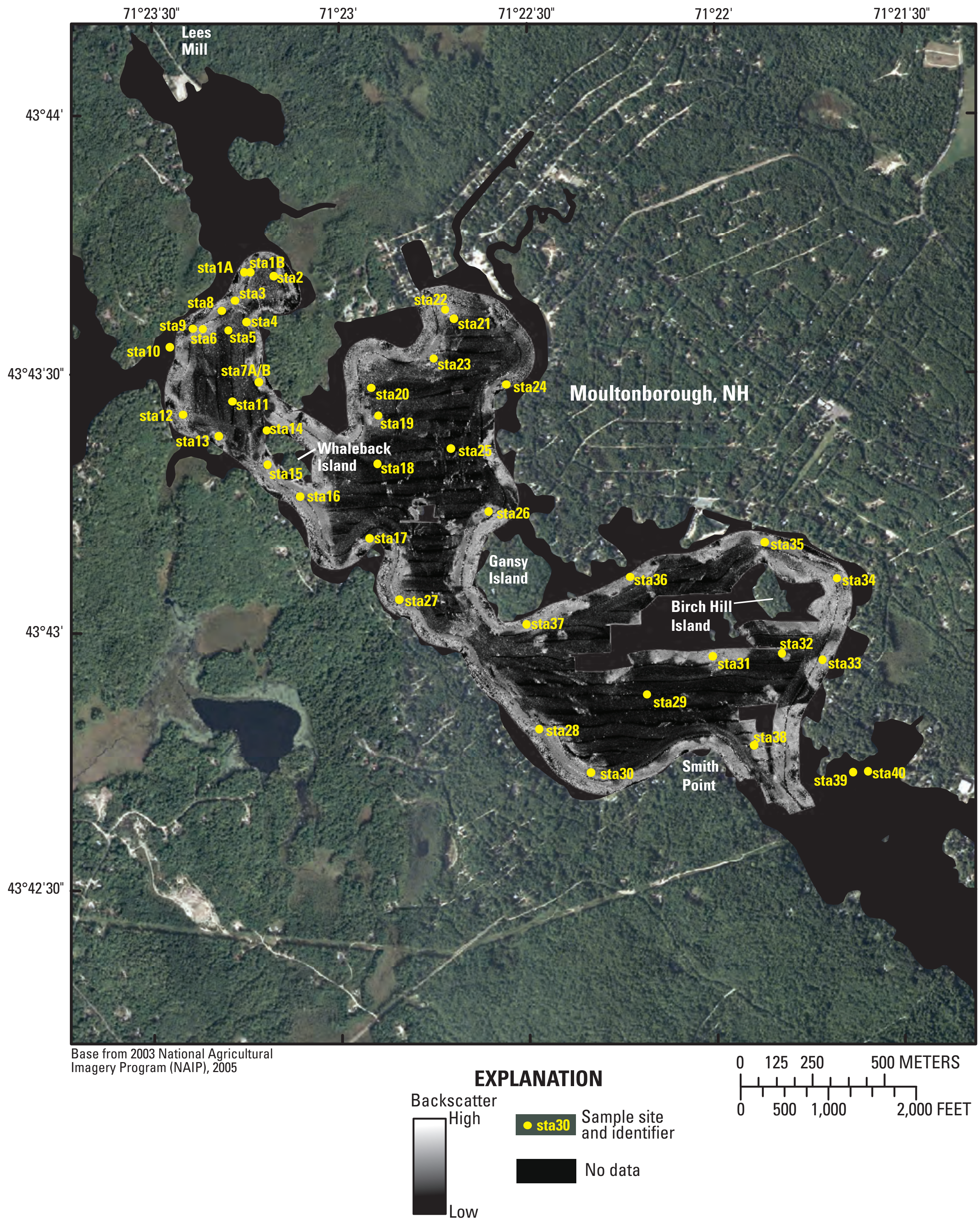


Figure 5. Sidescan-sonar imagery from Moultonborough Bay, Lake Winnipesaukee, New Hampshire, and the locations and names of the sites where samples were taken to provide ground truth for sonar data. (Light tones represent high backscatter and dark tones represent low backscatter within the image. See appendix 1 for sediment-texture data.)

Acoustic Ground Discrimination System Survey

A dual-frequency digital echosounder system (by Biosonics) with two 6° single-beam transducers (120 and 420 kHz) was used to map the SAV and characterize surficial sediments (Burczynski and others, 2005a). The AGDS data were acquired in a linear pattern throughout the study area and in three concentric transects that follow the margin of the shoreline. The concentric transects were spaced approximately 10 m, 20 m, and 30 m from the shoreline. Boat speed was maintained at approximately 2.5 knots to maintain a horizontal resolution of approximately 2 m (Valley and Drake, 2005). AGDS data at the 24 sampling sites were collected from stationary vessel positions.

Geographic location was determined with a Trimble *Ag*GPS 124/132 receiver and integrated with the AGDS data. The 120-kHz transducer was configured to send five pings at a pulse duration of 0.4 ms and to collect the reflected signal at a threshold of -60 decibels (dB). The 420-kHz transducer was configured to send five pings at a pulse duration of 0.1 ms and to collect the reflected signal at a threshold of -130 dB.

The 120-kHz echosounder data were processed by using Visual Bottom Typer (VBT) software developed by Biosonics (Burczynski and others, 2005b). Every group of 20 consecutive data points was summarized by VBT software into a single report representing approximately 5 m of the lake floor. These bottom-type data included the DGPS location, bottom depth, energy levels from different sections of the acoustic echo envelope (E_0), and the fractal dimension (FD), which is a measure of the roughness of the bottom sediment (Lubniewski and Stepnowski, 1997). Fractal dimension classifies the bottom type by characterizing the shape of the bottom echo (Burczynski and others, 2005a). The median number of reports generated during stationary-boat positioning for each of the 24 sampling sites was 15. Information from each of the reports was evaluated to determine bottom-type information for the 24 sampling sites.

The 420-kHz echosounder data were processed by using EcoSAV software developed by Biosonics (Burczynski and others, 2005a). Every group of eight consecutive data points was summarized by EcoSAV software into a single report representing approximately 2 m of the lake floor. The processed vegetation data included a DGPS location, binary information on plant presence or absence, the average plant height, and bottom depth. The percentage of vegetative cover was calculated by using plant presence and plant absence information for each AGDS data point along the linear and concentric transects as well as at each of the 24 sampling sites. The median number of reports generated during stationary-boat positioning for each of the 24 sampling sites was 32. Information from the reports was averaged to determine the percentage of vegetative cover, average plant height, and bottom depth at each of the sampling sites.

The percentages of vegetative bottom cover from the transects were used to create an interpolated vegetation map. A natural-neighbor technique was used to interpolate between measured points for the percentage of vegetative cover. This interpolator technique is a hybrid between inverse distance-weighted (IDW) and Euclidean allocation (Environmental Systems Research Institute, 2002; 2004). The interpolated data values were derived by a weighted average of the percentage of bottom cover from the nearest measured points as determined by their Euclidean allocation areas. To eliminate false vegetation detections, information about plant presences recorded at depths greater than 4.3 m were set to zero. This helped to prevent false positives below the photic zone, the bottom of which is estimated to be at 1.7 times the Secchi-disc depth (Wetzel, 1983).

Water Column, Interstitial Pore Water, and Surficial-Sediment Sampling

Water-column samples were collected by using a peristaltic pump and polyethylene tubing placed approximately 2 ft from the bottom of the lake. All samples were handled and processed according to standard USGS surface-water protocols (Wilde and Radtke, 1998a; 1998b).

Interstitial pore-water samples were collected by using two methods. When bottom sediments allowed for sufficient yield, a pushpoint sampler was used to collect the interstitial pore water (Zimmerman and others, 2005). When bottom sediments did not yield sufficient water to maintain continuous low-flow pumping, a piezometer was installed. Piezometers were constructed of polyvinyl chloride (PVC) material with a 6-in. slotted-screen interval. Once the piezometer was installed, it was allowed to equilibrate for approximately one hour prior to pumping. The water level in the piezometer, specific conductance, pH, and temperature were monitored prior to sample collection. A sample was collected when all field parameters had been stable for three consecutive independent readings (Wilde and Radtke, 1998a).

Water-column and interstitial pore-water samples were analyzed for concentrations of potassium, dissolved nitrite plus nitrate, ammonium nitrogen, total ammonia plus organic nitrogen, total phosphorus, dissolved orthophosphate, iron, and organic carbon at the New Hampshire Department of Environmental Services Laboratory in Concord, New Hampshire. Field measurements for specific conductance, pH, temperature, dissolved oxygen, and Secchi-disk depth also were made.

Sediment samples were collected for chemical and grain-size analysis from the upper 0 to 10 cm of the lake sediment at 24 sites according to standard USGS protocols (Sheldon and Capel, 1994). A small polyethylene scoop was used to collect sediment at sites where the water depth was less than 1.5 m. A hand-held coring device was used to collect sediment at sites where the water depth was greater than 1.5 m. All sediment samples were analyzed at SGS Environmental Services Laboratory in Lakefield, Ontario for concentrations of potassium, dissolved nitrite plus nitrate, ammonium nitrogen, total ammonia plus organic nitrogen, total phosphorus (determined by using a strong-acid digest), soluble phosphorus (determined by using the Olsen method), loosely sorbed phosphorus, iron-bound phosphorus, and iron; percentage total organic carbon; percentage moisture; and grain-size composition.

Quality Assurance and Quality Control

Quality assurance and quality-control procedures for water- and sediment-chemistry data included analyses of field blanks and replicate samples. Field blanks provide information on bias or potential for contamination of samples by collection, processing, and analysis (Spahr and Boulger, 1997). Concentrations for constituents discussed in this report were below the detection limits for the field-blank samples. Replicate samples provide information on the variability of analytical results caused by sample collection, processing, and analysis (Spahr and Boulger, 1997). In this report, the constituent concentrations in environmental and replicate samples from the water column had a median absolute difference of 0.004 mg/L; the absolute differences between replicate pairs ranged from 0 to 0.2 mg/L. The constituent concentrations in environmental and replicate samples of interstitial pore water had a median absolute difference of 0.05 mg/L; the absolute differences between replicate pairs ranged from 0.007 to 0.4 mg/L. The differences in sediment grain-size composition between environmental and replicate samples were within 3 percent. In summary, these results indicate that sample processing and analysis did not introduce enough variation in the environmental data to affect the interpretation of results.

Quality assurance of the accuracy of the interpolated maps was accomplished by two methods. Fifty-five randomly selected locations representing variable leaf water-milfoil, other SAV, no SAV, or transition points where the interpolated map shows changes in the vegetation density were verified against video data from the ADGS survey. This comparison demonstrated that interpolation of AGDS data in areas where the percentage of vegetative bottom cover changes substantially over a short distance may affect the accuracy of estimated vegetation densities. The smoothing effect of interpolation techniques may not accurately portray abrupt changes in vegetation density.

The percentage of vegetative bottom cover at each of the 24 sampling sites was compared to the interpolated values for the percentage of bottom cover from the interpolated map. Nine of the interpolated values were within 5 percent, and 13 of the interpolated values were within 20 percent of the percentage of bottom cover measured at the 24 sampling sites. The difference in values for two sites in areas with large boulders was greater than 20 percent (28 and 43 percent). The AGDS data indicated plant material at site QW4 (37.9 percent), but ground-truth information revealed no SAV. Underwater video showed less transparent water and increased amounts of flocculent matter on the sediment surface at this site, whereas flocculent matter was absent at all other sites. The presence of flocculent matter on the lake floor and in the water column may yield false identification of SAV by AGDS methods (Burczynski and others, 2005a).

Statistical Methods

The Wilcoxon and Kruskal-Wallis group-comparison tests (nonparametric) were used to determine significant statistical differences in the ranks of the median concentrations of the constituent values (Helsel and Hirsch, 1992). If the Kruskal-Wallis test indicated significant differences, the Tukey multiple-comparison test was applied to rank-transformed data to determine which site types (variable leaf water-milfoil sites, other-SAV sites, and no-SAV sites) differed significantly (Helsel and Hirsch, 1992). The Spearman rank-correlation test was used to determine the strength of association between two variables (Helsel and Hirsch, 1992). Water-quality and sediment-constituent concentrations compared between and among site types were considered statistically different if the probability was less than or equal to 5 percent ($p < = 0.05$). Measures chosen to describe the grain-size distribution of the sediment samples were the 16th (d16: fine fraction), 50th (d50: median fraction), and 84th (d84: coarse fraction) percentiles of the cumulative-frequency distribution curves (Inman, 1952). Figure 6 shows how the d16, d50, and d84 are determined from two representative curves. In this example, 16 percent of the sediment sample from one of the other-SAV sites (QW7) is smaller than 0.15 mm, whereas 16 percent of the sediment sample from one of the variable leaf water-milfoil sites (QW12) is smaller than 0.32 mm (fig. 6). Statistical differences between site types were determined on the basis of these three measures. All statistics were analyzed by using SAS software (Statistical Analysis Software Institute, 1999, 2002).

Characterization of the Lake Environment

Swath bathymetry, sidescan-sonar, seismic-reflection and sediment-grain-size analysis were used to define the lake-floor environment in terms of depth, surficial-sediment distribution, and underlying geology. AGDS survey data were used to characterize the spatial distribution of SAV and bottom types. Water and sediment were sampled to determine selected constituent concentrations in the water column, interstitial pore water, and the top 10 cm of sediment. Additionally, grain size was analyzed in the surficial-sediment samples. Data were used to determine whether there were correlations between the presence of variable leaf water-milfoil and measures of the lake-floor environment, including water and sediment quality, and surficial sediments.

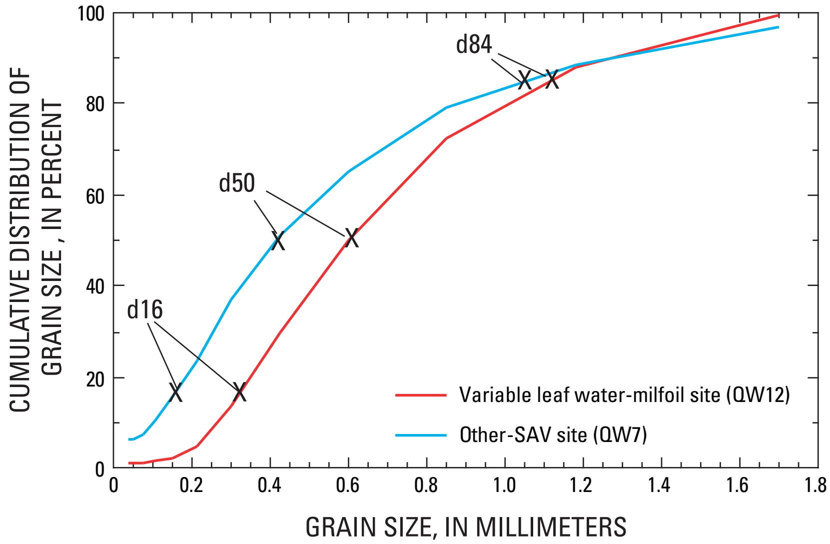


Figure 6. Measures chosen to describe the grain-size distribution of sediment samples include the 16th (d16: fine fraction), 50th (d50: median grain size), and 84th (d84: coarse fraction) percentiles of the cumulative-frequency distribution curves (using the method of Inman, 1952). (SAV, submerged aquatic vegetation; see figure 3 for site locations QW7 and QW12.)

Lake Floor

Moultonborough Bay ranged in depth from less than 1 m (within 100 m of the shore) to about 15 m in the deepest parts of the localized embayments. The deepest areas within the bay were northwest of Smith Point and north of Gansy Island, with water depths of 13 and 15 m, respectively (fig. 7). The shallow margins of the bay ranged from steep-sided to gently sloping with depths increasing toward the centers of the embayments. Slopes were steepest along the western and southern margins of the southern embayment and along the shoreline north of Gansy Island.

Sidescan-sonar data revealed three distinct patterns of acoustic backscatter from the lacustrine sediments of Moultonborough Bay: high backscatter, mottled backscatter, and low backscatter (fig. 5) (table 2). High-backscatter areas were generally along bay margins in water depths less than 5 m. Exceptions occurred along Gansy Island and in the southern embayment where high backscatter was observed at 7.5–8 m water depth. High-backscatter areas contained sediments that ranged from silt to very coarse sand (median grain sizes 0.07 to 1.2 mm, respectively). Isolated pockets of high backscatter were detected throughout the bay center and along the shoreward margin and were associated with boulders or exposed bedrock. Mottled-backscatter areas were predominantly along the northwest, north, and eastern margins of the bay where water depths were less than 5 m. Mottled backscatter was characterized by a diffuse mixture of low and high backscatter (fig. 5), with surface sediments that ranged in grain size from silt to coarse sand (median grain size 0.01–0.74 mm). Isolated pockets of gravel and boulders also were observed within these regions. Low-backscatter areas were found in the deeper waters of the bay (5–15 m water depth) and were characterized by fine-grained sediments (silt with median grain size less than 0.06 mm), with the finest grain sizes collected in the deepest waters.

The subsurface geology of Moultonborough Bay exhibited four distinct acoustic units: bedrock (preglacial), glaciolacustrine (glacial), lacustrine (postglacial), and gas (fig. 8). Bedrock in this region consists of metamorphic and igneous rocks ranging in age from 380 million years (Lower Devonian) to 180 (Triassic) million years (Quinn, 1941; Goldthwait, 1968; Van Diver, 1987; Lyons and others, 1997). The more easily erodible igneous rocks, such as the Winnipesaukee Tonalite (Lyons and others, 1997), were deeply scoured by glaciers to form the present bays and lakes (Goldthwait, 1968). Seismic-reflection profiles show glacial scour of the underlying bedrock. Depth to bedrock (as measured from the lake surface) ranged from 2.5 m along the bay margins to 27 m in the center embayments (fig. 9). Bedrock is commonly exposed along the bay margins and less commonly in the central areas as isolated topographic

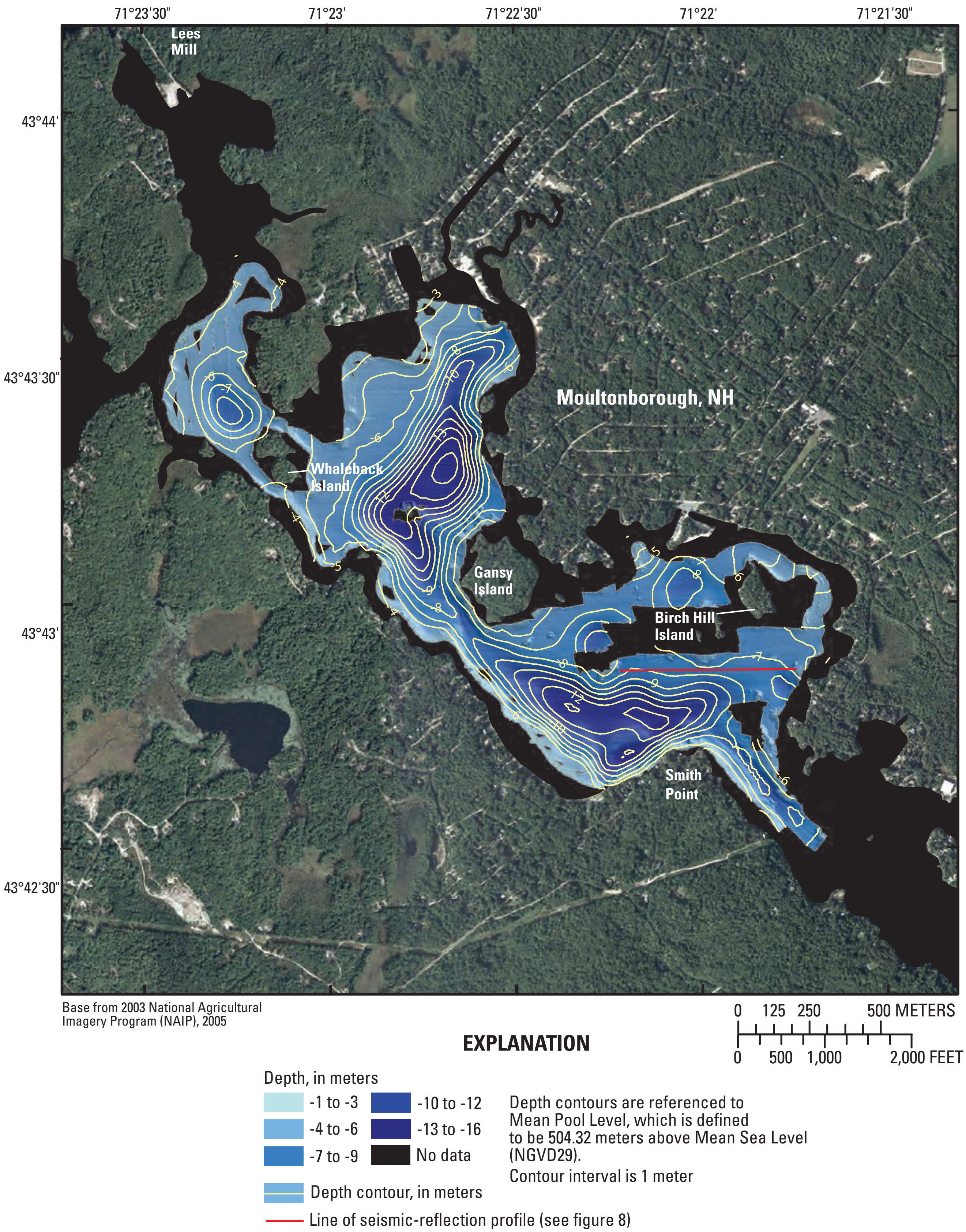


Figure 7. Bathymetry for Moultonborough Bay, Lake Winnipesaukee, New Hampshire. Red line indicates location of seismic-reflection profile in figure 8.

Table 2. Lake-floor environments, sidescan-sonar backscatter patterns, descriptions, sediment textures, and water depths in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[m, meters; mm, millimeters; <, less than]

Lake-floor environment	Backscatter pattern	Description	Sediment texture	Water depth (meters)
Rocky nearshore	High	Primarily along bay margin; bedrock outcrop and boulders; thin accumulation of sediment; high-relief	Silt to very coarse sand, (median grain size 0.07 to 1.2 mm); boulders and exposure of bedrock	< 5
Mixed nearshore	Mottled	Primarily along bay margin; diffuse mixture of low and high backscatter; isolated pockets of high-backscatter associated with gravel and boulders; thickness of sediment ranges from < 1 to 5 m; moderate to high-relief	Silt to coarse sand, (median grain size 0.01–0.74 mm); isolated gravel, boulders	< 5
Muddy basin	Low	Located in deep waters of the bay; uniform low-backscatter pattern; thickest accumulation of sediment (1 to 15 m); low relief	Silt, (median grain size < 0.06 mm)	5–15

highs that form small islands. Bedrock was obscured by gas in the overlying sediments (figs. 8 and 9) in some parts of the seismic records.

Sediment accumulations up to approximately 15 m thick overlie high-relief bedrock within Moultonborough Bay, with the greatest accumulation in the central areas of the embayments and thinner layers (less than 1 m thick) along the bay margins (fig. 10). Three acoustic signatures were detected in the sediments (fig. 8). The first unit was well laminated and draped conformably over bedrock, and most likely represents glaciolacustrine sediments deposited during the retreat of the Laurentide ice sheet. These deposits are probably composed of glacial till and outwash, and contain a mixture of rock, sand, silt, and clay, which is characteristic of glaciolacustrine deposits (Goldthwait, 1968; Van Diver, 1987; Benn and Evans, 1998). Along the bay margins, this unit was truncated by a strong, flat reflector that may represent an erosional surface formed during periods of lower lake level. The second unit was generally acoustically transparent, with the exception of closely spaced internal reflectors in small-scale topographic lows (fig. 8), and is thought to represent modern (Holocene) lacustrine deposits. Internal reflectors present within the topographic lows may represent cyclic deposition within the lake. A third unit is characterized by gas in the sediments (fig. 8). Gas was found within the central portions of the embayments and obscures parts of the seismic record in these areas. The gas was probably generated by decomposition of organic matter in the Holocene (post-glacial) lake sediments.

Moultonborough Bay was characterized by three lake-floor environments: rocky nearshore, mixed nearshore, and muddy basin (fig. 11). Rocky nearshore environments were mapped in water shallower than 5 m and consisted of high-backscatter coarse-grained sediments, boulders, and bedrock outcrop. Seismic-reflection profiles show thin accumulations of glaciolacustrine and modern (Holocene) sediments and underlying bedrock close to or at the lake floor in these areas. Mixed nearshore environments were also mapped in water shallower than 5 m; these areas are characterized by mottled backscatter and sediments ranging from silt to coarse sand. Data collected with bottom photographs and video revealed differing densities of aquatic vegetation in these areas. Seismic-reflection profiles show an accumulation of glaciolacustrine and modern (Holocene) sediment from less than 1 to 5 m thick and exposures of bedrock in isolated areas along the bay margin. Muddy basin environments were mapped in water deeper than 5 m and were characterized by low-backscatter fine-grained sediments (silt). This low-backscatter sediment represents modern deposition within the bay and most likely corresponds to the upper acoustically transparent unit interpreted from the seismic-reflection profiles.

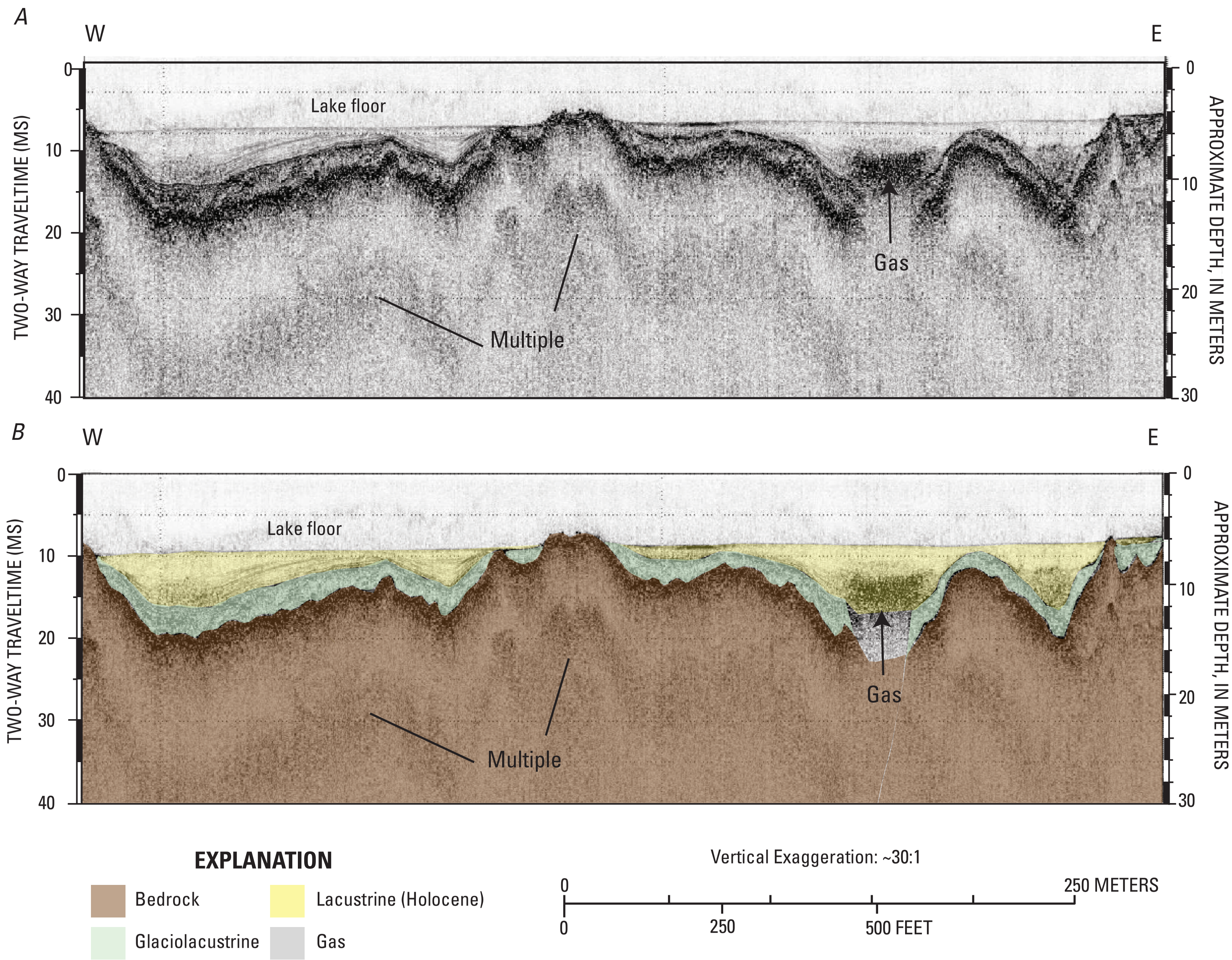


Figure 8. Seismic-reflection profile in Moultonborough Bay, Lake Winnipesaukee, New Hampshire: (*A*) original image and (*B*) interpreted profile showing bedrock, glaciolacustrine sediments, and lacustrine sediments. Gas is present in the glaciolacustrine and lacustrine sediments. (See figure 6 for location; multiples are "echos" of the seismic signal.)

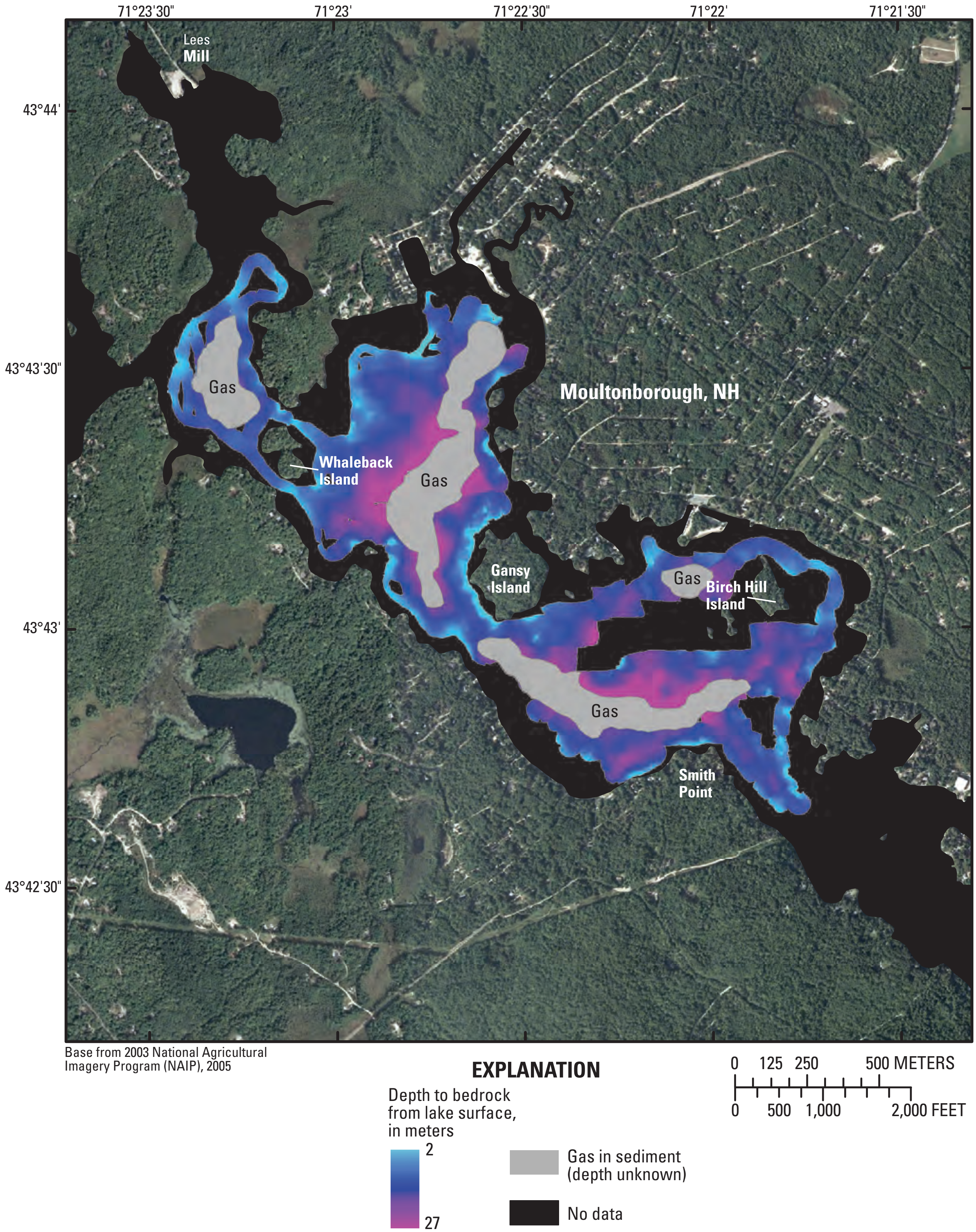


Figure 9. Depth to bedrock as measured from the lake surface in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, determined through the use of seismic-reflection data.

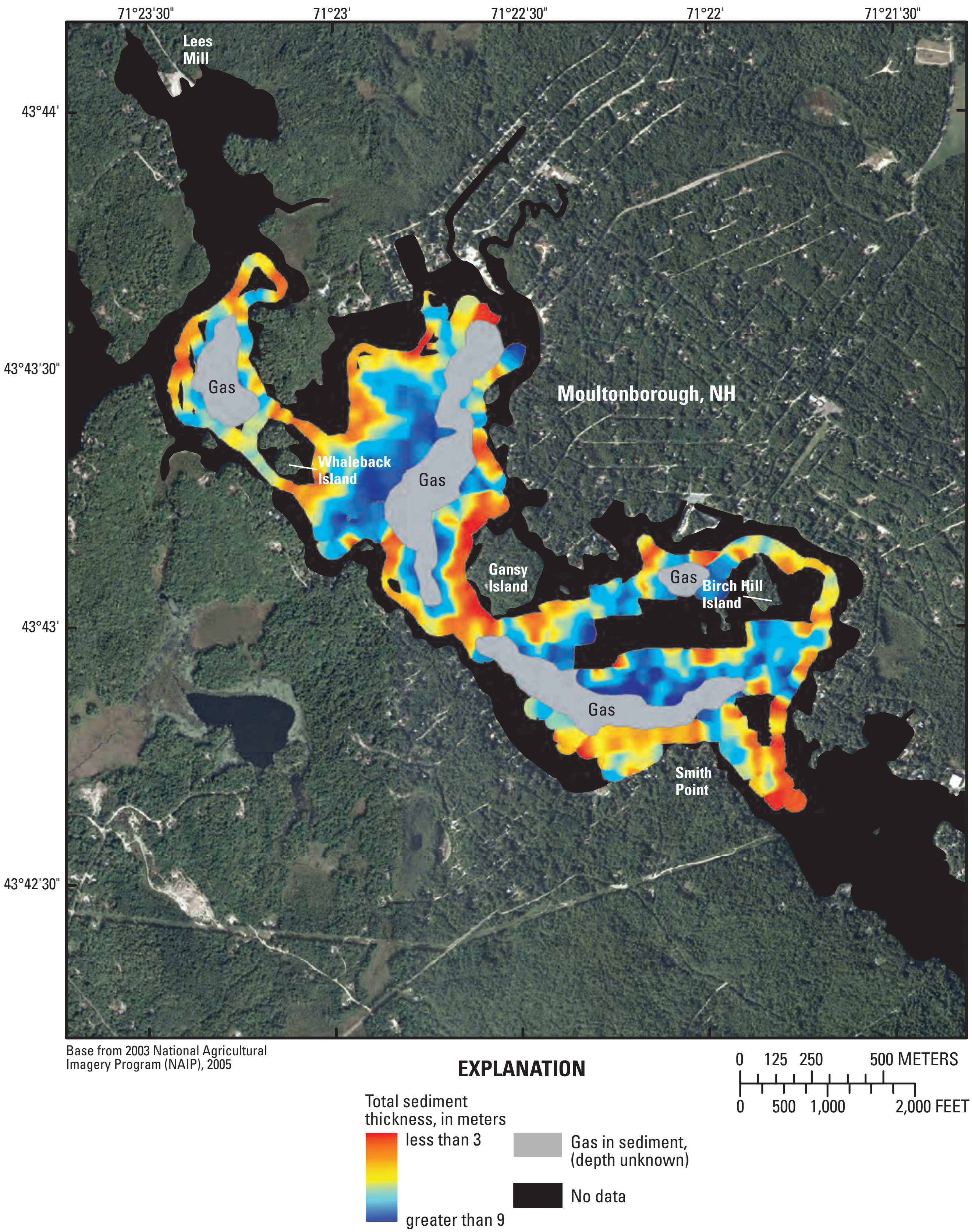


Figure 10. Total sediment thickness in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, determined through the use of seismic-reflection data.

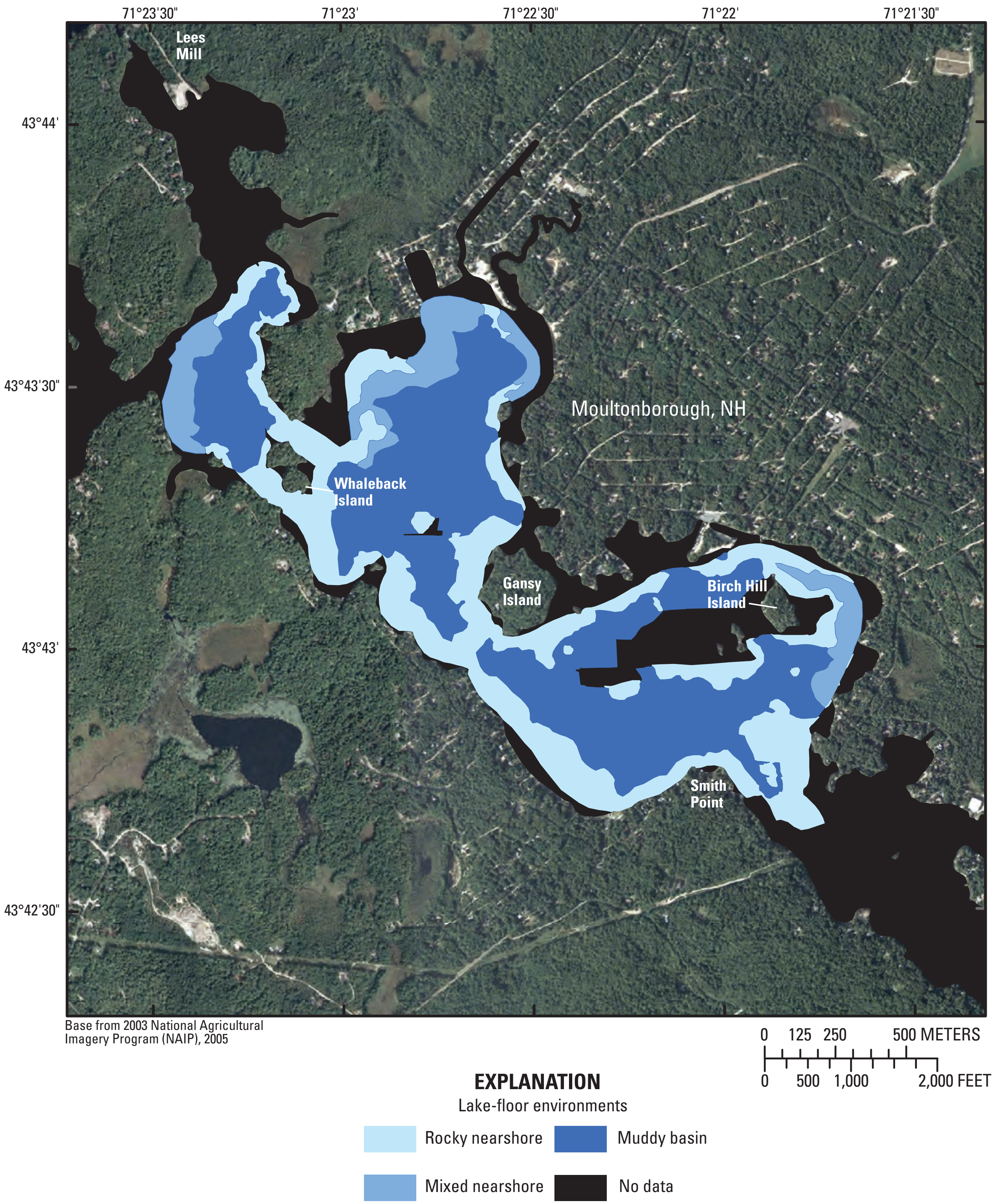


Figure 11. Three lake-floor environments in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, as interpreted from geophysical and sediment-sample data.

Submerged Aquatic Vegetation

AGDS data were used to generate an interpolated map showing the percentage of SAV, including variable leaf water-milfoil, native milfoil, bassweed, pipewort, and other species (table 1). SAV was predominantly found near shoreward margins and at depths ranging from less than 1 m to about 4 m. Overall, 86 percent of the littoral zone (the area along the margins of the bay and islands that extends from 0 to 4.3 m in water depth) had some SAV (fig. 12). AGDS data also indicated that approximately 36 percent of the littoral-zone area had SAV bottom cover of 25 percent or less; 43 percent had moderate SAV bottom cover of greater than 25 percent and less than 75 percent; and 7 percent had heavy SAV bottom cover of 75 percent or greater.

Water Quality of the Water Column and of Interstitial Pore Water

Summary statistics were determined for selected field parameters (specific conductance, pH, and temperature). The specific conductance ranged from 63 to 67 µs/cm for water-column samples and from 61 to 207 µs/cm for interstitial pore-water samples (table 3). The ranges of specific conductance for water-column and interstitial pore-water samples were significantly different ($p < 0.0001$). Similarly, pH values of the interstitial pore-water samples had a significantly greater range ($p < 0.0001$) than pH values of the water-column samples (5.9 to 7.0 and 6.6 to 7.2 standard units, respectively) (table 3). Temperatures measured in the water-column samples were significantly higher ($p < 0.0001$) than temperatures measured in the interstitial pore-water samples, (25.3 to 29.5ºC and 22.4 to 25.6ºC, respectively) (table 3).

Most water-column constituent concentrations were similar among sampling sites. An exception was iron concentrations, which ranged from 0.07 to 0.39 mg/L (table 4). An exceptionally high total ammonia plus organic nitrogen value of 6 mg/L was recorded at site QW4. An excessive amount of flocculent matter was observed at this site; although the sample was filtered, the flocculent matter may have affected the concentration measured.

Constituent concentrations in interstitial pore-water samples had a greater range and were generally higher than concentrations measured in the water-column samples for the same constituent (table 4). Total ammonia plus organic nitrogen concentrations in interstitial pore-water samples ranged from less than 0.25 to 3.6 mg/L. The three highest concentrations were measured in samples collected at sites QW1 (3.6 mg/L); QW3 (3.4 mg/L), in the northwestern part of the bay near Lees Mill; and at QW20 (3.0 mg/L), in the southeastern part of the bay across from Smith Point (fig. 3). Total phosphorus concentrations generally were low and ranged from 0.01 to 1.01 mg/L (table 4).

Chemical Characteristics of the Surficial Sediment on the Lake Floor

Concentrations of potassium and iron in the surficial-sediment samples ranged widely among sampling sites (8,300 to 29,000 mg/kg and 9,400 to 30,000 mg/kg, respectively) (table 5). Total nitrite, total nitrate, ammonia plus ammonium, and phosphorus measured by the Olsen method were rarely detected. Concentrations of total ammonia plus organic nitrogen were generally low and similar in the samples collected from all of the sites. A strong acid digest method was used to measure the concentrations of all recoverable phosphorus in the sediment samples; these concentrations ranged from 210 to 1,100 mg/kg. Concentrations of loosely sorbed phosphorus ranged from 2.0 to 11 mg/L and concentrations of iron-bound phosphorus ranged from 1.4 to 3.1 mg/L. The percentage of total organic carbon (TOC) measured in the sediment samples ranged from 0.19 to 8.13 percent (table 5). The three highest percentages of TOC were measured in samples from sites QW3 (3.46 percent), QW6 (6.67 percent), and QW21 (8.13 percent). Samples collected at these three sites also had the highest percentage of fine sediment grains (silt) (table 6).

Characterization of the Distribution of Variable Leaf Water-Milfoil

Results of the EcoSAV and VBT analysis from the 24 sampling sites (fig. 3) were used to differentiate variable leaf water-milfoil from other SAV in Moultonborough Bay. About 24 reports containing the summary data for approximately 20 consecutive points were generated and evaluated at each sampling site. To determine bottom-typing characteristics, 116 reports were used for the 9 variable leaf water-milfoil sites, 107 reports were used for the 7 other-SAV sites, and 88 reports were used for the 8 no-SAV sites.

Significant differences were determined in the percentage of vegetative bottom cover ($p < 0.0001$), echo energy level for the segment directly above the first bottom echo (E_0) ($p < 0.0001$), and FD of the bottom sediments ($p < 0.0001$) between the variable leaf water-milfoil and other-SAV sites (fig. 13). The percentage of bottom cover at the 24 sampling sites ranged from 59 to 95 percent for the variable leaf water-milfoil sites and from 1 to 95 percent for the other-SAV sites (fig. 13A). E_0 is a measure of the reflected-energy level from material, including plants, directly above the lake bottom and ranged from 0.000005 to 0.00002 dB for variable leaf water-milfoil and from 0.0000015 to 0.000005 dB for the other-SAV sites (fig. 13B). FD ranged from 1.03 to 1.06 for variable leaf water-milfoil and from 0.92 to 1.05 for the other-SAV sites (fig. 13C). For this study, an SAV site was labeled variable leaf water-milfoil if the percentage of vegetative

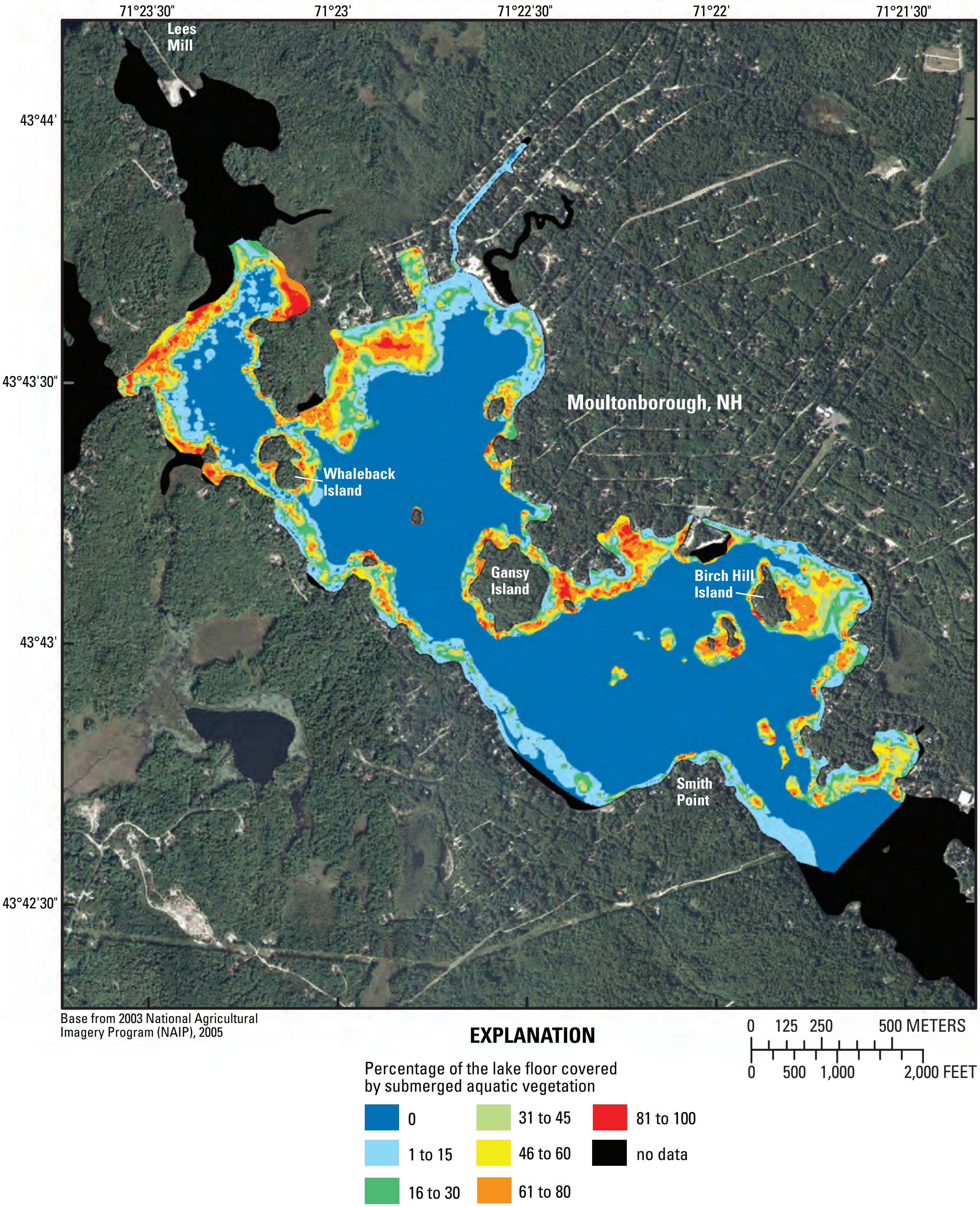


Figure 12. Distribution and percentage of the lake floor covered by submerged aquatic vegetation in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

Table 3. Site numbers, site names, locations, water depths, selected field parameters, median surficial-sediment grain sizes, and percentages of vegetative bottom cover for sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[SAV, submerged aquatic vegetation; WC, water column; IW, interstitial pore water; µS/cm, microsiemens per centimeter; °C, degrees Celsius; --, not applicable]

U.S. Geological Survey site number	Site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Water depth (meters)	Specific conductance (µS/cm)		pH		Temperature (°C)		Median grain size (millimeters)	Percentage of vegetative bottom cover
					WC	IW	WC	IW	WC	IW		
Variable leaf water-milfoil sites												
434326071232801	QW8	43.72576	71.39118	1.27	63	88	6.8	6.5	28.0	24.8	0.71	76.0
434321071230601	QW11	43.72240	71.38515	2.06	65	97	7.0	5.9	28.1	24.8	0.61	59.2
434326071230101	QW12	43.72402	71.38366	3.19	64	105	7.0	6.1	28.1	24.8	0.60	72.8
434328071223401	QW17	43.72457	71.37616	2.45	65	132	7.1	6.6	28.3	24.9	0.70	63.0
434305071222301	QW18	43.71819	71.37305	2.89	65	122	7.0	6.4	28.2	25.2	0.66	80.2
434244071213401	QW20	43.71214	71.35958	3.85	66	67	7.0	7.0	26.2	24.9	0.81	64.9
434242071213101	QW22	43.71178	71.35872	2.18	65	83	7.1	6.6	27.1	25.2	0.60	94.6
434306071214201	QW26	43.71833	71.36139	3.41	66	141	7.1	6.8	27.8	22.4	0.62	67.0
434311071221401	QW27	43.71972	71.37056	2.86	66	140	7.0	6.3	28.0	24.8	0.62	75.0
Median		--	--	**2.86**	**65**	**105**	**7.0**	**6.5**	**28.0**	**24.8**	**0.62**	**72.8**
Other-SAV sites												
434339071230501	QW3	43.72755	71.38481	1.94	65	207	6.8	6.3	28.6	22.9	0.52	95.0
434337071232401	QW5	43.72680	71.39007	1.33	63	62	6.9	6.5	28.0	25.0	0.58	15.9
434335071232801	QW7	43.72637	71.39064	1.22	63	103	6.8	6.2	28.0	24.0	0.41	70.9
434314071230701	QW9	43.72062	71.38543	1.51	64	122	7.0	6.5	28.2	24.7	0.54	32.5
434341071224301	QW14	43.72799	71.37865	1.27	66	93	6.9	6.3	27.9	24.9	0.28	7.47
434331071222801	QW16	43.72529	71.37446	1.50	65	105	7.1	6.3	28.1	25.6	0.42	15.8
434305071213601	QW19	43.71798	71.35988	1.36	66	114	7.2	5.9	27.8	25.1	0.18	17.5
Median		--	--	**1.43**	**65**	**105**	**6.9**	**6.3**	**28.0**	**24.9**	**0.42**	**17.5**
No-SAV sites												
434341071231001	QW1	43.72801	71.38609	3.41	67	67	6.6	6.9	27.5	23.1	0.86	1.23
434341071231501	QW4	43.72806	71.38750	3.89	64	73	6.9	6.1	28.5	25.4	0.91	[1]37.9
434337071231801	QW6	43.72686	71.38813	4.41	64	61	6.7	6.9	25.3	24.1	0.04	0.8
434315071230901	QW10	43.72071	71.38594	1.37	64	110	7.0	6.4	28.2	24.9	0.57	0.33
434335071222701	QW15	43.72645	71.37416	1.38	66	124	7.1	6.4	27.9	24.9	0.47	0.0
434249071213101	QW21	43.71356	71.35853	1.46	66	122	7.0	6.4	28.6	24.6	0.33	0.0
434246071222901	QW23	43.71272	71.37468	1.40	65	129	7.2	6.4	28.9	24.9	0.19	0.0
434307071230301	QW25	43.71853	71.38410	1.38	65	117	7.1	6.3	29.5	24.9	0.24	0.43
Median		--	--	**1.43**	**65**	**114**	**7.0**	**6.4**	**28.4**	**24.9**	**0.40**	**0.38**

[1] False-positive result.

Table 4. Concentrations of potassium, dissolved nitrite plus nitrate, ammonium nitrogen, total ammonia plus organic nitrogen, total phosphorus, dissolved orthophosphorus, iron, and total organic carbon measured in water samples from sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[SAV, submerged aquatic vegetation; WC, water column; IW, interstitial water; <, less than; mg/L, milligrams per liter]

Site name	Potassium (mg/L)		Dissolved nitrite plus nitrate (mg/L)		Ammonium nitrogen (mg/L)		Total ammonia plus organic nitrogen (mg/L)		Total phosphorus (mg/L)		Dissolved ortho-phosphorus (mg/L)		Iron (mg/L)		Total organic carbon (mg/L)	
	WC	IW	WC	IW	WC	IW	WC	IW	WC	IW	WC	IW	WC	IW	WC	IW
Variable leaf water-milfoil sites																
QW8	0.6	1	<0.05	<0.05	<0.05	0.3	0.3	1.1	0.01	0.08	<0.01	<0.01	0.14	4.8	5.3	7.2
QW11	0.6	1	<0.05	<0.05	<0.05	<0.05	0.3	<0.25	0.01	0.04	<0.01	0.02	0.11	3.8	4.5	4.8
QW12	0.6	1	<0.05	0.07	0.05	0.1	0.3	0.3	0.01	0.07	<0.01	<0.01	0.13	6.6	5.1	4.1
QW17	0.6	2	<0.05	<0.05	<0.05	0.9	0.3	1.5	0.01	0.53	<0.01	0.03	0.11	4.1	5.0	5.0
QW18	0.6	1	<0.05	<0.05	<0.05	0.5	<0.25	0.7	0.01	0.07	<0.01	<0.01	0.09	6.9	3.9	4.8
QW20	0.6	4	<0.05	<0.05	<0.05	<0.05	0.3	3.0	0.01	0.52	<0.01	<0.01	0.09	20	4.0	5.3
QW22	0.6	1	<0.05	<0.05	<0.05	0.3	<0.25	0.6	0.01	0.15	<0.01	<0.01	0.07	1.9	3.8	4.5
QW26	0.6	3	<0.05	<0.05	<0.05	0.3	<0.25	1.4	0.01	1.01	<0.01	<0.01	0.09	29	4.7	5.5
QW27	0.6	1	<0.05	<0.05	<0.05	0.4	<0.25	0.9	0.01	0.07	<0.01	0.01	0.11	8.7	4.4	7.3
Median	**0.6**	**1**	**<0.05**	**<0.05**	**<0.05**	**0.3**	**0.3**	**0.9**	**0.01**	**0.08**	**<0.01**	**<0.01**	**0.11**	**7.0**	**4.5**	**5.0**
Other-SAV sites																
QW3	0.6	2.2	<0.05	<0.05	<0.05	2.1	<0.25	3.4	0.01	0.18	<0.01	0.01	0.21	9.1	5.8	13
QW5	0.6	0.6	<0.05	0.05	<0.05	<0.05	0.3	0.4	0.01	0.01	<0.01	<0.01	0.15	0.2	5.5	5.7
QW7	0.6	0.8	<0.05	<0.05	<0.05	<0.05	0.4	0.5	0.01	0.05	<0.01	<0.01	0.24	4.3	5.5	7.1
QW9	0.6	1.6	<0.05	<0.05	<0.05	0.2	0.3	0.3	0.01	0.07	<0.01	<0.01	0.13	4.8	4.8	3.9
QW14	0.6	1.2	<0.05	<0.05	<0.05	0.1	0.3	0.3	0.01	0.02	<0.01	<0.01	0.22	3.8	5.0	5.3
QW16	0.6	1.1	<0.05	<0.05	<0.05	0.2	0.3	0.4	0.01	0.02	<0.01	<0.01	0.15	3.2	4.4	4.0
QW19	0.6	1.1	<0.05	<0.05	<0.05	0.1	<0.25	0.3	0.01	0.24	<0.01	<0.01	0.08	1.6	3.7	6.3
Median	**0.6**	**1.1**	**<0.05**	**<0.05**	**<0.05**	**0.1**	**0.3**	**0.4**	**0.01**	**0.05**	**<0.01**	**<0.01**	**0.15**	**4.0**	**5.0**	**5.7**
No-SAV sites																
QW1	0.6	1.7	<0.05	<0.05	<0.05	0.1	0.3	3.6	0.01	0.40	<0.01	<0.01	0.39	9.8	5.8	7.3
QW4	0.5	1.1	<0.05	<0.05	<0.05	<0.05	6.0	0.3	0.20	0.02	<0.01	<0.01	0.18	1.6	5.7	6.3
QW6	0.6	0.6	<0.05	<0.05	<0.05	0.2	0.3	0.4	0.01	0.01	<0.01	<0.01	0.23	0.3	5.8	5.5
QW10	0.6	2.9	<0.05	<0.05	<0.05	0.3	0.3	0.5	0.01	0.10	<0.01	<0.01	0.14	3.3	4.5	3.2
QW15	0.6	1.3	<0.05	<0.05	<0.05	0.3	0.3	0.5	0.01	0.14	<0.01	0.016	0.14	6.0	4.8	3.9
QW21	0.6	1.8	<0.05	<0.05	<0.05	0.4	0.3	0.6	0.01	0.22	<0.01	<0.01	0.08	3.9	4.1	3.3
QW23	0.6	2.1	<0.05	<0.05	0.06	<0.05	0.3	<0.25	0.14	0.01	<0.01	<0.01	0.10	2.4	1.0	4.2
QW25	0.6	1.7	<0.05	<0.05	<0.05	0.2	<0.25	0.3	0.01	0.11	<0.01	0.013	0.13	6.7	4.5	2.9
Median	**0.6**	**1.7**	**<0.05**	**<0.05**	**<0.05**	**0.2**	**0.3**	**0.45**	**0.01**	**0.10**	**<0.01**	**<0.01**	**0.14**	**4.0**	**4.7**	**4.1**

Table 5. pH (ratio); concentrations of potassium, total nitrate, total nitrite, ammonia plus ammonium, total ammonia plus organic nitrogen, phosphorus (strong acid digest), phosphorus (Olsen method), loosely sorbed phosphorus, iron-bound phosphorus, and iron; percent total organic carbon; and percent moisture measured in sediment samples from sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[SAV, submerged aquatic vegetation; <, less than; mg/kg, milligrams per kilogram; mg/L, milligrams per liter; %, percent]

Site name	pH [1](ratio)	Potassium (mg/kg)	Total nitrate (mg/kg)	Total nitrite (mg/kg)	Ammonia plus ammonium (mg/kg)	Total ammonia plus organic nitrogen (mg/kg)	Phosphorus [2](strong acid digest) (mg/kg)
Variable leaf water-milfoil sites							
QW8	6.4	19,000	<0.01	<0.01	<0.01	0.02	680
QW11	6.3	10,000	<0.01	<0.01	<0.01	0.03	390
QW12	6.0	8,900	<0.01	<0.01	<0.01	0.04	540
QW17	6.4	16,000	<0.01	<0.01	<0.01	0.02	320
QW18	6.7	8,300	<0.01	<0.01	<0.01	0.02	570
QW20	7.1	10,000	<0.01	<0.01	<0.01	0.03	320
QW22	6.2	12,000	<0.01	<0.01	<0.01	0.02	260
QW26	7.1	16,000	<0.01	<0.01	<0.01	0.01	290
QW27	6.3	14,000	<0.01	<0.01	<0.01	0.02	300
Median	**6.4**	**12,000**	**<0.01**	**<0.01**	**<0.01**	**0.02**	**320**
Other-SAV sites							
QW3	6.3	13,000	<0.01	<0.01	<0.01	0.11	550
QW5	6.5	16,000	<0.01	<0.01	<0.01	0.02	490
QW7	6.2	19,000	<0.01	<0.01	<0.01	0.03	450
QW9	6.3	29,000	<0.01	<0.01	<0.01	0.02	380
QW14	7.4	17,000	<0.01	<0.01	<0.01	0.02	300
QW16	7.2	17,000	<0.01	<0.01	<0.01	0.03	300
QW19	7.2	16,000	<0.01	<0.01	<0.01	0.02	210
Median	**6.5**	**17,000**	**<0.01**	**<0.01**	**<0.01**	**0.02**	**380**
No-SAV sites							
QW1	6.2	13,000	<0.01	<0.01	<0.01	0.02	640
QW4	6.2	12,000	<0.01	<0.01	<0.01	0.02	490
QW6	6.6	14,000	<0.01	<0.01	<0.01	0.14	1,100
QW10	6.4	20,000	<0.01	<0.01	<0.01	0.02	300
QW15	6.4	15,000	<0.01	<0.01	<0.01	0.02	270
QW21	6.8	9,700	<0.01	<0.01	<0.01	0.05	340
QW23	6.3	14,000	<0.01	<0.01	<0.01	0.02	320
QW25	6.8	19,000	<0.01	<0.01	<0.01	0.02	350
Median	**6.4**	**14,000**	**<0.01**	**<0.01**	**<0.01**	**0.02**	**345**

Table 5. pH (ratio); concentrations of potassium, total nitrate, total nitrite, ammonia plus ammonium, total ammonia plus organic nitrogen, phosphorus (strong acid digest), phosphorus (Olsen method), loosely sorbed phosphorus, iron-bound phosphorus, and iron; percent total organic carbon; and percent moisture measured in sediment samples from sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.—Continued

[SAV, submerged aquatic vegetation; <, less than; mg/kg, milligrams per kilogram; mg/L, milligrams per liter; %, percent]

Site name	Phosphorus [3](Olsen method) (mg/kg)	Loosely sorbed phosphorus (mg/L)	Iron-bound phosphorus (mg/L)	Iron (mg/kg)	Total organic carbon (%)	Moisture (%)
			Variable leaf water-milfoil sites			
QW8	<10	6.2	2.2	17,000	0.33	0.18
QW11	11	10	3.1	11,000	0.34	0.18
QW12	<10	7.9	2.3	13,000	0.37	0.26
QW17	<10	6.2	1.7	15,000	0.38	0.24
QW18	<10	8.2	2.5	14,000	0.29	0.20
QW20	<10	5.6	2.9	14,000	0.28	0.25
QW22	<10	10	2.2	9,400	0.19	0.20
QW26	<10	6.0	1.9	14,000	0.26	0.23
QW27	<10	8.2	2.0	11,000	0.26	0.19
Median	**<10**	**7.9**	**2.2**	**14,000**	**0.26**	**0.20**
			Other SAV sites			
QW3	<10	3.0	2.6	18,000	3.46	0.28
QW5	<10	9.2	1.5	13,000	0.35	0.19
QW7	<10	6.7	1.4	13,000	0.59	0.18
QW9	<10	7.2	2.5	16,000	0.35	0.17
QW14	<10	8.4	2.1	10,000	0.44	0.18
QW16	<10	5.0	3.1	12,000	0.67	0.17
QW19	<10	8.4	2.1	12,000	0.60	0.23
Median	**<10**	**7.2**	**2.1**	**13,000**	**0.59**	**0.18**
			No SAV sites			
QW1	<10	6.2	2.5	21,000	0.27	0.15
QW4	12	6.8	2.5	13,000	0.45	0.24
QW6	12	2.0	3.1	30,000	6.67	0.25
QW10	<10	8.2	1.8	14,000	0.22	0.19
QW15	<10	3.0	3.1	15,000	0.69	0.23
QW21	<10	3.9	2.4	22,000	8.13	0.23
QW23	<10	11	1.8	12,000	0.20	0.20
QW25	<10	6.8	1.5	16,000	0.32	0.22
Median	**<10**	**6.5**	**2.4**	**15,500**	**0.38**	**0.22**

[1] Sediment pH (ratio) was determined as a paste of two parts sediment to one part distilled water.

[2] Sample is digested by a four-acid mixture of HNO_3, HF, $HClO_4$, and HCL to obtain a near total digest of 30 elements on low mineralized samples.

[3] The soil extraction is derived from the Olsen ($NaHCO_3$) soil test for phosphorus.

Table 6. Percentage of the total sediment samples that were finer than the sieve diameter from sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[SAV, submerged aquatic vegetation; mm, millimeters; -- not calculated]

Site name	Sediment, total sieve diameter, percent finer than 0.038 (mm)	Sediment, total sieve diameter, percent finer than 0.053 (mm)	Sediment, total sieve diameter, percent finer than 0.075 (mm)	Sediment, total sieve diameter, percent finer than 0.106 (mm)	Sediment, total sieve diameter, percent finer than 0.150 (mm)	Sediment, total sieve diameter, percent finer than 0.212 (mm)	Sediment, total sieve diameter, percent finer than 0.30 (mm)	Sediment, total sieve diameter, percent finer than 0.425 (mm)	Sediment, total sieve diameter, percent finer than 0.60 (mm)
Variable leaf water-milfoil sites									
QW8	1	1	1	2	3	4	10	21	39
QW11	0.1	0.2	0.3	0.4	1	4	13	28	49
QW12	1	1	1	2	2	5	13	30	50
QW17	0.1	1	1	2	3	4	8	18	39
QW18	0	0.2	1	1	2	5	12	25	45
QW20	2	0.1	0.2	0.5	1	3	7	17	33
QW22	1	2	2	3	4	8	16	30	51
QW26	2	1	1	2	3	4	11	26	48
QW27	2	2	2	3	5	8	15	29	48
Median percent	**1**	**1**	**1**	**2**	**3**	**4**	**12**	**26**	**48**
Other-SAV sites									
QW3	16	16	17	19	20	25	31	41	56
QW5	3	3	3	4	5	11	21	36	51
QW7	6	6	8	10	16	24	37	51	65
QW9	1	1	1	3	5	14	22	35	57
QW14	0.1	0.4	2	9	22	35	53	73	90
QW16	9	10	13	16	21	30	39	51	64
QW19	1	2	3	9	19	82	96	99	99
Median percent	**3**	**3**	**3**	**9**	**19**	**25**	**37**	**51**	**64**
No-SAV sites									
QW1	6	6	6	6	7	9	13	20	33
QW4	2	2	2	3	3	5	8	16	29
QW6	88	92	93	96	98	100	100	100	100
QW10	2	2	4	8	12	16	23	34	53
QW15	5	6	8	9	11	18	28	44	64
QW21	21	23	24	27	31	37	46	61	73
QW23	0.2	0.4	5	7	23	63	91	98	99
QW25	4	5	7	10	17	28	51	69	81
Median percent	**4**	**5**	**6**	**9**	**15**	**23**	**37**	**52**	**69**

Table 6. Percentage of the total sediment samples that were finer than the sieve diameter from sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.—Continued

[SAV, submerged aquatic vegetation; mm, millimeters; --, not calculated]

Site name	Sediment, total sieve diameter, percent finer than 0.850 (mm)	Sediment, total sieve diameter, percent finer than 1.180 (mm)	Sediment, total sieve diameter, percent finer than 1.70 (mm)	Sediment, total sieve diameter, percent finer than 2.36 (mm)	Sediment, total sieve diameter, percent finer than 3.35 (mm)	Sediment, total sieve diameter, percent finer than 4.75 (mm)	Sediment, total sieve diameter, percent finer than 6.70 (mm)	Sediment, total sieve diameter, percent finer than 9.50 (mm)	Sediment, total sieve diameter, percent finer than 12.50 (mm)
Variable leaf water-milfoil sites									
QW8	62	79	94	97	98	99	100	100	100
QW11	72	87	97	--	--	--	--	--	--
QW12	72	88	99	--	--	--	--	--	--
QW17	63	81	95	98	100	100	100	100	100
QW18	65	83	98	--	--	--	--	--	--
QW20	53	69	85	89	92	93	94	98	100
QW22	71	85	97	--	--	--	--	--	--
QW26	69	85	98	--	--	--	--	--	--
QW27	69	83	96	--	--	--	--	--	--
Median percent	**69**	**83**	**97**	**97**	**98**	**99**	**100**	**100**	**100**
Other-SAV sites									
QW3	74	87	98	--	--	--	--	--	--
QW5	68	80	92	95	97	99	100	100	100
QW7	79	89	97	--	-	--	--	--	--
QW9	76	87	96	99	100	100	100	100	100
QW14	97	99	100	--	--	--	--	--	--
QW16	77	86	94	97	99	100	100	100	100
QW19	100	100	100	--	--	--	--	--	--
Median percent	**77**	**87**	**97**	**97**	**99**	**100**	**100**	**100**	**100**
No-SAV sites									
QW1	49	66	86	91	94	97	99	100	100
QW4	46	66	91	94	96	97	99	100	100
QW6	100	100	100	--	--	--	--	--	--
QW10	76	90	98	--	--	--	--	--	--
QW15	81	90	97	--	--	--	--	--	--
QW21	85	93	98	--	--	--	--	--	--
QW23	100	100	100	--	--	--	--	--	--
QW25	91	96	100	100	100	100	100	100	100
Median percent	**83**	**91**	**98**	**94**	**96**	**97**	**99**	**100**	**100**

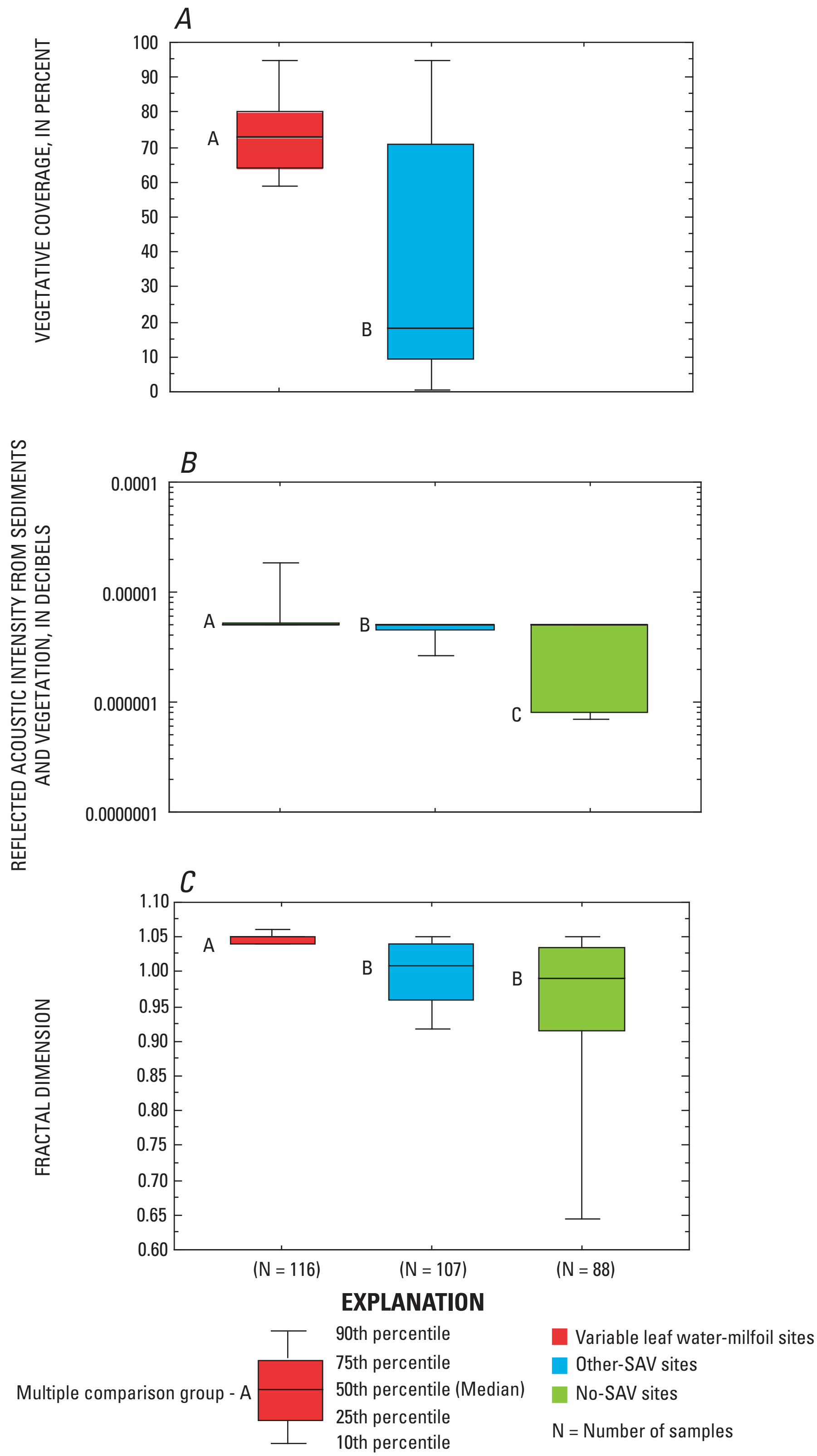


Figure 13. Comparison of data from the acoustic ground-discrimination system survey reports for *(A)* vegetative cover, *(B)* reflected acoustic intensity of the sediments and vegetation, and *(C)* fractal dimension among variable leaf water-milfoil sites, other-SAV sites, and no-SAV sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. [SAV, submerged aquatic vegetation; results of Tukey's multiple comparison test (Helsel and Hirsch, 1992) among site types are presented as letters, and distributions with at least one letter in common do not differ significantly.]

bottom cover was greater than 59 percent, E_0 was greater than or equal to 0.000005 dB, and FD was greater than or equal to 1.03. Two other-SAV sites (QW3 and QW7, table 3) had percentages of vegetative cover that were within the range defined for variable leaf water-milfoil (59–95 percent). Although the percentage of bottom cover and FD values for site QW3 were within the defined ranges for variable leaf water-milfoil (95 percent and 1.04 to 1.06, respectively), the E_0 values were all equal to 0.0000008, less than the lower E_0 limit used to define variable leaf water-milfoil (0.000005). Site QW7 met all three criteria for a variable leaf water-milfoil site. Continuous underwater video at this site showed that although QW7 was designated as an other-SAV site, some variable leaf water-milfoil was present. Therefore, the inclusion of the area around site QW7 on the interpolated map of the distribution and percentage of bottom cover of variable leaf water-milfoil was considered appropriate, although the percentage of variable leaf water-milfoil may be overestimated in that area. Overall, evaluation of the data indicated that these three criteria were useful in minimizing the amount of other SAV that may have been erroneously qualified as variable leaf water-milfoil on the interpolated map. Acoustic data are especially useful in distinguishing variable leaf water-milfoil from other types of SAV because variable leaf water-milfoil primarily forms dense, homogenous beds.

AGDS data were used as input in GIS to create a vegetation map that distinguished variable leaf water-milfoil from other types of SAV in Moultonborough Bay (fig. 14). This map shows that approximately 21 percent of the littoral zone was characterized to be variable leaf water-milfoil at 59 percent or greater bottom cover. In addition, depth, sediment texture, and percentage of vegetative bottom cover were used to define areas that may be susceptible to future infestation by variable leaf water-milfoil. When depth was less than 4.3 m, the FD was greater than or equal to 1.03, and the percentage of vegetative bottom cover was less than 59 percent, interpolation was used to define areas that may be susceptible to variable leaf water-milfoil spread (fig. 14). These criteria were used to identify areas that had habitat conducive to the growth of variable leaf water-milfoil but, at the time of the study (2005), did not have high percentages (greater than 59 percent) of variable leaf water-milfoil. The total percentage of the littoral-zone area susceptible to variable leaf water-milfoil was estimated by this method to be 44 percent (fig. 14).

The amount of light reaching the sediment surface is an important factor in the distribution and species composition of SAV communities. SAV exhibit distinct morphological variations in relation to light intensity; specifically, shade-adapted leaves tend to be finely divided (Wetzel, 1983; Barko and others, 1981). Variable leaf water-milfoil has finely dissected leaves and was found at depths that ranged from 1 to 4 m. Sites with other types of SAV had depths that ranged from 1 to 2 m. The differences in depth between variable leaf water-milfoil sites and other-SAV sites were statistically significant ($p = 0.04$) (fig. 15). Although variable leaf water-milfoil was observed at greater depths than other types of SAV, it was not observed at depths below 4.3 m, the lower boundary of the photic zone.

Concentrations of iron in the water-column samples were significantly different among the three site types ($p = 0.04$) and consistently lowest at the variable leaf water-milfoil sites (fig. 16; table 4). The percentage of TOC measured in sediment samples also was significantly different among the three site types ($p = 0.04$) and consistently lowest at the variable leaf water-milfoil sites (table 5). Most constituent concentrations, however, were not correlated with the presence of variable leaf water-milfoil. Other studies of SAV also have had limited success in relating water-column, interstitial pore-water, and sediment-constituent concentrations to the presence or density of SAV (Barko and others, 1986; Barko and Smart, 2006; Kimball and Baker, 1982).

In this study, differences in surficial-sediment composition among the three site types had the strongest correlation with the presence of variable leaf water-milfoil, which was growing in areas where the sediments were predominately coarse sand. The grain size of the fine fraction (d16) differed significantly between the variable leaf water-milfoil sites and other-SAV sites and no-SAV sites ($p = 0.005$). The median grain size of the fine fraction (d16) of the variable leaf water-milfoil sites was 0.33 mm but was 0.14 mm and 0.17 mm at the other-SAV sites and no-SAV sites, respectively (fig. 17A). The median grain size (d50) of the sediment samples from the variable leaf water-milfoil sites ranged from 0.60 to 0.81 mm with a median of 0.62 mm (coarse sand) (table 3). The median grain size of the sediment samples from the other-SAV and no-SAV sites ranged from 0.18 mm to 0.58 mm and from 0.04 to 0.91, with median values of 0.42 mm and 0.40 mm (medium sand), respectively (table 3). A significant difference also was found in the median grain size (d50) between variable leaf water-milfoil sites and other-SAV sites ($p = 0.008$), but not between variable leaf water-milfoil sites and no-SAV sites ($p > 0.05$) (fig. 17B). The coarse fraction (d84) at the variable leaf water-milfoil sites was significantly larger in grain size as compared to the coarse fraction (d84) from the other-SAV and no-SAV sites ($p = 0.05$) (fig. 17C). These statistical differences indicate that the largest percentages of coarse sediment and the smallest percentages of fine sediment were at the variable leaf water-milfoil sites (table 7) (sediment textures were defined by using definitions in Wentworth, 1922). Thus, sediment grain size may be one control for SAV community types and their distribution in Moultonborough Bay.

The grain size of the median fraction (d50) of the sediment samples also correlated (Rho = 0.49) with water depth at depths less than 4.3 m (fig. 18). The relation between grain size and depth is unimodal, and sidescan-sonar interpretations suggested that surficial-sediment grain size decreased with increasing depth in areas deeper than 5 m. Depth and grain size were correlated in the littoral zone, and both habitat characteristics were correlated with the presence of variable leaf water-milfoil. These factors may affect the distribution of variable leaf water-milfoil.

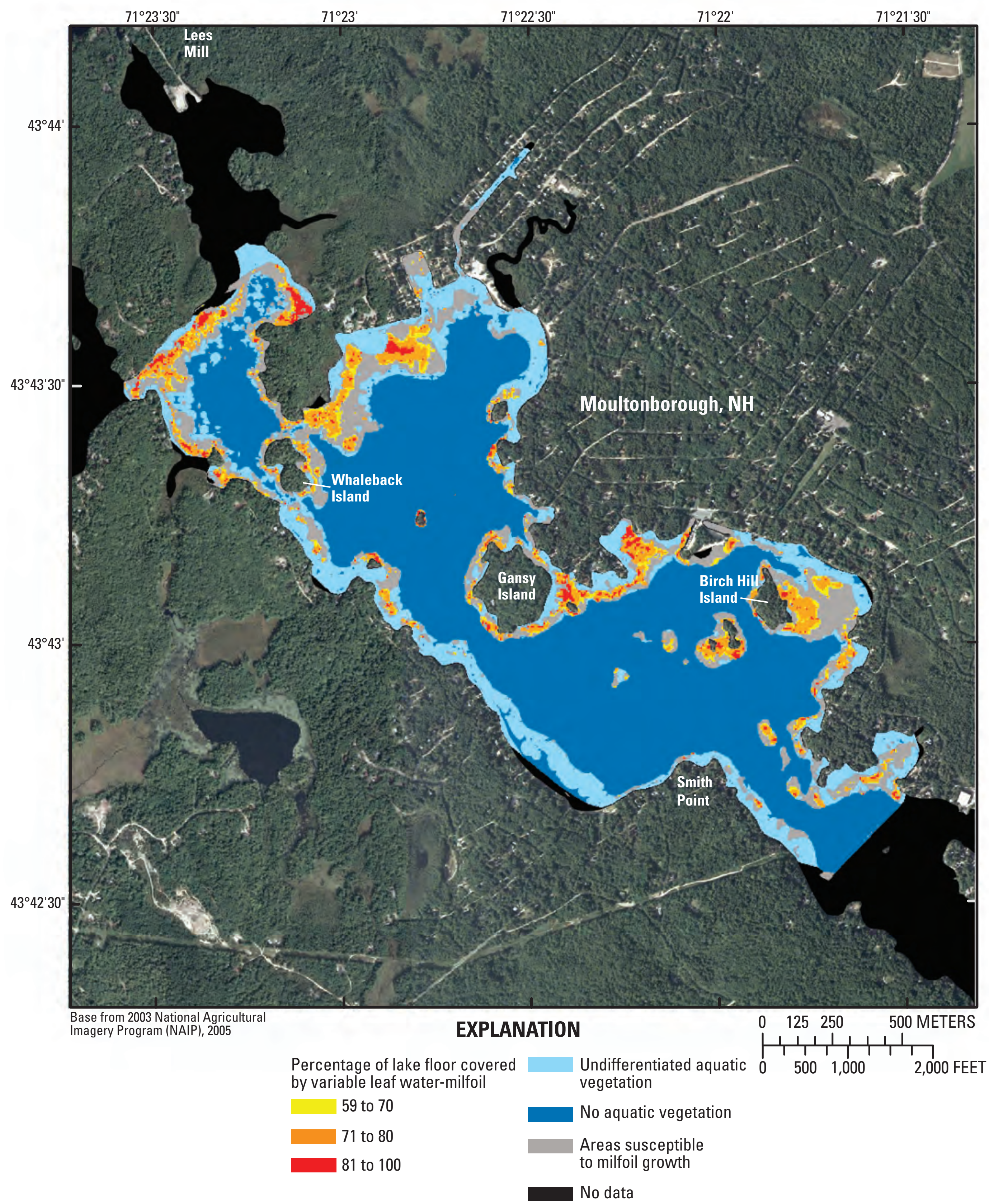


Figure 14. Distribution and percentage of the lake floor covered by variable leaf water-milfoil and areas susceptible to variable leaf water-milfoil growth in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

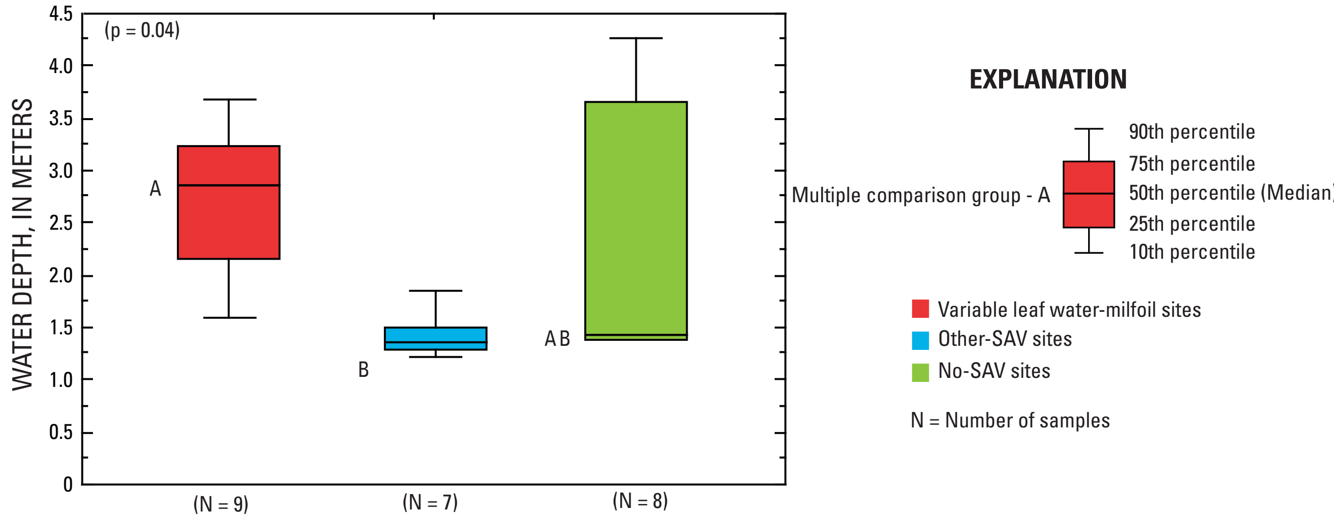


Figure 15. Comparison of water depth among the variable leaf water-milfoil sites, other-SAV sites, and no-SAV sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. [SAV, submerged aquatic vegetation; results of Tukey's multiple comparison test (Helsel and Hirsch, 1992) among site types are presented as letters, and distributions with at least one letter in common do not differ significantly.]

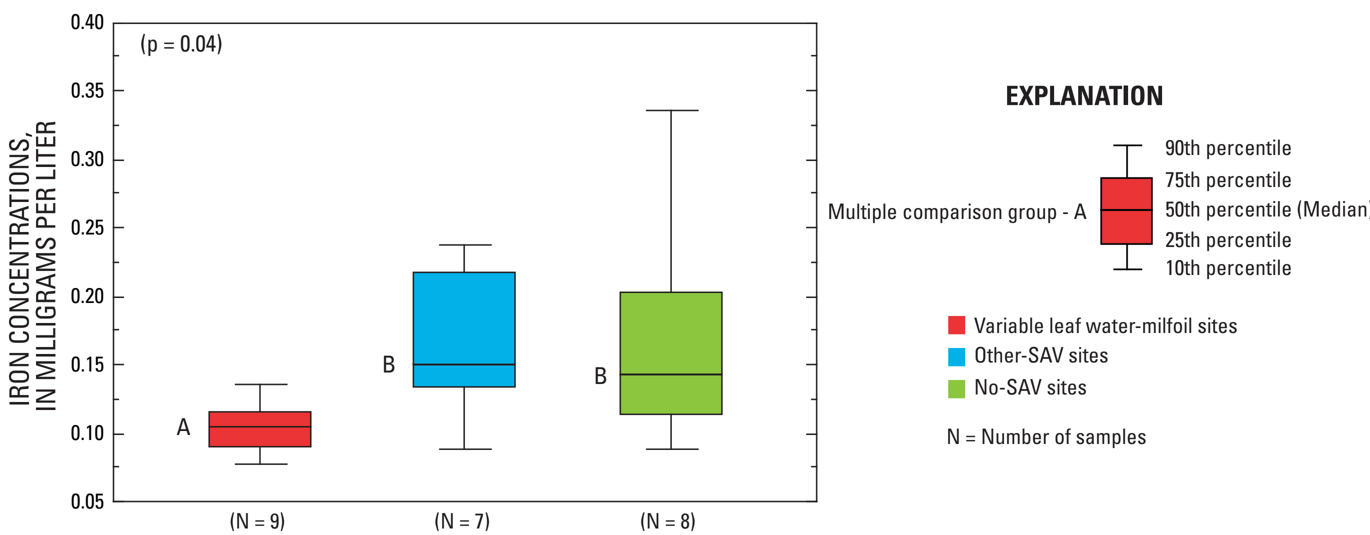


Figure 16. Comparison of iron concentrations in water-column samples among the variable leaf water-milfoil sites, other-SAV sites, and no-SAV sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. [SAV, submerged aquatic vegetation; results of Tukey's multiple comparison test (Helsel and Hirsch, 1992) among site types are presented as letters, and distributions with at least one letter in common do not differ significantly.]

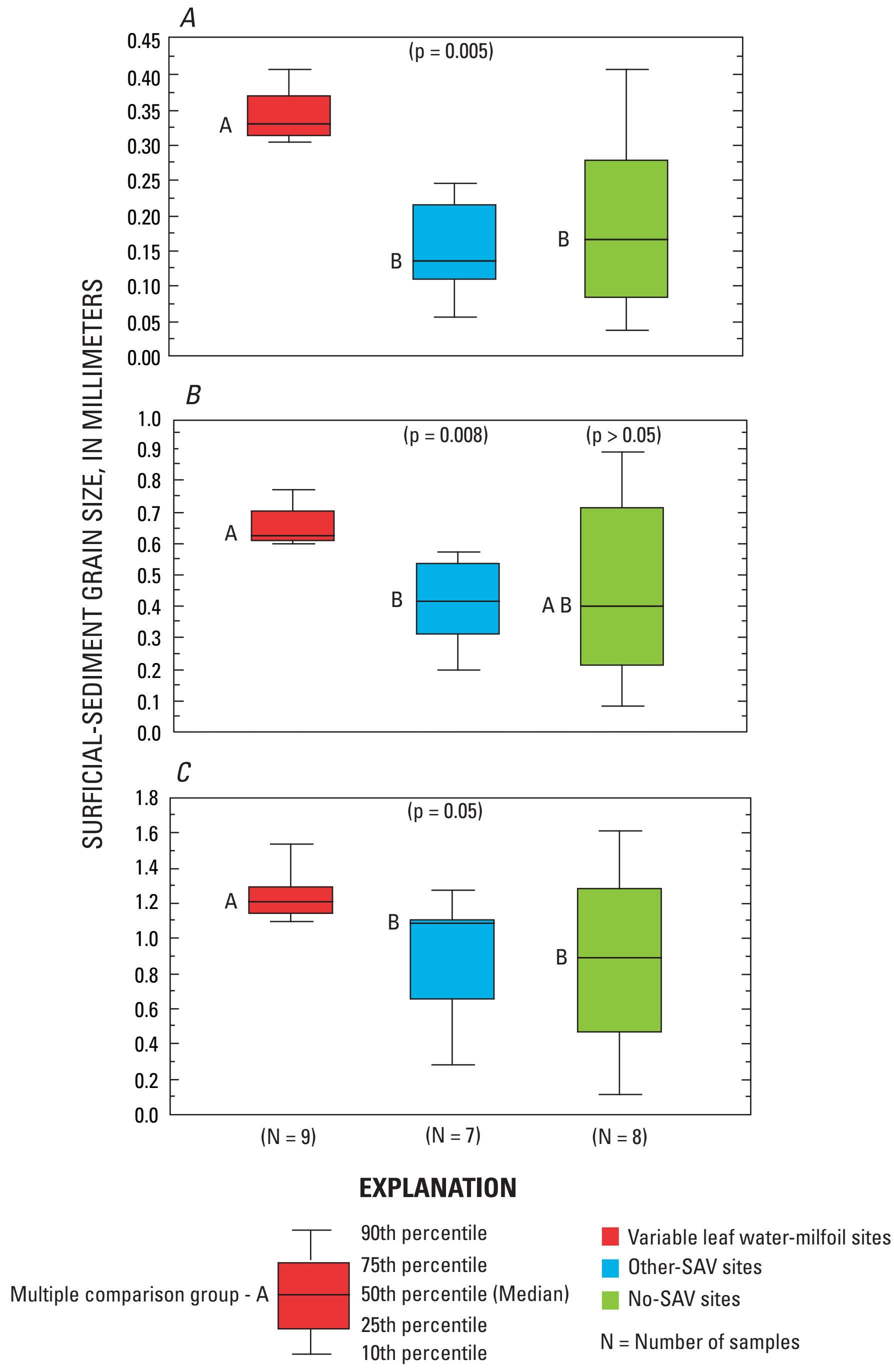


Figure 17. Comparison of surficial-sediment grain size for (*A*) the fine fraction, 16th percentile (d16), (*B*) the median grain size, 50th percentile (d50), and (*C*) the coarse fraction, 84th percentile (d84) among variable leaf water-milfoil sites, other-SAV sites, and no-SAV sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. [SAV, submerged aquatic vegetation; results of Tukey's multiple comparison test (Helsel and Hirsch, 1992) among site types are presented as letters, and distributions with at least one letter in common do not differ significantly.]

Table 7. Comparison of sediment composition of variable leaf water-milfoil and other-SAV sampling sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

[Sediment textures from Wentworth, 1922; SAV, submerged aquatic vegetation; **Boldface** indicates that differences are statistically significant (p-value <0.05)]

Site type	Number of samples	Gravel	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Silt	Clay
Variable leaf water-milfoil sites	9	2.3	16.0	37.7	32.9	9.2	1.3	0.3	0.9
Other-SAV sites	8	1.4	9.0	20.8	26.2	27.4	8.6	1.3	5.4
Absolute difference		0.9	**7.0**	**16.9**	6.65	**18.3**	**7.2**	**1.0**	**4.5**

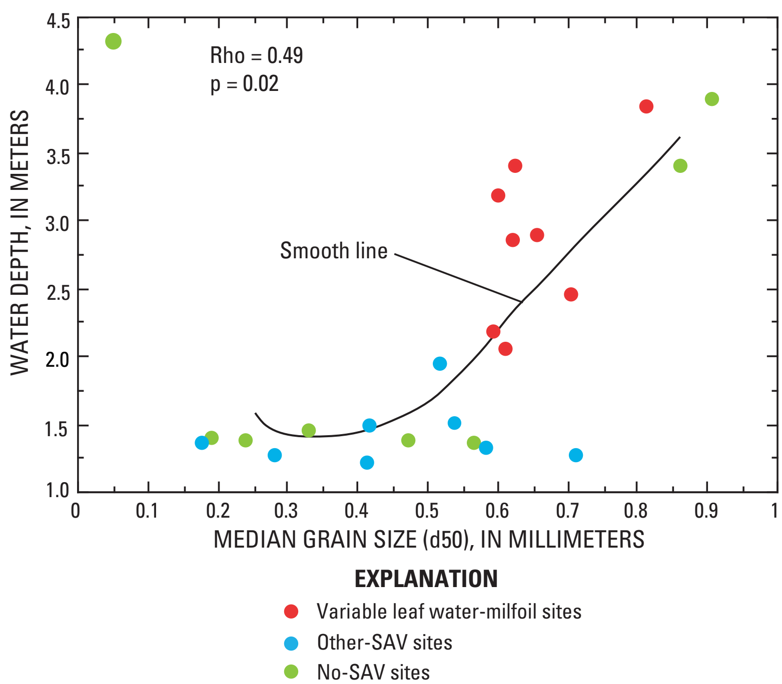


Figure 18. Water depth and the median (d50) surficial-sediment grain size for all study sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire. (SAV, submerged aquatic vegetation.)

In addition to depth, grain size also was correlated with concentrations of total ammonia plus organic nitrogen, and total phosphorus from interstitial pore-water samples. Concentrations of total ammonia plus organic nitrogen had the strongest correlation with median sediment-grain size (d50) (Rho = 0.47; p = 0.02) (fig. 19). Total phosphorus concentrations in the interstitial pore-water samples also were positively correlated to median grain size (d50) (Rho = 0.44; p = 0.05). The correlations between total ammonia plus organic nitrogen and total phosphorus to median grain size (d50) may indicate that nutrients were affecting the distribution of variable leaf water-milfoil, although this correlation was not directly significant. Other studies (Loeb and Hackley, 1988; Lodge and others, 1989) evaluated ground-water inflows as a factor for SAV distribution in oligotrophic lakes. Lodge and others (1989) suggested that ground-water inflows may be a source of additional nutrients for SAV. The apparent relation of nutrients to coarse grain sediments and the strong relation of coarse grain sediments to variable leaf water-milfoil distribution indicated that ground-water inflows in the coarse, sandy areas of Moultonborough Bay may be another control on SAV community type and distribution. Lodge and others (1989) also suggested that ground-water inflows maintain higher winter temperatures in sediments, which may enhance winter survival of perennial SAV. Water temperature also has been identified as an important influence on the photosynthetic rates of aquatic plants (Nichols and Shaw, 1986; Smith and Barko, 1990). Kimball and Baker (1983) reported that variable leaf water-milfoil maintained a considerable amount of green biomass through the winter. The ability to maintain green biomass through the winter and early spring growth may give variable leaf water-milfoil a competitive advantage within the aquatic-plant community and enhance its dominance in the littoral zone. In addition to variable leaf water-milfoil potentially outcompeting other types of SAV with early spring growth, the apparent difference in sediment texture and depth ranges between the habitats of variable leaf water-milfoil and other-SAV may indicate that variable leaf water-milfoil is able to occupy niches that were previously open water, further enhancing its dominance in the littoral zone.

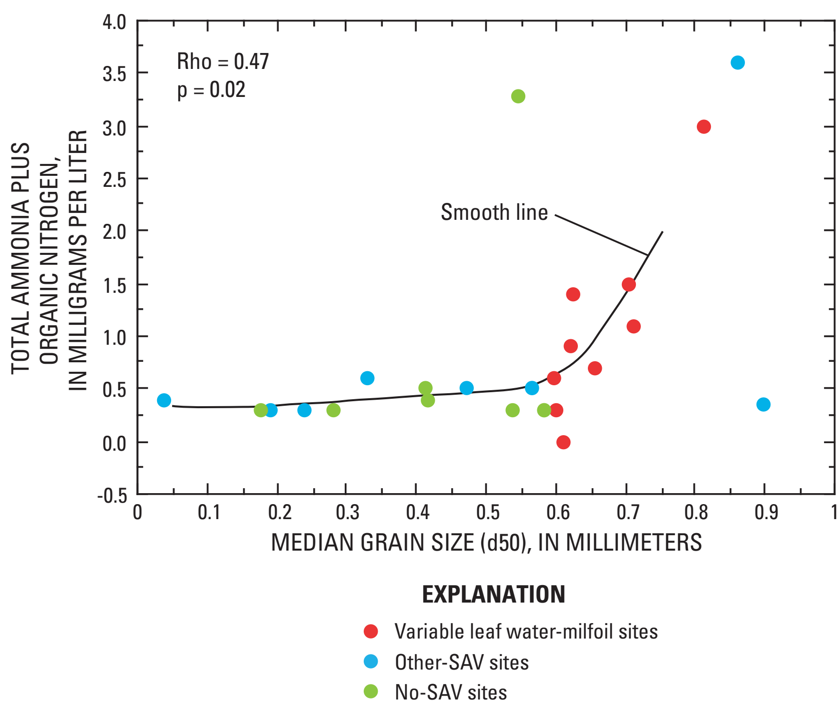


Figure 19. Concentrations of total ammonia plus organic nitrogen from interstitial pore-water samples and the median (d50) surficial-sediment grain size for all study sites in Moultonborough Bay, Lake Winnipesaukee, New Hampshire.

Summary and Conclusions

Variable leaf water-milfoil is an invasive aquatic plant in New Hampshire waterbodies. The number of waterbodies affected by variable leaf water-milfoil continues to rise. Its growth often leads to reduced quality of habitat for fish and other wildlife. In addition, infestations of variable leaf water-milfoil reduce recreational uses of and property values near affected waterbodies. The U.S. Geological Survey, in cooperation with the New Hampshire Department of Environmental Services, designed an interdisciplinary study to determine environmental factors that may affect the spatial distribution of variable leaf water-milfoil within Moultonborough Bay of Lake Winnipesaukee. Geophysical, water-quality, and surficial-sediment surveys were done to characterize the lake-floor environment, water quality, and surficial-sediment composition. Geophysical surveys were done throughout a 180-km^2 area, and water-quality and sediment samples were collected from 24 sites in the survey area during July 2005. Data from this study were evaluated to identify environmental characteristics associated with the presences of variable leaf water-milfoil. A goal of this study was to characterize the distribution of variable leaf water-milfoil in an affected waterbody.

Moultonborough Bay ranged in depth from less than 1 m to about 15 m and included three embayments. Three lake-floor environments were defined as and characterized by: (1) rocky nearshore environments mapped in water less than 5 m deep and contained high-backscatter coarse sediments and bedrock outcrop; (2) mixed nearshore environments mapped in shallow water less than 5 m deep and contained varying densities of aquatic vegetation. These areas were characterized by a mottled backscatter pattern in the sidescan-sonar data, silt to coarse sand sediments, and isolated exposures of bedrock; and (3) muddy-basin environments mapped in water depths greater than 5 m, contain low-backscatter fine-grained sediments, and the thickest accumulations of glaciolacustrine and Holocene lacustrine sediments.

Acoustic ground discrimination systems survey data were used to describe the distribution of submerged aquatic vegetation (SAV) in the littoral zone of Moultonborough Bay. SAV included variable leaf water-milfoil, native milfoil, bassweed, pipewort, and other species growing in water ranging from less than 1 to 4 m deep. Overall, 86 percent of the littoral zone had some SAV. These data were used to create an interpolated map that distinguished variable leaf water-milfoil from other SAV in the bay. Criteria were determined for depth, sediment texture, and the percentage of vegetative bottom cover, and were used to identify areas in the littoral zone where the SAV is likely to be variable leaf water-milfoil. In 2005, 21 percent of the littoral zone had variable leaf water-milfoil at a density of 59 percent or greater bottom cover. The criteria also were used to define areas in the littoral zone that may be susceptible to the spread of variable leaf water-milfoil. Approximately 44 percent of the littoral zone was estimated to have habitat suitable for variable leaf water-milfoil and would likely be susceptible to future growth of the plant.

Difference in depth between variable leaf water-milfoil sites and other-SAV sites was significant ($p = 0.04$). Variable leaf water-milfoil was found at depths that ranged from 1 to 4 m, whereas other SAV was found at depths that ranged from 1 to 2 m. Concentrations of iron in water-column samples were significantly lower at variable leaf water-milfoil sites than at the other-SAV sites and no-SAV sites ($p = 0.04$). The percentage of TOC in the sediment samples also was significantly lower at the variable leaf water-milfoil sites than at the other-SAV sites and no-SAV sites ($p = 0.04$).

Measures of the fine (d16), median (d50), and coarse (d84) fractions of the sediment were interpolated to characterize the sediment composition at each site. The presence of variable leaf water-milfoil was most strongly correlated with differences in surficial-sediment composition. Variable leaf water-milfoil was found in areas of coarse sand (with a median grain diameter of 0.62 mm). Concentrations of phosphorus and total ammonia plus organic nitrogen in interstitial pore water were both correlated with the median grain size (d50) (Rho = 0.44; $p < 0.05$ and Rho = 0.47; $p = 0.02$, respectively).

The use of geophysical surveys provided a comprehensive assessment of the lake-floor environment and SAV distribution; these techniques could be used to guide additional sampling and monitoring of lake environments, including the growth and spread of aquatic vegetation. The techniques made it possible to discern the differences in the spatial distributions of variable leaf water-milfoil and other types of SAV and to identify habitat for potential growth. These tools also may be valuable for assessing the susceptibility of lakes to aquatic invasive species. Habitat and SAV maps that indicate variable leaf water-milfoil distribution and density may be useful in identifying areas susceptible to future infestation or may help predict the success of eradication efforts to remove the plant. Results from this study indicate that variable leaf water-milfoil is present at differing densities in most areas where the sediment characteristics are conducive to its growth. The study also demonstrated a methodology that integrated geophysical, water-quality, and sediment surveys for identifying areas on a lake floor susceptible to variable leaf water-milfoil infestation. Results from this study may be useful in the management and allocation of resources for monitoring and controlling variable leaf water-milfoil infestations at similar sites.

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Appendix 1

Appendix 1. Site names, locations, water depths, textural compositions, median surficial-sediment grain sizes, standard deviations, skewness, kurtosis, and "verbal equivalents" (Shepard, 1954) for sediment samples collected in Moultonborough Bay, Lake Winnipesaukee, New Hampshire, July 2005. This information was used to ground-truth sidescan-sonar data.

[%, percent; mm, millimeters]

Site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Water depth (meters)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Median grain size (mm)	Standard deviation	Skewness	Kurtosis	Verbal equivalent (Shepard, 1954)
STA1A	43.72825	71.38752	3.0	8.06	31.52	48.69	11.73	0.17	3.33	0.10	-1.03	GRAVEL > 10%
STA1B	43.72825	71.38725	3.0	0.61	5.08	55.50	38.81	1.32	2.47	0.43	0.97	GRAVEL > 10%
STA2	43.72812	71.38621	4.0	12.87	76.14	10.99	0.00	0.02	1.80	-0.20	0.78	SILT
STA3	43.72734	71.38794	4.0	8.38	45.21	45.81	0.60	0.05	2.70	0.03	-0.90	SILTY SAND
STA4	43.72665	71.38743	5.0	13.36	69.90	16.74	0.00	0.02	1.92	-0.16	0.10	SANDY SILT
STA5	43.72637	71.38824	5.0	24.60	71.90	3.50	0.00	0.01	1.59	-0.08	0.29	CLAYEY SILT
STA6	43.72642	71.38937	3.5	19.78	71.76	8.46	0.00	0.01	1.81	-0.22	0.74	CLAYEY SILT
STA7A	43.72471	71.38689	5.5	4.57	17.68	75.96	1.78	0.08	1.64	0.53	4.30	SAND
STA7B	43.72471	71.38689	5.5	0.95	5.91	88.32	4.82	0.38	1.83	0.61	2.76	SAND
STA8	43.72700	71.38854	4.5	16.09	79.50	4.41	0.00	0.01	1.60	0.00	0.64	SILT
STA9	43.72643	71.38982	2.5	20.51	68.12	11.37	0.00	0.01	1.91	-0.28	0.42	CLAYEY SILT
STA10	43.72584	71.39084	2.0	23.78	68.55	7.67	0.00	0.01	1.86	-0.39	1.19	CLAYEY SILT
STA11	43.72408	71.38807	9.5	21.38	77.98	0.64	0.00	0.01	1.47	0.11	-0.04	SILT
STA12	43.72367	71.39027	2.5	14.57	75.25	10.18	0.00	0.01	1.80	-0.23	1.09	SILT
STA13	43.72298	71.38868	3.0	2.29	13.42	71.82	12.47	0.52	2.53	0.51	0.83	GRAVEL > 10%
STA14	43.72314	71.38655	3.5	0.99	4.88	63.33	30.80	0.75	2.29	0.45	1.38	GRAVEL > 10%
STA15	43.72205	71.38651	5.0	2.35	16.49	80.72	0.44	0.19	1.96	0.57	1.62	SAND
STA16	43.72102	71.38508	4.5	0.47	2.49	93.37	3.67	0.39	1.42	0.61	5.12	SAND
STA17	43.71966	71.38200	7.1	5.46	22.87	66.72	4.94	0.24	2.87	0.32	-0.60	SILTY SAND
STA18	43.72206	71.38164	7.5	19.97	67.67	12.36	0.00	0.01	2.17	-0.53	1.21	CLAYEY SILT
STA19	43.72362	71.38158	5.5	2.66	19.86	76.24	1.24	0.32	2.39	0.49	0.23	SAND
STA20	43.72451	71.38190	5.1	16.35	77.43	6.23	0.00	0.01	1.65	-0.11	0.71	SILT
STA21	43.72673	71.37822	5.0	13.85	68.83	17.32	0.00	0.02	1.79	-0.07	-0.29	SANDY SILT
STA22	43.72702	71.37860	4.1	10.46	55.73	33.62	0.20	0.02	1.94	0.06	-0.50	SANDY SILT