Teaching Geohydrology Through Analysis of Ground-Water Resources and Glacial Geology in Northwestern Vermont

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ABSTRACT
Sixteen Geohydrology students from the University of Vermont used over 500 well-completion reports and numerous field observations to understand better the ground-water resources and subsurface glacial geology of Jericho, Vermont, an upland, rural town now facing rapid residential development. Our approach provides a model for cooperation among educational institutions and regulatory agencies in which existing, but underutilized, geologic data provide both the means for hands-on learning and a rational framework for aquifer protection.

Three confined, unconsolidated glacial aquifers occupy bedrock valleys in the Jericho area. Cross sections and the hypothesized configuration of ice margins during retreat suggest that confining layers are most often glaciolacustrine, fine-grain sediments deposited in ice-marginal glacial lakes. Pumping-test data collected from one aquifer confirm its confined nature, demonstrate that the aquifer can supply large amounts of water, and indicate that there is significant hydraulic communication between the unconsolidated aquifers and the underlying fractured bedrock.

Keywords: Education — geoscience; education — undergraduate; hydrogeology and hydrology; surficial geology — Quaternary geology.

INTRODUCTION
Sixteen Geohydrology students from the University of Vermont conducted an assessment of the ground-water-resource potential for the Town of Jericho, Vermont. Through the use of well-completion reports provided by the State, existing pumping-test data, and field observations, the students were able to determine locations, geometry, and hydrologic characteristics of aquifers and potential sources of contamination to these aquifers. This paper describes our findings, the methodology we used, and the geology and hydrology of Jericho, Vermont.

Geography
The Town of Jericho (86.7 km²) is located in northwestern Vermont, between the Green Mountains and Lake Champlain with elevations ranging from a maximum of 579 m above sea level (1900 ft) to a minimum of 76 m above sea level (250 ft) (Figure 1). The Jericho landscape is predominantly one of rolling hills consisting of agricultural land and large residential tracts; over the past decade many smaller housing developments and small commercial areas have been built. Jericho's climate is that of northern New England; the town receives an average of 838 mm (33 in) of precipitation annually. Although the central Village of Jericho, Jericho Center, and Underhill Flats (35-40% of the 3600 residents) are now supplied municipal water from the Champlain Water District, nearly all other areas of the town are dependent on individual, residential wells.

Surface Hydrology & Major Basins
The town of Jericho can be subdivided into three large drainage basins each with a westerly flowing river system (Figure 1). The southern third of the town drains into Mill Brook and is a sub-drainage basin within the much larger Winooski River drainage basin. The Mill Brook basin is bounded by the Underhill Range to the north and a smaller series of mountains to the south and east. The middle third of the town drains into the Lee River, which occupies a basin bounded by the peaks of the Underhill Range. The Browns River and its associated drainage basin occupy the northern third of the town and are bounded by the Underhill Range to the south, Mount Mansfield and the Green Mountains to the east, and some smaller foothills to the north. The Browns River is joined by the Lee River in the Village of Jericho where it flows to the north and west, eventually joining the much larger Lamoille River.

Bedrock Geology
Jericho is located on the western limb of the northsouth-trending Green Mountain Anticlinorium. The bedrock consists of highly metamorphosed phyllites, schists, and gneisses of the lower Cambrian Pinnacle and Underhill Formations. These rocks have substantial numbers of fractures, joints, and faults (Doll and others, 1961), which provide secondary porosity and allow large volumes of ground water to travel through otherwise low-permeability bedrock. The bedrock crops out primarily in the highlands of the town where the overburden is thin or absent. Bedrock surface and depth-to-bedrock contour maps, along with cross sections, indicate that there are deep bedrock valleys beneath the surface and that these are the primary features in which deep, unconsolidated deposits have accumulated (Figure 2). These bedrock valleys most likely represent preglacial river valleys that have been further deepened by repeated glaciation during the Pleistocene.

Figure 1. Contour map of Jericho, Vermont showing potential confined aquifers, aquifer recharge, and areas with potential contamination sources. Lines of cross-section for Figure 3 are also shown.

Surficial Geology

The unconsolidated surficial materials in Jericho were deposited as a result of the advance and retreat of the Laurentide Ice Sheet, ending approximately 13 ka (LaDue, 1982). A relatively thin layer of glacial till was deposited over most of the bedrock surfaces. This glacial till is a dense, unsorted, unstratified mixture of sediments ranging from boulders to fine silt and clay, and has a very low permeability. As the glacier retreated, meltwater streams (possibly englacial) deposited the thick sequences of sorted and relatively permeable sand and gravel on the valley floors. As
the ice retreated down the valleys, to the north and west, it dammed the upland streams forming glacial lakes. Once the lakes had formed, fine-grained sediments settled out as blankets of silt and clay overlying the sand and gravel (Ladue, 1982), confining the unconsolidated and bedrock aquifers of the Mill Brook basin, the Brown’s River basin, and the Lee River basin. In several lowland areas within Jericho, there are sequences of glaciolacustrine sediments up to 27.4 m (90 ft) in thickness (Figure 2).

Since deglaciation, fluvial sands and gravels have been deposited over the glaciolacustrine sediments. The total volume of overburden estimated from the depth to bedrock contour map (Figure 2) is approximately 1.07 km$^3$ (0.26 mi$^3$). The deposits are thickest in the deep bedrock valleys and thin toward the highlands where the bedrock is exposed.

In several locations, material identified as glacial till seems to confine permeable sands and gravels. This diamicct most likely results from the downslope movement of colluvium from the glacially over-steepened upland valley walls, as well as episodes of flowtill slumping off the melting ice front. Alternatively, the presence of glacial till may indicate that the ice experienced pulses of re-advance or could possibly indicate deposition of outwash in front of the advancing ice sheet. It is also possible, in some cases, that either we or the well driller has misidentified the stratigraphy.

Figure 2. Thickness (ft) of unconsolidated materials map for Jericho, Vermont. Constructed by contouring spatial data from well-completion reports, this map shows the depth to bedrock from the ground surface. Coordinates are from Vermont State Grid.

METHODS

Data Collection and Organization

Using well-completion reports provided by the State of Vermont, a group of 16 students working as eight pairs, field located 350 of the 500 residential wells of the Town of Jericho, and recorded the locations on 1:5000-scale aerial orthophotographs. A hand-held global-positioning unit was made available to aid in establishing the location of the wells. The locations were digitized and entered into an Excel 4 (Microsoft, 1992) spreadsheet through the use of the software package, Digitize (Rockware, 1993). Data points were then transferred to USGS 7.5-minute quadrangle maps in order to determine ground surface elevations at each well location. Three-dimensional and spatial relationships between wells were then established.

Stratigraphic data from the well-completion reports were interpreted and each stratigraphic unit was classified as either bedrock, weathered bedrock, till, silt and clay, or sand and gravel. The identification of stratigraphic units from well logs is often a matter of judgment.

Graphical Representation and Interpretation

Students learned the use of the well-log-representation program, Logger 1.11 (Rockware, 1994), by manually entering the stratigraphy described in each of the well-completion reports. Logger allows the students to visualize the stratigraphy at any particular well location in two dimensions. The well-log data from Logger, as well as the location data previously entered into the Excel spreadsheet, were then transferred to both Deltagraph 2.02 (Deltapoint, 1992) and the cross section drawing program, Mac Section (Rockware, 1993). Deltagraph, with its contouring function, allowed the students to make bedrock-surface and depth-to-bedrock contour maps (Figure 2). These simplified contour maps made it possible to determine the most probable aquifer locations and to determine the
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Figure 3. Cross sections of the Browns River and Lee River Basins. Constructed from well logs (outlined in figure) adapted from well-completion reports, these cross sections display ideal stratigraphy for confined, unconsolidated aquifers. Cross-section locations are shown on Figure 1.

The total volume of surficial material overlying bedrock.

Mac Section allowed the students to choose multiple cross-sectional lines throughout the town along which they could easily create and view two-dimensional cross sections (Figure 3) and three-dimensional fence diagrams. Choice of the lines of cross section were based on the depth-to-bedrock contour maps. The cross sections and fence diagrams allowed the students to visualize the geology and geometry of the surficial deposits as well as the underlying bedrock. Once the subsurface geology was better understood, the students were able to apply the concepts of groundwater hydrology, learned in the classroom, to determine the geometry of potential aquifers as well as the potential for contamination of these aquifers.

Pumping-Test Data

Pump-test data from a well field located within the Browns River drainage basin, one of the major potential aquifers, were used to calculate the transmissivity ($T$), storage coefficient ($S$), and the hydraulic conductivity ($K$) of the aquifer.

Transmissivity is a measure of the ability of an aquifer to transmit water to a well. A high $T$ value (>10,000 gal day$^{-1}$ ft$^{-1}$) is sufficient for municipal water supply whereas a low $T$ value (<1,000 gal day$^{-1}$ ft$^{-1}$) may only be sufficient for low-yield domestic uses. Transmissivity can be calculated from pumping-test data by the use of time-drawdown plots (Figure 4) and the Jacob approximation:

$$T = \frac{264}{\Delta s} \quad \text{(eq. 1)},$$

where:

$Q =$ discharge of pumping well (gal/min), and

$\Delta s =$ change in drawdown (ft) (from semi-logarithmic time vs drawdown plot).

The storage coefficient ($S$) of an aquifer represents the volume of water that is available for withdrawal from a well and is a ratio of the amount of available water to the amount of water stored in the pore spaces of the aquifer. Low values of $S$ (<0.01) are indicative of confined aquifers, and high values (>0.01) indicate unconfined aquifers (Driscoll, 1989). The storage coefficient can be calculated from pumping-test data by the use of time-drawdown plots (Figure 4) and the Jacob approximation:

$$S = 0.3 \frac{T \cdot t_0}{r^2}, \quad \text{(eq. 2)},$$

where:

$t_0 =$ intercept at zero drawdown (days) (from semi-logarithmic time vs drawdown plot), and

$r =$ distance from pumping well to observation well (ft).

The hydraulic conductivity ($K$) is the flow of water through a porous medium in feet or meters per day (Dunne and Leopold, 1978). If the aquifer thickness ($b$) is known, transmissivity can be converted to a hydraulic conductivity by using the relationship:

$$T = K \cdot b. \quad \text{(eq. 3)}$$
Figure 4. Time versus drawdown plot using data from pumping tests conducted by Phillips and Emberley, Inc. (1980). This plot is used to calculate the transmissivity (T), storage coefficient (S), and hydraulic conductivity (K) through the use of equations 1-3. Calculated T and S values are shown in Table 1.

Formal Presentation of Data
When their work was completed, the students prepared written reports to the town of Jericho discussing the results of the study, potential sources for aquifer contamination, and recommendations on aquifer protection. A formal poster session was also given at the University of Vermont Geology Department for which each pair of students prepared and defended their research. Guidelines for the poster session were based on those used by the Geological Society of America.

AQUIFER POTENTIAL
There are several geologic environments within the town of Jericho that provide the potential for storing and supplying ground water. Bedrock aquifers provide excellent potable water, yet drilling costs are high and pumping can be energy intensive if the bedrock well is deep. Shallow, unconfined, and unconsolidated deposits are extensive in the lowlands throughout the town and when deposited over an impermeable layer of sediment or bedrock, can store and yield large volumes of easily accessible water. However, it is this ease of access that make shallow unconfined aquifers susceptible to contamination. Confined aquifers in unconsolidated materials can be found underlying many of the shallow unconfined aquifers and are generally the cleaner of the two. The migration of contaminants to the aquifer is retarded by the impermeable layers that confine the aquifer and in many cases result in an upward flow gradient.

Bedrock Aquifers and Aquifer Interconnection
Pumping-test data show that wells in Jericho's highly metamorphosed bedrock can produce sufficient water for residential use. The bedrock aquifers in the town of Jericho have yields ranging from 1 to 75 gpm (9.2 gpm average), which is adequate for residential or light municipal use. It is likely that the faults and fractures within the bedrock play a major role in the recharge of any overlying confined aquifers in unconsolidated materials. In 1988, a bedrock well pumping test (Heindel, 1988) recorded a drawdown in several wells that are terminated in the surficial deposits overlying the bedrock and are located 597 m (1,960 ft) and 558 m (1,833 ft) from the pumped well, respectively. Therefore, not only are the bedrock and confined aquifers in unconsolidated materials in communication, but it is likely that the quality of the water within these aquifers is similar to that of the confined aquifers in unconsolidated materials.

In reviewing the drilling logs for the town, we found many instances where a well was drilled through a potentially high-yield, unconsolidated, confined aquifer, deep into the underlying bedrock. In the Browns River basin, a well yielding 80 gpm from confined unconsolidated sediments is directly adjacent to a well that passes through this same unconsolidated layer, into the underlying bedrock, and yields only 0.8 gpm. Likewise, in the Lee River basin, a well yielding 75 gpm from confined unconsolidated sediments is located directly adjacent to a well that passes through the same unconsolidated layer, into the underlying bedrock, and yields only 7 gpm. Because of the likelihood that the bedrock fractures provide much of the recharge to the overlying confined aquifers in unconsolidated materials, it is our belief that in areas where a confined aquifer in unconsolidated materials exists, it is unnecessary and more costly to drill deep bedrock wells without considering extraction of water from the overlying unconsolidated confined aquifer.

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<table>
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<th>Aquifer Characteristics</th>
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<th>Pumped Well</th>
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<td>46</td>
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<tr>
<td>average hydraulic conductivity (K) for aquifer (gpd ft⁻²)</td>
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Table 1. Aquifer characteristics of three observation wells and one pumped well using data from pumping tests conducted by Emberley (1980). These wells are located in the Browns River Basin and the resulting values of T, S, and K support the conclusion that wells tap a large confined aquifer in unconsolidated material.

Shallow Unconfined Aquifers

Shallow unconfined aquifers can be easily accessible, inexpensive sources of water. A small fraction of the wells drilled in the past few decades have made use of this resource and field observations show that many older hand-dug wells tap these aquifers. Such shallow wells are all located in valley bottoms and yield up to 20 gpm. The shallow unconfined aquifers are often found above a confined aquifer (Figure 3). Although shallow unconfined aquifers are the least expensive source of ground water, they are also the most easily contaminated. Shallow unconfined aquifers communicate readily with surface waters such as streams, lakes, and ponds and are therefore likely to have water quality similar to that of the surrounding surface waters. Shallow unconfined aquifers can also contain contaminants leached directly from the ground surface above. These aquifers, although of uncertain quality for human consumption, could safely be used for irrigation of crops and lawns.

Confined Aquifers in Unconsolidated Materials

Confined aquifers in unconsolidated materials are an excellent source for potable ground water. Confined aquifers have low susceptibility to contamination and when of sufficient size, exhibit high transmissivity values, therefore, readily and reliably yielding water at a relatively low cost. Drilling costs are often lower for wells in unconsolidated materials, which are generally shallower and more easily drilled than wells in bedrock. In this study, three confined aquifers in unconsolidated materials have been identified (Figure 1), the Mill Brook aquifer, the Browns River aquifer, and the Lee River aquifer, named for the major tributary leaving the drainage basin containing the aquifer. These aquifers all show high yields (15-100 gpm), and thus are a good potential source for potable water.

The Mill Brook aquifer has typical confined-aquifer stratigraphy of permeable sands and gravels overlain by impermeable, fine-grained glaciolacustrine deposits or glacial till. The aquifer has an estimated maximum thickness of 27.5 m (90 ft) over an estimated area of 6.2 km² (2.4 mi²). Drillers' data indicate yields of 15 to 100 gpm for this aquifer. Recharge to the Mill Brook Aquifer is primarily in the uplands of a relatively undeveloped area and should therefore be generally clean, however, potential contamination sources do exist and should be investigated further if large-scale municipal well development were to occur.

The Browns River aquifer also displays typical confined-aquifer stratigraphy of permeable sands and gravels overlain by impermeable, fine-grained glaciolacustrine deposits or till. The aquifer has an estimated maximum thickness of 23 m (75 ft) over an estimated area of 5.4 km² (2.1 mi²), and has yields up to 80 gpm. Recharge areas for this aquifer include conservation land, commercial land, and agricultural land. Because of its confined nature, the aquifer should have low potential for contamination.

The Village of Jericho is located above the Browns River aquifer, and until the early 1980s the Village obtained its water supply from a well field consisting of four wells within the unconfined aquifer as well as a bedrock well and several natural springs. In 1980, the Village employed the firm of Phillips & Emberley, Inc. (Emberley, 1980) to perform a pumping test on the well field as was recommended by the State of Vermont Department of Health. A seventy-two hour pumping test was run on two of the four wells during which recovery and drawdown readings were taken.

Using the data from Emberley (1980) tests and time versus drawdown plots (Figure 4), average values of transmissivity (T) and storativity (S) were calculated to be 23.9 m² m⁻¹ day⁻¹ (2x10⁸ gal day⁻¹ ft⁻¹) and 4 x 10⁻⁴ respectively (Table 1). These calculated T and S values agree with typical T values for confined aquifers ranging from 12.41 to 124.1 m³ m⁻¹ day⁻¹ (1,000 to 10,000 gal day⁻¹ ft⁻²), and typical S values for confined aquifers ranging from 10⁻⁵ to 10⁻³ (Driccios, 1989). Hydraulic conductivity (K) was also calculated for the aquifer (Table 1), yielding a value of 3.9 m day⁻¹ (96 gal day⁻¹ ft⁻²). This value indicates that the aquifer is comprised of coarse sand to fine gravel (Driccios, 1989), which is consistent with the well-log data and exposures in nearby gravel pits. The pumping-test data and the calculated S values

confirm our hypothesis that the Brown's River aquifer is, indeed, confined.

The Lee River aquifer also displays typical confined-aquifer stratigraphy of permeable sands and gravels overlain by impermeable, fine-grained, glaciolacustrine deposits or till. The aquifer has an estimated maximum thickness of 36.6 m (120 ft) over an estimated area of 2.07 km² (0.80 mi²), and has yields of 25-80 gpm. The recharge areas (Figure 1) are zoned agricultural and village and therefore could be susceptible to contamination although no major hazardous contamination sites exist.

POTENTIAL FOR AQUIFER CONTAMINATION

The potential for ground-water contamination within the confined and bedrock aquifers is limited due to the rural setting of Jericho and the nature of the confined aquifers. However, there are several potential sources of contamination which are detailed below (also see Figure 1). Potential source areas for contaminants were determined by field reconnaissance, aerial photographs, topographic maps, and reference to Ladue (1982). Virtually all of the potential sources of contamination are located on the valley floors and thus pose the greatest threat to shallow unconfined aquifers.

Confined aquifers in bedrock or unconsolidated materials are less susceptible to contamination because the overlying aquiclude (silt and clay) prevents downward migration of contaminants into the aquifer. Vertical hydraulic gradients tend to be in an upward direction, and the recharge areas for these aquifers are in areas of higher elevation where less development and less potential for contamination occurs. Potential pollutants found in the valley floors would only become a contamination problem if: (1) the confining layer was disrupted or penetrated from above, and (2) the flow of the aquifer was in a downward direction, the result of high pumping rates. Both of these cases would allow for communication and thus pollutant migration between the two aquifers.

The riverside business district, the Village of Jericho, and Jericho Center are all areas of dense population and traffic (Sites 1, 3 and 5, Figure 1). Site 1 has a large lumber mill where servicing of machines and large vehicles occurs. All three sites have filling stations that have the potential to contribute gasoline, solvents, greases, and oils to the water supply. These three sites are also commercially zoned and have increasing populations, thereby making future industrial and septic contamination possible.

There are abandoned dumps at sites 2 and 6, and a landfill at site 10. Leachates from these sites could contaminate shallow, unconfined aquifers. Site 4, Mount Mansfield Union High School, has large fuel tanks, a large leach field, and uses a variety of chemicals in science and photography laboratories all of which could be potential contaminants.

Sites 7, 8, and 9 are part of Fort Ethan Allen and have a variety of potential contaminants. At site 7 the operation and servicing of machinery and vehicles could contribute gasoline, solvents, greases and oils to the water supply. Site 8 is the Ethan Allen Firing Range, which has the potential for contributing metals such as lead and arsenic. Finally, site 9 formerly was the location of several storage tanks with unknown contaminant potential.

Ladue (1982) identified high levels of sodium and chloride in the unconfined shallow aquifer of the Browns River basin. Agricultural lands located in the recharge zones as well as areas of road salting are other possible sources of contamination to this aquifer as well as other shallow, unconfined aquifers.

Although a number of potential contamination sources have been identified throughout the Town of Jericho, nearly all of these sources are located on the valley floors. The recharge areas identified (Figure 1) are relatively clear of any present-day contamination problems, yet the demand for housing is leading to increased development in the uplands of the town, and may pose a future threat to ground-water quality.

CONCLUSIONS & RECOMMENDATIONS

The students of the 1994 University of Vermont Geohydrology class, through the use of well-completion data, field observations, and previous study data, have identified three potential ground-water aquifers within the Town of Jericho, each of which may be suitable for a public water supply. The Browns River aquifer, Lee River aquifer, and Mill Brook aquifer are confined aquifers in unconsolidated materials and are overlain by shallow unconfined aquifers. The underlying bedrock throughout the town is a productive source of ground water, although the yields are generally lower than those in the confined aquifers in unconsolidated materials.

Communication between a bedrock well and wells completed in unconsolidated materials in the town well field (Heindel, 1988) suggests that recharge to the confined aquifers in unconsolidated materials probably comes from the underlying bedrock in addition to the upland areas identified in Figure 1. It is therefore our recommendation that these three major confined, unconsolidated aquifers be further explored as an economical source of potable water, and that the upland recharge areas for these potential aquifers be controlled with respect to development to protect the town's ground-water resources.

Our study is an example of a hands-on approach to learning geohydrology during which students gather field data, consider these data in light of what they have learned in the classroom, and use these data to produce a final report of interest to local residents. We believe that our approach provides a useful model for the interaction of town, university, and state personnel.

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A Useful First Lab for Introductory Geoscience Courses

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ABSTRACT
The first laboratory session of an introductory earth-science course is often under utilized for teaching. A very effective laboratory exercise can be developed based on the various graphs, tables, and diagrams found in most college textbooks. This lab should illustrate a variety of ways of presenting data, the differences among them, and their individual strengths and weaknesses. This serves many other purposes as well, including: reviewing the concepts of reading graphs, exposing students to major class topics, allowing students to interact, and creating an informal and cooperative classroom atmosphere. Using this approach, I generally find that students are better able to read, interpret, and discuss graphs and diagrams during the remainder of the course.

Keywords: Education - geoscience; education - laboratory; education - science; education - undergraduate; earth science - teaching and curriculum; areal geology - maps, charts, photographs.

Introduction
Deciding what to do in the first session of a college-level introductory earth-science laboratory can be challenging. Often many students do not yet have their lecture or lab texts and some students will be adding the class at a later date. This makes it difficult to assign a lab in place of regular class material as students who miss the first lab will have to make it up later or miss it entirely. In addition, in classes with multiple lecture and lab sections, the lab may even meet before the first lecture.

For these and other reasons, many instructors merely distribute and briefly discuss the syllabus and class requirements – keeping the laboratory in session for perhaps thirty to forty-five minutes and delaying presentation of the first lab topic until the following week. I consider this a missed teaching opportunity.

Laboratory Concept
For my earth science labs, I have developed what I call my "graphics review" lab. Introductory college earth-science textbooks today take a very visual