Teaching Winter Geohydrology Using Frozen Lakes and Snowy Mountains

Sara Elizabeth Gran, Paul Robert Bierman, Kyle Keedy Nichols
Department of Geology
University of Vermont
Burlington, Vermont 05405
e-mail: pbierman@zoo.uvm.edu

ABSTRACT
We have developed two ice- and snow-dependent geohydrology projects for the long, chilly Vermont winter. Both projects are field-oriented and allow the students to do original research. The first project involves investigating a pond and its surrounding drainage basin. In the second project, students explore the snowpack hydrology of a local skiing area.

At the pond, the students learn to survey, make bathymetric maps, measure water temperature and conductivity, calculate lake volume and water residence times, and collect and analyze a sediment core. In the skiing area, students calculate the volume of water in the snowpack, establish the relationship between water equivalent of snow and elevation, record snow stratigraphy, and calculate the effects of a hypothetical late-winter rainfall event on the snowpack. Both projects emphasize a hands-on, interactive-learning style based on data collection, field observation, and the application of geohydrologic principles rather than the memorization of information.

Keywords: Earth science – teaching and curriculum; education – geoscience; geohydrology and hydrology; miscellaneous and mathematical geology.

INTRODUCTION
It has been our experience at the University of Vermont that students enjoy field-based geology courses and get excited by doing original research. Because our geohydrology class is typically taught in the spring semester (January to May) and winter in Vermont can often last until early April, we created a set of projects that allows us to get outside and teach students about geohydrology even in sub-freezing temperatures (for other geology projects involving ice and snow, see Romney, 1983; Wise, 1990; Bjornerud, 1996).

During the past five years, we have developed a geohydrology course structured around three, day-long, weekend field projects in which students explore the relationships among water and earth-surface processes (for more information about this class, see the University of Vermont Geology Department web site, 1999). Lecturing is kept to a minimum and there are no exams in the course. Two of the field projects are specifically designed to be taught during the winter; one involves pond hydrology and the other is a snowpack analysis. The third project takes place later in the spring and usually involves ground-water or slope stability (Clapp and others, 1996). Field data for each project are collected during an all-day Saturday field trip. The students’ reports are written as formal scientific papers. All of the projects are open-ended and we, as the instructors, do not know what the results of each project will be until all the data are collected and analyzed.

Geohydrology is offered as an upper-level course, available for either undergraduate or graduate credit. Each year, the student body consists of 15 to 20 junior and senior undergraduates, predominantly from Geology, Environmental Science, and the Environmental Studies program, as well as graduate students from the School of Natural Resources, the Field Naturalist program, Civil Engineering, and the Geology Department.

In preparation for the weekend field trips, we introduce the upcoming project during the class period before the trip and demonstrate the equipment we expect to use. The project introduction gives the students the opportunity to think about how and what data should be collected. As instructors, we provide a list of questions to explore, a general structure for data collection, tools for data collection and analysis, and advice on how to approach the questions posed in the lab assignments. We allow the students to organize the data-collection procedures, and we encourage them to be efficient by organizing themselves into groups. All data are then shared among all class members. Many students are excited by the process of collecting and interpreting new data and enjoy the fact that there is no answer key and no “right” or “wrong” answer.

POND HYDROLOGY IN VERMONT
Lakes and ponds are important hydrogeologic features in Vermont. They store water, provide habitat for aquatic plants, fish, and wildlife, and act as sediment traps. Over the years, we have investigated several ponds within a 90-minute driving radius of Burlington (Bierman and others, 1997). In January 1998, we studied Richmond Pond, a small kettle pond located in Richmond, Vermont, 25 km east of Burlington (Figure 1).

Richmond Pond probably formed soon after the glaciers retreated about 15,000 years ago (Waite and Davis, 1988; Webb and others, 1993). About 200 years ago, clear-cutting of forests for settlement and agriculture began (Meeks, 1986). From the time of pond initiation to the present, inorganic and organic material has been deposited in the pond. Sediment from other ponds in Vermont consists mainly of gyttja (organic-rich detritus from primary productivity) interspersed with inorganic sediment layers (Brown,
Brown (1999) and Bierman and others (1997) suggest that inorganic, terrestrial sediment is deposited in ponds during hydrologic events such as large storms and possibly during times of deforestation.

Richmond Pond is situated among hills that rise 200 to 300 m above it and has a maximum depth of 3.5 meters and a surface area of about 7.6 x 10^4 m^2 (Figure 2). A distinct vegetation change above the current water level and a breached earthen dam suggest there was a former water level about 1.8 m higher than at present. The area of the Richmond Pond drainage basin is about 2.3 km^2. Several small streams enter the pond, each producing small alluvial fan-deltas (Figure 2). In January, the presence of soft ice near the toes of these deposits suggests that shallow ground water enters the pond through the fan-deltas. The only surface outflow for the pond cuts through the old earthen dam and several smaller beaver dams downstream.

For this project, students collect bathymetric data, measure water temperature and conductivity, locate ground-water inputs, and extract a sediment core. The students use an optical total station and a real-time kinematic global-positioning system to make a map of the bathymetry and the core location. They are then asked to use these data to draw conclusions about the movement of water within the pond, calculate pond-water residence time, and to hypothesize about the pond's depositional and hydrologic history.

**Purpose**

Pond hydrology is our first project of the semester, and aside from the scientific goals of the assignment, we want students to get to know each other, to work together, and to acclimatize to working outside in cold weather. From a scientific standpoint, we are interested in teaching the students how to collect data, organize observations, make surveys, and collect cores. Finally, we want them to understand the hydrology of ponds in the winter (considering residence time of water, inflows, outflows, water-column stratigraphy, and sediment record). Since nobody (including the instructors) knows specifically what the class will find at a pond, we are as interested in the students’ approaches to organizing and implementing their research as we are in their specific answers.

**Methods**

In January 1998, the class used five manual ice augers to drill 317 holes in the ice on Richmond Pond and used weighted measuring tapes to measure water depth at those holes (Figure 2). Using a YSI 3000 temperature and conductivity meter, the students measured the temperature and conductivity of the water as a function of depth at several locations. All auger holes were mapped using either a Trimble 4400 RTK Global Positioning System or a Pentax PCS-2c total station, both precise to several centimeters. This mapping could have been done using less sophisticated methods such as plane table and survey rod or pace and compass, but we wanted the students to have the experience of using the new tools that are available. We also mapped the old.
higher shoreline and the location of the breached dam. In addition, we gave the students two hours in the field to make observations of the pond, the inflow drainages, the outflow channel, and the vegetation in the basin. This encouraged them to think about the "big picture" of the Richmond Pond hydrology. Later, we plotted the auger hole and lake boundary points using DeltaGraph 4.0. The students then made hand- or computer-contoured bathymetric maps and temperature and conductivity cross sections (Figure 3).

The class collected a sediment core from the depocenter of the pond (about 3.5-m water depth). Our low-cost coring device (based on a design by Reasoner, 1993) consists of a 7.5-cm-diameter, 6-m-long, PVC core barrel which fits into a reusable core head; a "hammer" is used to pound the core barrel into the sediment (Figure 4). The core barrel and hammer are each independently controlled with rock-climbing rope by people on the ice surface. Using this equipment and a series of pulleys to aid in the extraction, the class was able to remove a 3.75-m-long core. Once the core was extracted, it was cut into three sections with a PVC saw and the ends capped for transportation to the University of Vermont.

In the laboratory the students performed several analyses on the sediment core. Magnetic susceptibility was measured by running the three sections of core

![Figure 4. Modified Reasoner coring apparatus (modified from Brown, 1999; original drawing by J. Robison).](image)

![Figure 3. Cross sections of Richmond pond. A. Temperature (°C). B. Conductivity (millihms). Depth and distance are measured in meters, presented with a twenty-fold vertical exaggeration.](image)
through a Bartington magnetic-susceptibility (MS) meter. The students then split the cores in half lengthwise and visually logged the sediment color, texture, and grain size; they also picked out some of the visible macrofossils for species identification and $^{14}$C dating. Each centimeter of core was sampled and measured for water content by weighing samples before and after drying in a 90°C oven. The students determined organic content in each centimeter of core using a loss-on-ignition (LOI) process, which consists of weighing dry samples before and after burning for several hours in a 450°C oven.

Results

The students were able to extract a great deal of information from one day of field work at Richmond Pond. The volume of water currently in the pond was calculated by digitizing the pond area and bathymetric contour lines, calculating the surface area between contour lines, and multiplying those areas by the average water depth between each contour. Students calculated contemporary water volumes on the order of $1.2 \times 10^5$ m$^3$, less than one half the pre-dam breaching volume of $3.0 \times 10^5$ m$^3$. Students measured the area of the Richmond Pond drainage basin by drawing the drainage divide onto photocopied of the USGS Vermont 7.5 minute quadrangle and digitizing the basin area. Using equations 1 and 2 below, they calculated an average pond-water residence time of about 18 days:

$$PA = Vr$$  \hspace{1cm} (1)

$$Vp / Vr = R$$  \hspace{1cm} (2)

where $P$ is the average yearly precipitation (m), $A$ is the area of the drainage basin (m$^2$), $Vr$ is the drainage basin rainfall volume (m$^3$ yr$^{-1}$), $Vp$ is the volume of water in the pond (m$^3$) and $R$ is the pond-water residence time (yr). For this simplified calculation, we did not require the students to take into account evapotranspiration, although some did this without our prompting.

Water temperature and conductivity were well stratified, implying little mixing throughout the water column. The water temperature at the bottom of the pond was about $4^\circ$C, while water near the surface (directly beneath the ice) was $0^\circ$C. The conductivity was highest in the water near the bottom and edges of the pond, probably due to a high ionic content of water near the bottom sediments (Figure 3).

Analysis of the sediment core yielded information regarding the depositional history of the Richmond Pond basin, though the sediment record from this core did not reach pre-pond glacial deposits. Magnetic susceptibility (MS) detects the presence of iron-bearing inorganic minerals, which we assume to have been eroded off the hillslopes and deposited in the pond. MS analysis showed that some layers of the core had relatively more terrestrial sediment than others, possibly suggesting that there were times of more rapid erosion on the hillslopes (Figure 5). Once the students split the core and saw what was in it (this was a big moment for the class), they found a few thin sandy layers, which they interpreted as discrete sediment-input events (Brown, 1999; Bierman and others, 1997). These layers were easy to find and appeared as light-gray or light-brown laminations interspersed with the predominantly homogeneous dark-brown gyttja.

![Figure 5. Compilation of sediment-core data, including stratigraphy, magnetic susceptibility (MS), loss-on-ignition (LOI), and water content. High MS and low LOI correlate to high mineral content. Terrestrially derived sediment input has varied throughout time, with periods of relatively high (zones 1 and 3) and low (zone 2) terrestrial-sediment input. Zone 1 does not have discrete sandy layers, suggesting that there has been increased background terrestrial sediment input in recent years. A spruce needle from the base of the core yielded a $^{14}$C age of 8850 ± 50 years; calibration results in a 2σ age range of 10,170 to 9,700 years BP.](image)

*Journal of Geoscience Education, v. 47, 1999, p. 423*
Loss-on-ignition (LOI) data agreed well with the MS data and also indicated there were variable amounts of terrestrial sediment in the core (Figure 5). Measurements of relative terrestrial-sediment content correlated well among all three logging methods: the visual-core log, LOI, and MS.

Students found a substantial number of macrofossils in the core, including leaves, shells, and twigs. A spruce needle found 386 cm below the top of the sediment core was $^{14}$C dated at Lawrence Livermore National Laboratory and yielded a calibrated $2\sigma$ age range of 10,170 to 9,700 years BP (LLNL #50818, 8850 ± 50 radiocarbon years). The radiocarbon calibration was done using the computer program CALIB 4.0 (Stuiver and Reimer, 1993). CALIB 4.0 can be downloaded free of charge from the University of Washington Quaternary Isotope Laboratory Home page (1999).

It appears that the terrestrial-sediment input, which depends on the basin-erosion rate and the ability for eroded sediment to be transported into the pond, has changed throughout time. Some students divided the sediment record into three zones based on relative abundances of terrestrial sediment. Many thin sandy layers were found between 370 and 125 cm depth (zone 3), and none were found between 125 and 40 cm (zone 2). Despite the lack of discrete layers in the upper 40 cm of the core (zone 1), there appears to be a fairly high inorganic sediment content, which is possibly due to recent (last 200 years) anthropogenic disturbance in the area (Bierman and others, 1997; Meeks, 1986).

**SNOW IN THE GREEN MOUNTAINS**

Snow is hydrologically important in Vermont. The highest point in Vermont, Mount Mansfield, receives about 76 cm of water equivalent, or 45% of the yearly precipitation, as snow (National Weather Service Burlington home page, 1998). Water stored in the snowpack is typically released by melting from mid-March to mid-May. This meltwater causes annual spring flooding, recharges aquifers, and supplies water for agricultural use. Snow is economically important because it provides the base, literally, for Vermont's lucrative ski industry.

For the past several years, the geohydrology class has investigated the snowpack on several local mountains. In February 1998, we studied Spruce Peak (elevation 1,331 m), located on the east side of Mt. Mansfield (Figures 1 and 6). This area is a popular skiing, hiking, and rock-climbing destination in northern New England. The summit of the mountain is above treeline, and high winds often clear it of snow. Vegetation grades with elevation from conifers just below the summit to deciduous trees near the bottom of the mountain.

**Purpose**

Our goals for this project are to teach students techniques for studying a snowpack, to determine how much water resides in the Spruce Peak snowpack, and to compare these results to previous years' data. Students learn how to measure water equivalent (the vertical equivalent depth of water contained in a column of snow), identify different types of snow metamorphism, find evidence of the winter's precipitation patterns, and judge whether the snowpack represents an avalanche hazard. The water-equivalent data are compared with data taken by previous classes (for water-equivalent data, see the University of Vermont Geology Department web site; GEOL 255, Geohydrology). As with the Richmond Pond project, we emphasize to the students that they are doing original research. There are no pre-determined answers to any of the questions posed in the project description.

**Methods**

The class, equipped with snow shovels, snow tubes, and snow kits (described below), took a ski lift (provided free each year by the Smuggler's Notch ski area) to the top of Spruce Peak, where we let the students divide into three groups of six, strap on snowshoes, and put on another sweater. We collected data at five elevations 100 to 200 vertical meters apart (determined using an altimeter and located on a topographic map from coordinates measured with a handheld Garmin 12 GPS). Each group measured water equivalent and dug a snow pit to log snow stratigraphy, examine snow-crystal metamorphism, and measure snow density and temperature. The students collected three sets of data from the upper four elevations (sites 1 to 4), and one set of data from the lowest elevation (site 5) (Figure 6).

To measure water equivalent, each group used a "snow tube," which is a 1.5 m length of 5-cm-diameter PVC pipe with a sharpened, serrated end, a centimeter scale marked on the side, and a hanging scale (Figure 6).
shortwave radiation per rainy day (p. 479). Students also used the temperature-index equations (13-19) and (13-20) on p. 482. Sample exercises using these equations can be found on p. 490. We consider this part of the project to be important because it integrates basic science, such as the physics of the ice-water phase transition, with original geohydrological research.

Results

The class calculated a cumulative water volume of about 2.3 x 10^6 m^3 in the 10 km^2 catchment, resulting in an average water-equivalent depth of 23 cm. Water equivalent generally increased with elevation, with the exception of the uppermost elevation (Figure 8). The highest elevation had different vegetation (dense conifer stands as opposed to deciduous trees) and a more southerly facing slope, which could explain why it held less water than the site 100 m below. Graphs of water volume as a function of elevation demonstrate that the water volume held on the mountain in February has not varied widely in the past few years (Figure 8B). Each year there has been a similar relationship between water equivalent and elevation. We will continue to monitor the snowpack on Spruce Peak yearly in order to develop a long-term data set for students to analyze.

Based on snow-crystal shape, the students were able to identify several layers within the snow of both constructive and destructive crystal metamorphism, which were most likely a result of warming and cooling on a diurnal cycle. There were several ice layers at all elevations. At lower elevations, there was a 2-cm-thick ice layer, beneath which all the snow was icy and compact. The class hypothesized that this layer was created in the infamous ice storm that occurred in January 1998, when about 5 cm of freezing rain fell at lower elevations. This rain probably soaked the existing snowpack and created a layer of ice. The ice layer was later covered with fresh snow.

The students calculated that the rainstorm would cause a 7-cm loss of water equivalent using the simplified basin snow-melt equations and an 8-cm water-equivalent loss using the temperature-index equations (these water-equivalent losses do not include the amount of rain that fell). The simplified basin snow-melt equations consider different energy inputs to the snowpack, including shortwave and longwave radiation, convective and sensible heat transfer, and the input of energy from precipitation (Dunne and Leopold, 1978). The students found that very little melting would occur as a result of energy transfer from the cooling of the rainfall (0.2 cm water equivalent) and that most would result from the warm wind (6 cm water equivalent). One creative student calculated that the energy the cooling of the rain adds to the snowpack would be equivalent to the calories contained in about 10 million Snickers bars.

PROJECT COMPLETION AND EVALUATION

The students were given three weeks after the day in the field to complete the Richmond Pond reports.
Figure 8. A. Cumulative water equivalent in snowpack, February, 1998, increases with elevation on Spruce Peak. B. Water equivalent versus elevation; data from Spruce Peak, 1994, 1995, and 1996. Each year, data were taken in February. The data indicate a consistent relationship between increasing elevation and water equivalent for the past few years, the result of both less melting and orographically enhanced precipitation at higher elevations.

We felt that this much time was necessary because of the volume of data collected and the time it took to analyze the sediment core. The snowpack report was due two weeks after the field trip. We limited the length of text in both reports to no more than five pages (double-spaced, size-12 font, 1-inch margins), but did not limit the number of figures or appendices used to present data and calculations. Each report was evaluated on the quality of the science, the writing, and the calculations. Instead of simply handing the reports back during class, we scheduled office hours during which students could pick up their graded reports and discuss our extensive evaluations.

For the snowpack report, we asked each class member to evaluate and edit another student's report and comment on it. Each student then received both the instructors' evaluation (without a grade written on it) and the peer evaluation and was allowed one week to rewrite the original report. We feel that it is important to give the students a chance to practice critical evaluation of peers' work and that both acting as an editor and receiving formal editorial comments from someone other than an instructor enhances the rewriting process.

CONCLUSIONS

By designing geohydrology field projects specifically for a wintry climate, we are able to structure the class around outdoor field work and data collection, despite frozen surface water and largely inaccessible ground water. The students gain surveying, coring, core analysis, and snowpack-analysis experience. They are given some freedom to decide which data to collect and what aspects of the hydrologic systems to investigate within the framework of the assignments.

Students in Geohydrology tend to be motivated and involve themselves in the class, in part because they are able to relate their individual interests and expertise to the projects we assign. Although preparation for this field-based method of teaching is more time consuming and complicated than that for a standard lecture format, we feel that we are able to keep the students more interested and involved in the class. We are fascinated by the creative and unexpected contributions students made both during class and in their reports. Cold weather and snow should not be a deterrent to anyone wanting to teach an interesting and effective field-based geohydrology course.

ACKNOWLEDGMENTS

We acknowledge the Geohydrology class of 1998: J. Alpaken, K. Brooks, D. Eurlich, S. Flemer, S. Gustafson, Z. Landis, M. Lescaze, J. Malczyk, T. Menesca, M. Muller, K. Nichols, M. O'Reilly, A. Perrault, J. Robison, B. Rosenheim, S. Rupard, D. Santos, J. Smith, and J. Talcott. We thank the Preston family for allowing us access to Richmond Pond and the Smuggler's Notch ski area for use of their ski lift. S. Brown assisted with sediment-core extraction and analysis. The radiocarbon sample was processed at Lawrence Livermore National Laboratory with the assistance of J. Southon. Funding for 

Teaching Winter Geohydrology Using Frozen Lakes and Snowy Mountains

from NSF CAREER grant EAR 9702643 to Bierman. Thoughtful reviews from K. Jennings, A. Noren, D. Santos, and two anonymous reviewers significantly improved the manuscript.

REFERENCES CITED


Webb, T., Bartlein, P.J., Harrison, S.P., and Anderson, K.J., 1993, Vegetation, lake levels, and climate in eastern North America for the past 18,000 years, in Wright, H.E., and others, editors, Global climates since the last glacial maximum: Minneapolis, University of Minnesota, p. 415-467.


ABOUT THE AUTHORS

The authors are part of a group studying surface processes at the University of Vermont. Associate Professor of Geology Paul Bierman and graduate students Sara Gran and Kyle Nichols have research interests that include the Quaternary and Holocene geology of New England, ground-water hydrology, glacial and de-glacial geomorphology, desert-surface processes, and applications of cosmogenic nuclide-abundance measurements to understanding tectonic and geomorphic processes.

"BUMMER. A SOOTHSAWER JUST TOLD ME THAT THE DINOSAUR I KILLED TO BECOME KING OF GONDWANALAND WAS MY OWN FATHER. AND THEN HE SAID THAT BESIDES BEING MY QUEEN YOU WERE ALSO MY MOM."

OEDIPUS T-REX