GROUND WATER IN AN UPLAND VALLEY, THE LINGERING INFLUENCE OF A GLACIAL LAKE: WILLIAMSTOWN, MASSACHUSETTS.

Paul Bierman
Department of Geology
University of Washington
Seattle, Washington 98195

Linda Marler and Blake Martin
Ground Water Associates
Arlington, Massachusetts 02174

ABSTRACT

On the basis of subsurface investigation, surficial mapping, aquifer testing, and consideration of geologic processes, we propose a qualitative model relating Quaternary stratigraphy to the distribution of ground water. Our study indicates that the geometry of the retreating ice margin and the resulting distribution of glaciofluvial, glaciolacustrine, and alluvial sediment control the occurrence of ground water. Because similar stratigraphy has been reported throughout New England, our model should be useful for planning and interpreting hydrogeologic investigations in other previously glaciated, upland valleys.

Our investigation delineated three hydrogeologic units overlying dolomitic bedrock: 1. An unconfined aquifer in alluvium (up to 12m of sand, gravel, and silt), 2. A glaciolacustrine aquitard of varying integrity -- rhythmic deposits of glacial Lake Bascom (4.5m to 37m of silt, clay, and fine sand), 3. A confined aquifer (up to 11m of head at the ground surface) in glaciofluvial deposits (7m to 10m of sand and gravel).

Chemical analyses of numerous ground water samples indicate that contamination is restricted to the uppermost aquifer and has not affected the deeper aquifer which is used as a public water supply. Glaciolacustrine sediment is sufficiently impermeable (10^{-4}m/day to 10^{-5}m/day) near several landfills to maintain upward hydraulic gradients between the two aquifers and to prevent downward migration of contaminated water.

Our model predicts that permeable, glaciofluvial sand and gravel overlie bedrock or till and underlie a glaciolacustrine aquitard. The lacustrine sediment is coarser or thinner, and less able to confine the lower aquifer, in the proximity of former ice margins, near valley walls, where streams entered the lake, or where the aquitard has been eroded. Our research suggests that a thorough literature survey, mapping of surface drainages, and identification of outwash heads (morphosequences) could direct and enhance the efficiency of subsurface investigation.

INTRODUCTION

In many areas of New England, unconsolidated Quaternary sediment is the most important factor determining the distribution of ground water. Extensive soil boring, linked with geophysical investigation, is the most reliable method for determining subsurface stratigraphy. However, the cost of site characterization often limits the amount of data available for analysis. To correctly understand and predict the texture and distribution of unconsolidated sediment, and thus the location of ground water, it is necessary to understand the processes which deposited the sediment. After the most important processes have been identified, a physically tenable, qualitative model of sediment distribution can be proposed to constrain hydrogeologic interpretations. The preliminary model can be used to design subsurface investigations. Once calibrated with field data, the model becomes a useful tool for planning and resource management.

We propose a qualitative model of sediment and ground water distribution in the Hoosic River Valley, western Massachusetts. Our model considers geologic processes active in the Berkshire highlands during and after deglaciation. Because similar stratigraphies have been reported in numerous glaciated valleys, our model may be used as a framework for other investigations.

REVIEW OF RELEVANT GEOLOGIC PROCESSES

Observation of present-day glaciers and models of ice flow have increasingly constrained the interpretation of glaciogenic sediment. To provide the background necessary for understanding hypotheses and nomenclature presented in this paper, we briefly review relevant processes. We refer the interested reader to Drewry (1986) for a more thorough discussion of glacial processes. Koteff and Pessl (1981) provide historical perspective and a model for the deglaciation of New England. Jopling and McDonald (1975) is a collection of papers about glaciolacustrine and glaciofluvial sedimentation.

Behavior of Glaciers

A glacier may be understood as a gravity driven conveyor of ice and sediment. If sufficiently thick, ice flows and slips under its own weight. The flow of a glacier is controlled by the slope of the ice surface. The shape of the ice surface has been measured on modern glaciers and reconstructed from geologic evidence left by Pleistocene ice sheets. Nye (1952) and Mathews (1974) provide methods for reconstructing ice surface profiles.

Maintenance of an active glacier margin is a balancing act. If more ice melts than flows to the margin, the glacier retreats; if more ice flows to the margin than melts, the glacier advances. As long as the glacier continues to flow, ice and sediment are delivered to the active margin. The volume of glaciogenic sediment deposited at any location depends upon the rate at which the glacier discharges sediment and the length of the time the active margin lingers near that location. To deliver the volume of sorted sediment found in most areas of New England, the ice sheet must have remained active as the margin retreated.

Various workers have suggested that as the glacier withdrew from New England, a zone of stagnant ice bordered the flowing ice. As ice at the margin of the glacier melted, a 2km to 3km section became too thin to flow and therefore stagnated. The active margin was then located up-glacier. Koteff and Pessl (1981) identified concentrations of sediment termed *morphosequences* which they believe represent recognizable packages of sediment deposited in and beyond this stagnant ice zone. Morphosequences grade from coarse, poorly sorted sediment near the interpreted position of the active ice margin to well sorted, finer sediment downstream of the active margin (Figure 1). Koteff and Pessl call the ice-proximal end of a morphosequence an *outwash head.*

Sediment Deposition

<u>Ice related</u> -- Except at the base of the glacier, most glacier ice contains little sediment; however, large volumes of sediment are carried by streams running within the glacier and in a layer of fluidized till below the ice. Till is commonly classified as basal or ablation till. *Basal till*, deposited below the ice, is poorly sorted, unstratified, and matrix supported. *Ablation* till, formed by melting of the ice surface, may be less compact, contains less fine sediment, and is often crudely stratified. Till, because it is poorly sorted and contains a wide range of particle sizes, is classified as a *diamicton* (Drewry, 1986).

Sediment is carried by streams flowing on the surface of the glacier and in tunnels within and under the ice. Sediment deposited by running water is better sorted and more stratified than till. We use the term *glaciofluvial* to describe coarse-grained sediment which originated from the ice, but may have been deposited some distance from the active margin. Glaciofluvial sediment is commonly found along valley walls where ice marginal drainages existed or in morphosequences extending down-gradient from the former ice margin. Glaciofluvial sediment may be deposited subaqueously, if a glacial lake borders the ice margin.

<u>Glaciolacustrine</u> -- Glaciers or accumulations of glacial debris commonly block surface drainages and impound temporary lakes. Coarse-grained sediment is deposited where hillslope and glacial drainages enter the lake. If sufficient sediment is available, these deposits show deltaic morphology and bedding adjusted to specific lake levels. If the lake is sufficiently deep and borders the ice margin directly, sediment discharged from the ice builds *subaqueous fans* below the surface of the lake. The apices of these fans shift as the fans grow, different drainages become active, and the ice margin retreats. Isolated deposits of unstratified, poorly sorted sediment may be deposited at the lake margins where debris flows (from the surface of the glacier or from recently deglaciated and still unvegetated slopes) enter the lake.

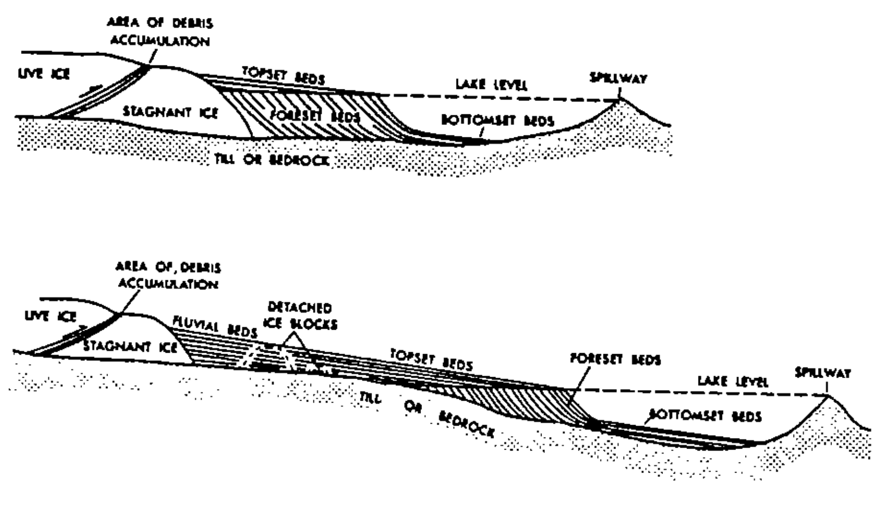


FIGURE 1 VARIETIES OF MORPHOSEQUENCES. FROM KOTEFF AND PESSL, 1981.

Fine-grained sediment enters the lake from the glacier and from adjacent hillslopes. In quiet water, silt, clay, and fine sand are deposited in a series of laminae. Rhythmicity may be caused by deposition from flows of turbid water along the lake bottom (*rhythmites*) or by deposition on a yearly cycle (*varves*). Because larger particles have higher settling velocities, they settle out before reaching the center of the lake. Clay-rich lacustrine sediment is deposited in the deepest part of the lake, farthest from lake margin sediment sources.

Alluvium – As ice continues to melt back, glacial lakes empty and drainage is restored (often in a series of stages). Fluvial processes dominate in the valleys and hillslope processes (landsliding, sheetwash, and gullying) modify the exposed lacustrine sediment. The trunk stream meanders across the former lake bottom. If the fluvial system is aggradational, alluvium is deposited above the glaciolacustrine unit. If incision dominates, glaciolacustrine sediment is eroded.

SETTING

History and Purpose of Study

We performed this investigation to determine the effects of waste disposal practices on the Williamstown environment and to assist the Town in siting additional water supply wells. Field investigation was conducted between April and July, 1987. Data collected during our study provide the basis for remedial engineering and town planning.

Williamstown commissioned this study in response to a Notice of Violation issued by the Massachusetts Department of Environmental Quality Engineering (DEQE). Alliance Technologies (Bedford, Massachusetts) was selected as the prime contractor for this investigation. Layne Well and Pump and Ground Water Associates (divisions of Hydro Group) installed monitoring wells, coordinated the pumping test, and assisted in the analysis of aquifer data. The Town of Williamstown, in conjunction with Williams College and a local industry, provided funding for the study.

Physiography

The Hoosic River drains 350km^2 (135miles^2) of Massachusetts and Vermont and flows north and west to the Hudson River (Figure 2). For much of its course, the Hoosic is restricted to a narrow, gently sloping plain (2.3m/km; 12'/mile) by steep, abutting highlands; elevations range from less than 167m (550') at the Massachusetts/Vermont border to 1063m (3487') at the summit of Mt. Greylock. Most tributary drainage basins are small and steep.

Sites investigated during this study were located in or near the flood plain of the Hoosic River. Subsurface investigation was restricted to areas adjacent to three former and active landfills near Williamstown. Figure 3 shows the area investigated during this study.

Geology

Several types of bedrock underlie unconsolidated sediment and crop out in Williamstown. Highlands are composed of schist, phyllite, and quartzite; lowlands are primarily dolomitic marble (Zen et al., 1983) The quartzite resists weathering and erosion; however, it is fractured and extensively jointed. The schist and phyllite are not pervasively jointed, but weather rapidly and are easily eroded. The dolomitic marble weathers primarily by dissolution.

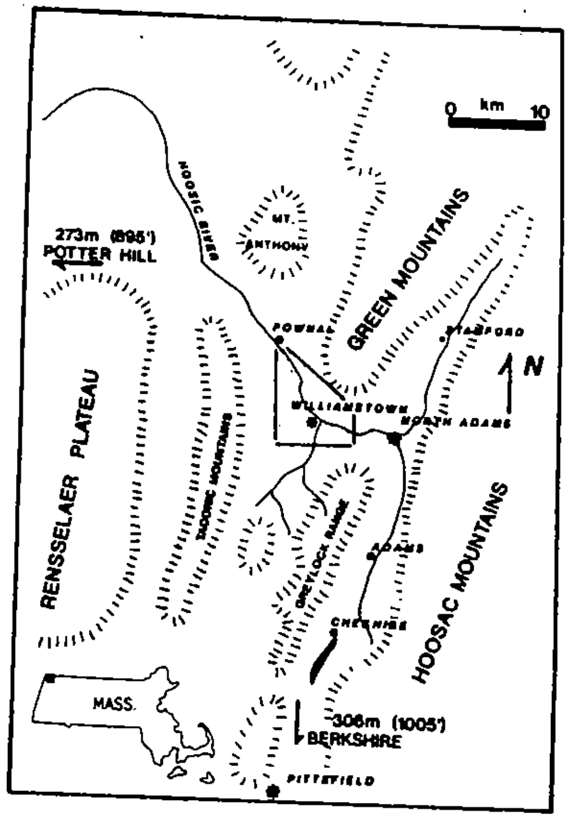


FIGURE 2 LOCATION MAP OF THE HOOSIC RIVER BASIN. STUDY AREA IS SHADED.

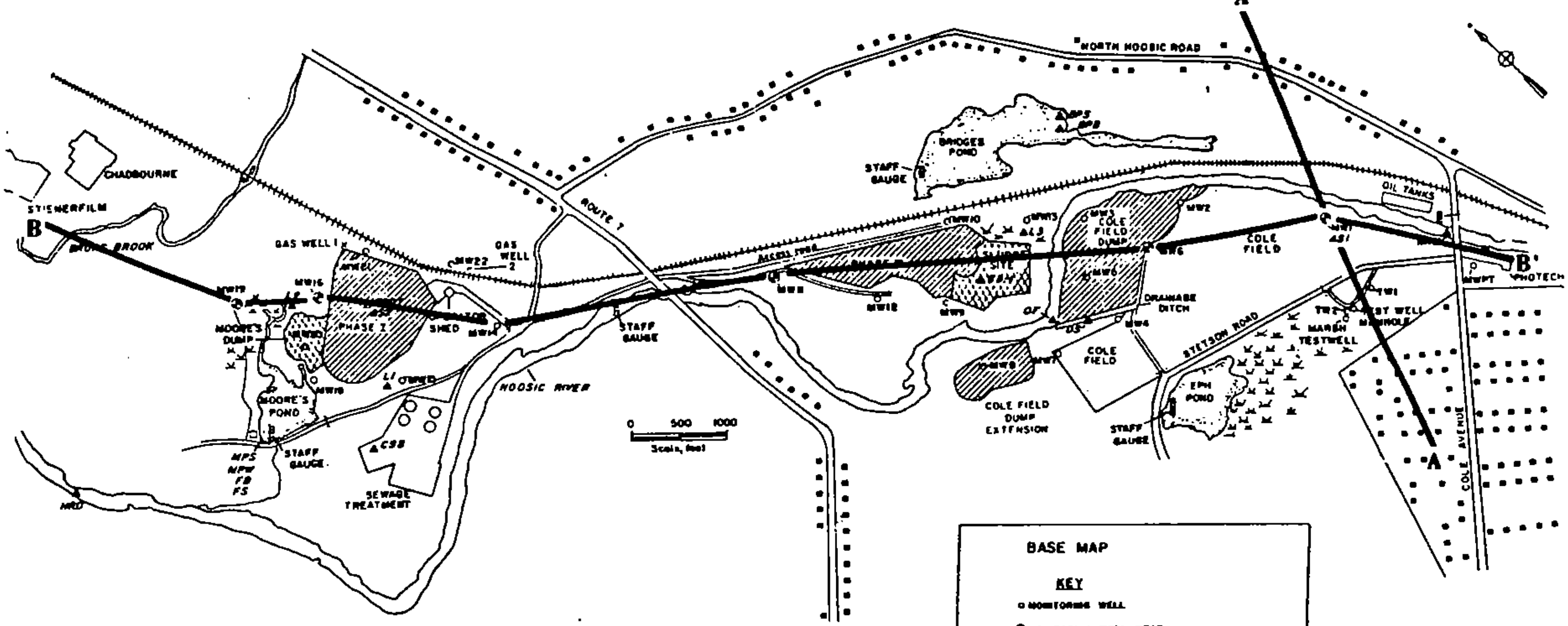
Geophysics and well log data indicate that up to 91m (300') of unconsolidated sediment overlie bedrock in the Hoosic River Valley (Hansen et al., 1973, 1974). Bierman and Dethier (1986) report that the character and thickness of unconsolidated sediment vary greatly within the Hoosic River Valley. Where bedrock is not exposed, till and colluvium cover much of the uplands. Although isolated exposures of sorted material occur as high as 535m (1755'), the largest volume of sorted glacial sediment is found on or near the lower valley walls, below 380m (1245'). Lesser volumes of deltaic and fan deposits are found at varying elevations where drainages enter the Hoosic River Valley. Most lacustrine sediment is found below 290m (950'). Extensive deposits of older and modern alluvium cover much of the valley floor.

As ice retreated from the Berkshires, it dammed the north-flowing Hoosic River, creating glacial Lake Bascom (Dale, 1906); Bierman and Dethier (1986) identified several levels of Lake Bascom (Figure 4). Lake levels between 317m (1040') and 306m (1005') were controlled by spillways at Berkshire, Massachusetts. The 273m (895') level was controlled by a spillway at Potter Hill, New York. Bierman and Dethier (1986) also identified several levels of Lake Bascom between 223m (730') and 159m (520'). Near Williamstown, Lake Bascom was up to 150m (490') deep.

METHODS

Well Installation and Development Techniques

We designed and installed a ground water monitoring network capable of monitoring ground water quality and head distribution in the unconfined and confined aquifers. Figure 3 shows the location of the wells installed and/or observed during this study.



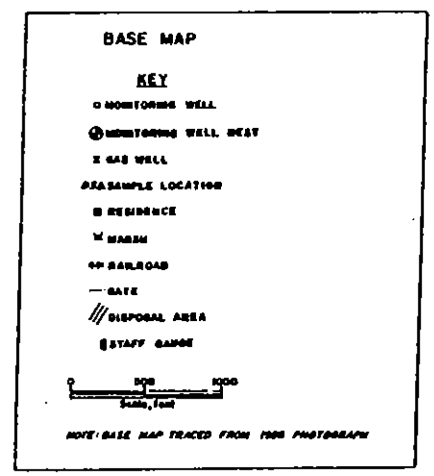


FIGURE 3 LOCATION OF WELLS INSTALLED AND/OR OBSERVED DURING THIS STUDY. LANDFILLS, SAMPLING LOCATIONS, AND LINES OF CROSS-SECTION ARE ALSO SHOWN. MAP TRACED FROM AERIAL PHOTOGRAPHS TAKEN IN 1986.

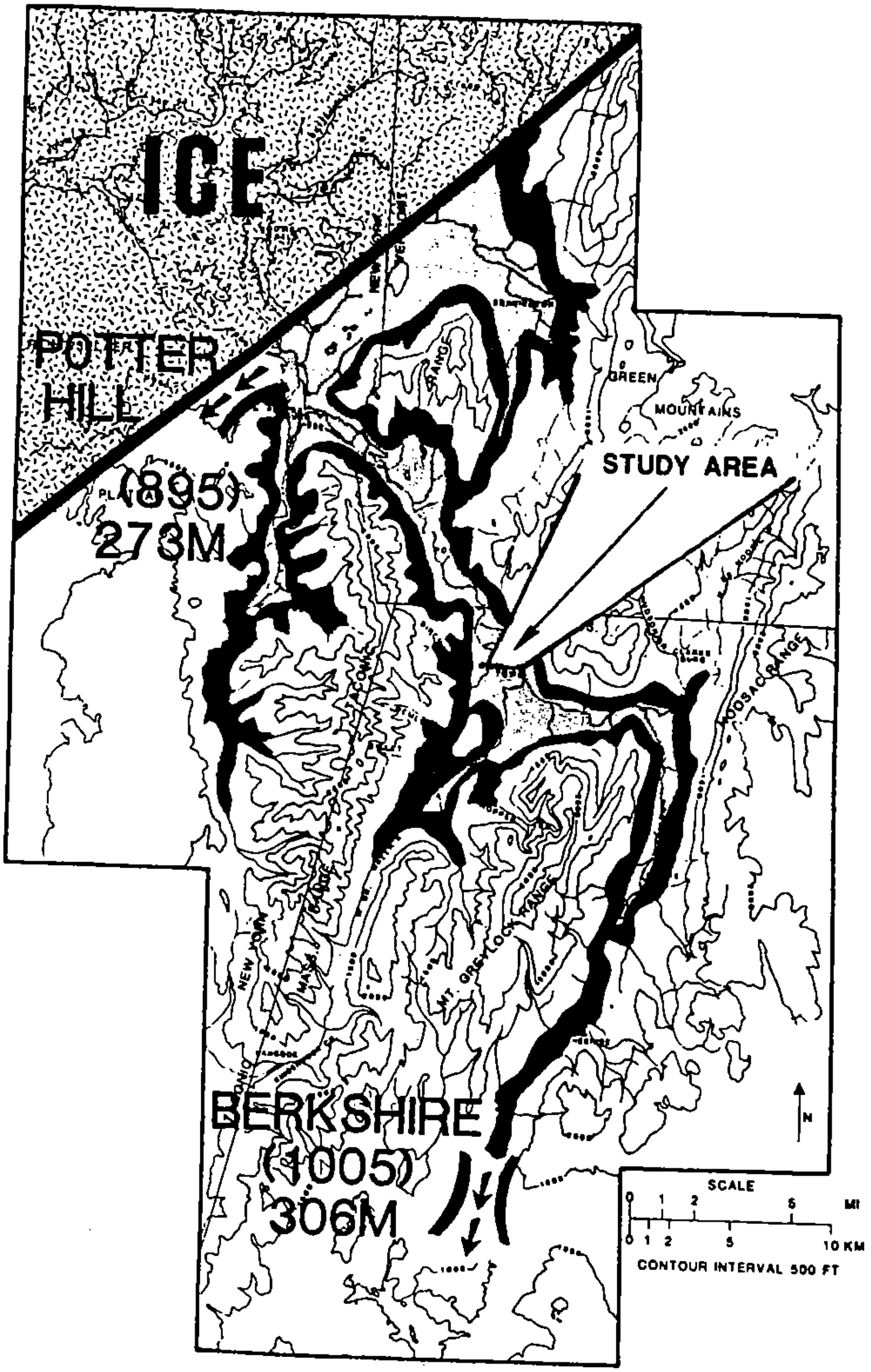


FIGURE 4 EXTENT OF LAKE BASCOM WHEN THE LAKE WAS CONTROLLED BY SPILLWAYS AT POTTER HILL, NEW YORK AND BERKSHIRE, MASSACHUSETTS. SAME AREA IS SHOWN IN THIS FIGURE AS IN FIGURE 2. SOLID PATTERN INDICATES EXTENT OF HIGH LEVEL LAKE BASCOM (BERKSHIRE SPILLWAY). STIPPLING INDICATES LOWER LEVEL LAKE BASCOM CONTROLLED BY POTTER HILL SPILLWAY. FIGURE MODIFIED FROM BIERMAN AND DETHIER, 1986.

Non-flowing monitoring wells were installed by means of hollow stem augers. Split spoon samples were taken at 1.5m (5') intervals or more frequently if necessary to properly define stratigraphy. Sediment samples were described in the field and collected for grain size analysis. Monitoring wells were constructed with 5cm (2") PVC, schedule 40 pipe and 0.25mm (0.010") slot size screens. Three meter (10') screens were set and sand packed at depths to intercept the water table. A bentonite pellet seal was placed over the sand pack and a bentonite/sand or bentonite/cement slurry was placed as backfill above the pellet seal. A cement surface seal and locking cap were placed on each well. All wells were developed after installation.

Flowing artesian monitoring wells, were installed by means of a dual air rotary drilling rig (Figure 5). Cuttings were described and collected for analysis at 1.5m (5') intervals. Wells were constructed with 15cm (6") mild steel casing and 3m (10') stainless steel screens. Slot size was based on the grain size distribution of the aquifer. Flowing artesian wells were developed by air jetting and surging.

Aquifer Test

We conducted a 74 hour pumping test to determine aquifer characteristics along a 4km (2.5mile) line of observation wells. Prior to the test, the Town wells were shut down for 38 hours allowing the aquifer to recover from previous pumping. During the test, Town well 2 was used as a pumping well (2860m^3/day, 525gpm) and we regularly monitored the response of both aquifers and several surface water bodies. We measured water level in non-flowing wells and water pressure in flowing wells. We analyzed drawdown and recovery data using standard methods including the Jacobs' straight line analysis.

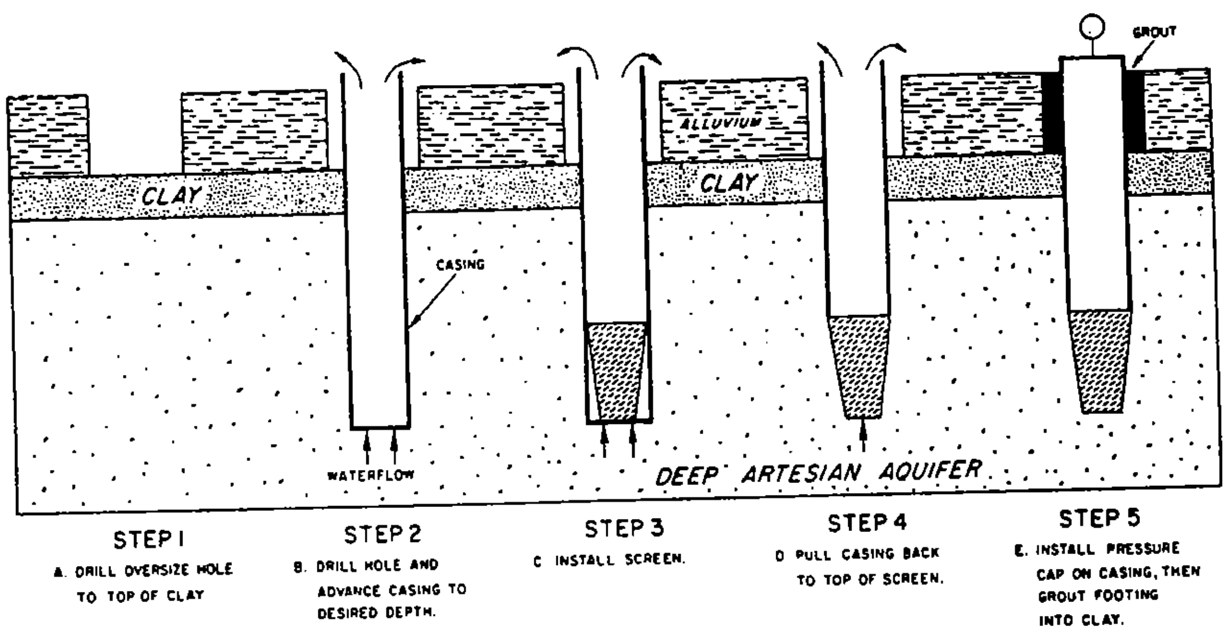


FIGURE 5 MONITORING WELL CONSTRUCTION TECHNIQUE USED WHERE CONFINED AQUIFER WAS FLOWING ARTESIAN.

Sediment Grain Size Analysis

Soil laboratories determined the grain size distribution and permeability of selected samples. Falling head permeability analyses were performed on Shelby tube samples taken from two depths in the glaciolacustrine silt/clay. Grain size distribution was determined for numerous glaciolacustrine samples using a Micrometrics optical sedigraph.

Chemical Sampling and Analysis

We collected samples of ground water, surface water, sediment, and biota. Samples were analyzed for a wide range of compounds including: metals, volatile organics, nutrients, chloride, and pesticides. All sampling was performed in accordance with EPA standards and laboratory analyses were performed according to standard EPA methods by certified laboratories.

DATA

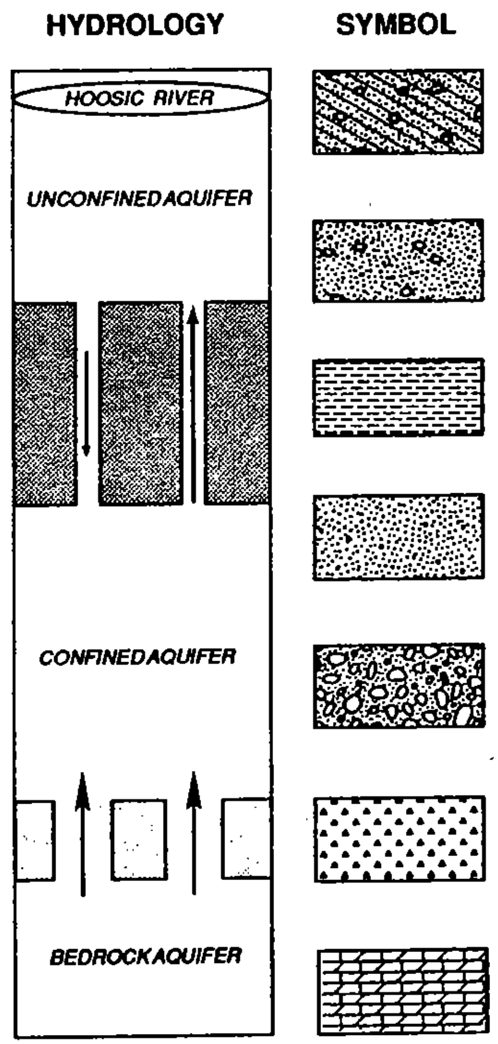
Subsurface Stratigraphy

We present a generalized hydrogeologic stratigraphic column and several cross-sections representing subsurface conditions in the Hoosic River Valley near Williamstown (Figures 6-8). Our proposed stratigraphy is based on data gathered during this investigation, boring and seismic data presented in Hansen et al. (1974) and Motts and MacFadyen (1983), depth to bedrock data presented in Hansen et al. (1973), personal communication with David Dethier, and geologic data presented by Bierman (1985).

On the basis of stratigraphic relationships, texture, and accepted glacial and sediment transport processes, we have classified sedimentary units according to presumed genesis. We interpret compact diamicton underlying other unconsolidated sediment as *glacial till*. The diamicton is overlain by permeable gravel and sand which we interpret as *glaciofluvial* sediment deposited by water flowing through and away from the glacier. We interpret thinly bedded and laminated sand, silt, and clay as *glaciolacustrine* sediment deposited in glacial Lake Bascom. Sediment deposited above the glaciolacustrine sediment is referred to as *alluvium*.

<u>Alluvium</u> -- Many of the soil borings advanced during this investigation encountered sand, gravel, and silt deposited by the Hoosic River or its tributaries. The alluvium is predominately sand with lesser amounts of silt and gravel. The thickness of alluvium varies greatly. In some areas, the Hoosic eroded some of the underlying glaciolacustrine silt and clay and deposited almost 12m (40') of alluvium. In other areas there is no alluvium and glaciolacustrine sediment crops out.

<u>Glaciolacustrine silt and clay</u> -- The alluvium is underlain by fine-grained glaciolacustrine material: silt, clay, and fine sand. Split spoon samples revealed that this lacustrine sediment is irregularly bedded and laminated -- layers of fine sand alternate with layers of silt and clay. Grain size analyses indicate that composition of glaciolacustrine unit ranges from 48% sand, 49% silt, 3% clay to 19% silt, 81% clay. The average grain size of the glaciolacustrine silt/clay unit increases toward the northwestern part of the study area (Figure 9). The glaciolacustrine unit thins toward the valley walls and the northern part of the study area (Figure 10). Fine-grained glaciolacustrine sediment was underlain in some borings by a layer of dark grey, fine and medium sand containing 15% to 40% silt. This sand stratum is up to 14m (45') thick.



DESIGNATION	DESCRIPTION
ARTIFICIAL FILL (0 - 14 m)	UNSTRATIFIED, LOOSE GREY TO TAN GRAVEL, SAND, SILT, AND REFUSE. LOWER SECTIONS ARE BLACK AND ASHY. DEPOSITED IN FORMER AND ACTIVE LANDFILLS. SOME FILL IS WATER SATURATED. WATER QUALITY IS POOR.
ALLUVIUM (0 - 12 m)	STRATIFIED, LOOSE BROWN AND TAN SAND WITH LESSER AMOUNTS OF SILT AND GRAVEL. LOWER PART OF THE UNIT IS GREY, SILTIER, AND MORE COMPACT. CROPS OUT NEAR HOOSIC RIVER. DEPOSITED DURING AND AFTER THE DRAINING OF LAKE BASCOM. PROVIDES WATER OF VARIABLE QUALITY IN SMALL QUANTITIES (UP TO 110 M^3/DAY).
GLACIOLACUSTRINE SILT AND CLAY (16 - 37 m)	THIN BEDDED AND LAMINATED, COHESIVE GREY SILT, CLAY, AND FINE SAND. EXPOSED IN THE VALLEY BOTTOM AND ALONG LOWER VALLEY WALLS. DEPOSITED IN DEEPER SECTIONS OF GLACIAL LAKE BASCOM. RETARDS MOVEMENT OF WATER ($K=10^{-4}$ TO 10^{-5} M/DAY).
GLACIOLACUSTRINE SAND (0 - 14 m)	THIN BEDDED, LOOSE GREY SAND AND SILT. NOT EXPOSED. DEPOSITED IN DISTAL PORTIONS OF SUBAQUEOUS FANS OR DELTAS WHICH PROGRADED INTO LAKE BASCOM. PROVIDES SMALL QUANTITY OF WATER (UP TO 30 M^3/DAY).
GLACIOFLUVIAL SAND AND GRAVEL (7 - 10 m)	LAYERS OF LOOSE BLACK, GREY, AND WHITE GRAVEL AND SAND WITH GREY SILT. NOT EXPOSED. DEPOSITED SUBAQUEOUSLY BY MELTWATER STREAMS. PROVIDES LARGE QUANTITIES OF POTABLE WATER (UP TO 6500 M^3/DAY).
TILL	UNSTRATIFIED, COMPACT, GREY/GREEN SILT, SAND, AND GRAVEL. EXPOSED ON VALLEY WALLS AND IN UPLANDS, DEPOSITED AT THE BASE OF THE GLACIER. RETARDS MOVEMENT OF WATER.
BEDROCK	WHITE, CRYSTALLINE DOLOMITIC MARBLE WITH SMALL AMOUNTS OF QUARTZITE AND PHYLLITE. WEATHERED MARBLE IS SOFT AND RED. FLOWING WELLS IN VALLEY BOTTOM PROVIDE LARGE QUANTITY OF WATER (UP TO 3800 M^3/DAY).

FIGURE 6 HYDROGEOLOGIC STRATIGRAPHIC SECTION, WILLIAMSTOWN, MASSACHUSETTS.

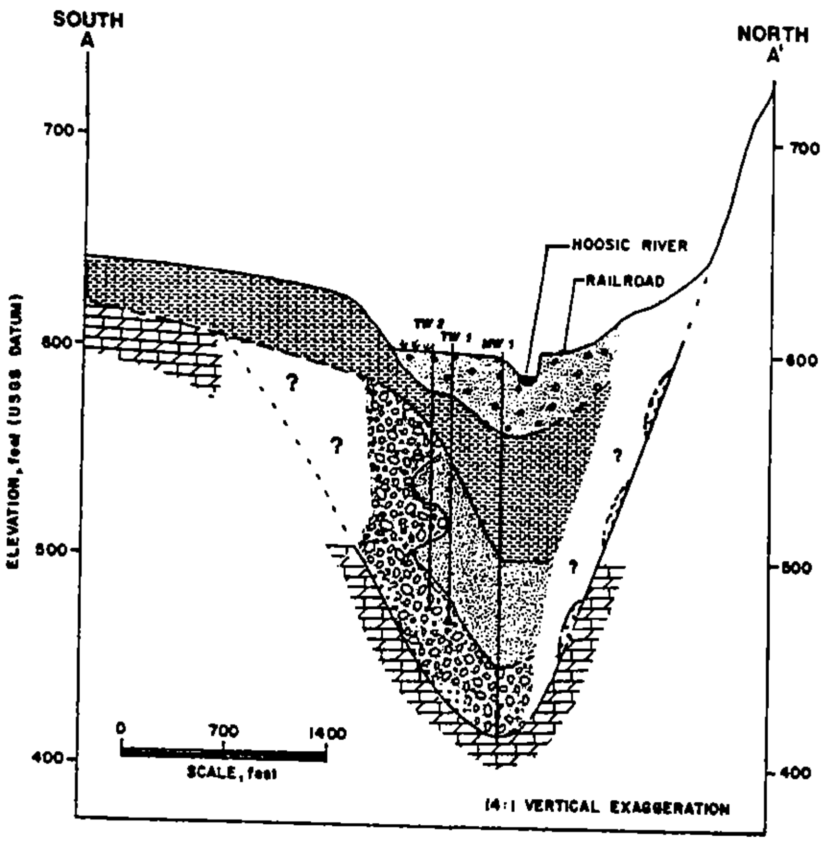


FIGURE 7 CROSS-SECTION A – A'. REFER TO FIGURE 3 FOR LOCATION.

Glaciofluvial sand and gravel -- Six borings were advanced through the glaciolacustrine sediment into predominately coarse-grained, stratified deposits. All deep borings penetrated at least 6.7m (22') of coarse sand and gravel before encountering till or bedrock. The top of the glaciofluvial sand and gravel is closest to the surface near the valley walls and in the northern part of the study area (Figures 7 and 8). The rounded clasts of marble, phyllite, and quartz resemble rocks which crop out in western Massachusetts and southern Vermont.

Bedrock and till -- Dolomitic marble underlies unconsolidated sediment in the Hoosic River Valley near Williamstown. Boring MW-1B terminated at 57m (186') in white, crystalline carbonate rock. The upper 120cm (4') of rock were soft and stained red/brown. The lower 15cm (6") of rock were hard and white. There are lithologically similar outcrops in Williamstown above the Hoosic River flood plain. Glacial till probably underlies the glaciofluvial sand and gravel in some places. Monitoring well 19B terminated in dense, compact diamicton with rounded gravel (till or an off-ice debris flow); however, MW-1B, which was advanced into the bedrock, did not encounter till.

Ground Water Hydrology

We identified two aquifers and an aquitard in unconsolidated sediment of the Hoosic River Valley. Williamstown and several industries draw water from the confined aquifer. Landfill units are in contact with the unconfined aquifer.

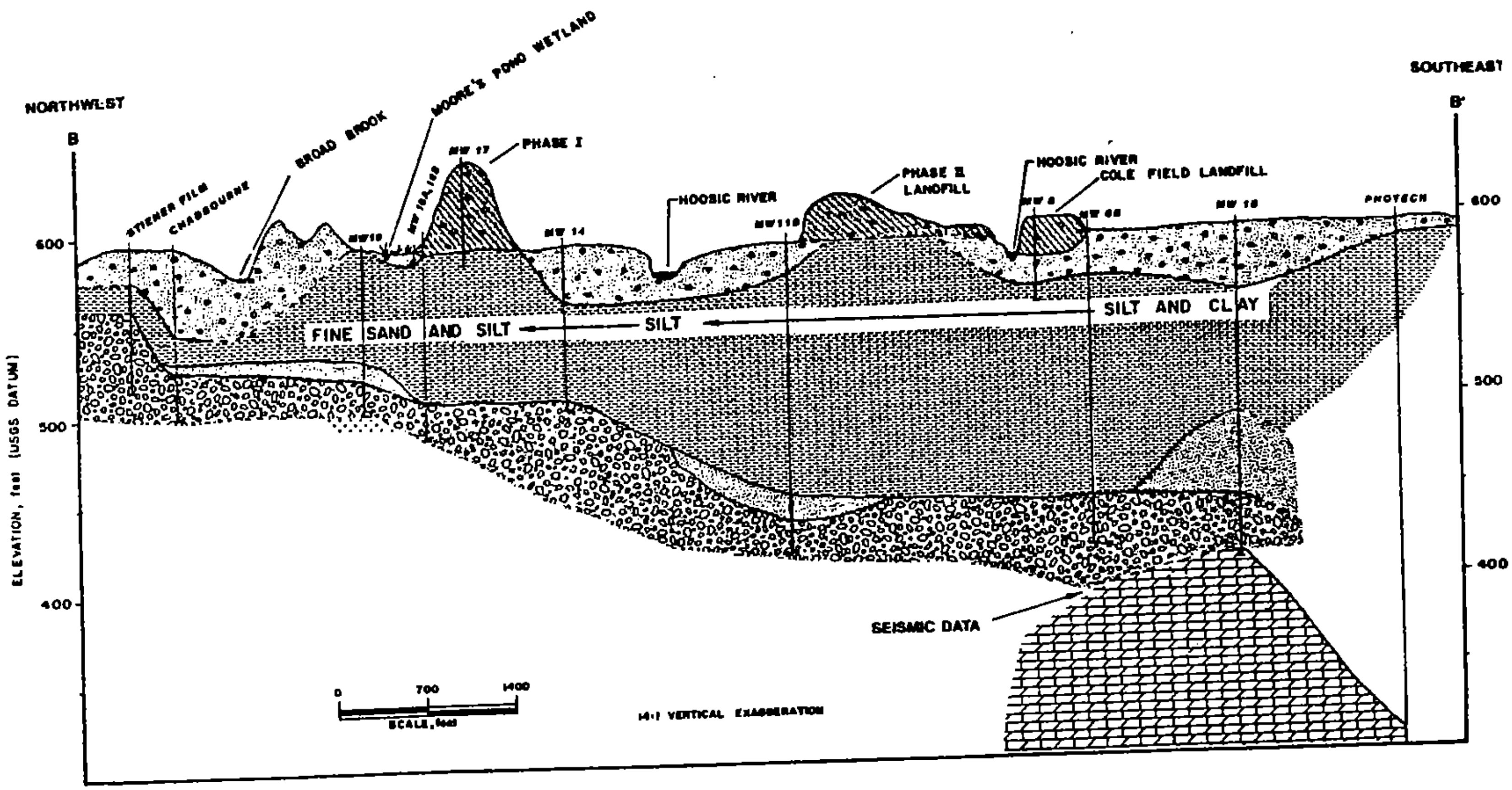


FIGURE 8 CROSS-SECTION B – B'. REFER TO FIGURE 3 FOR LOCATION.

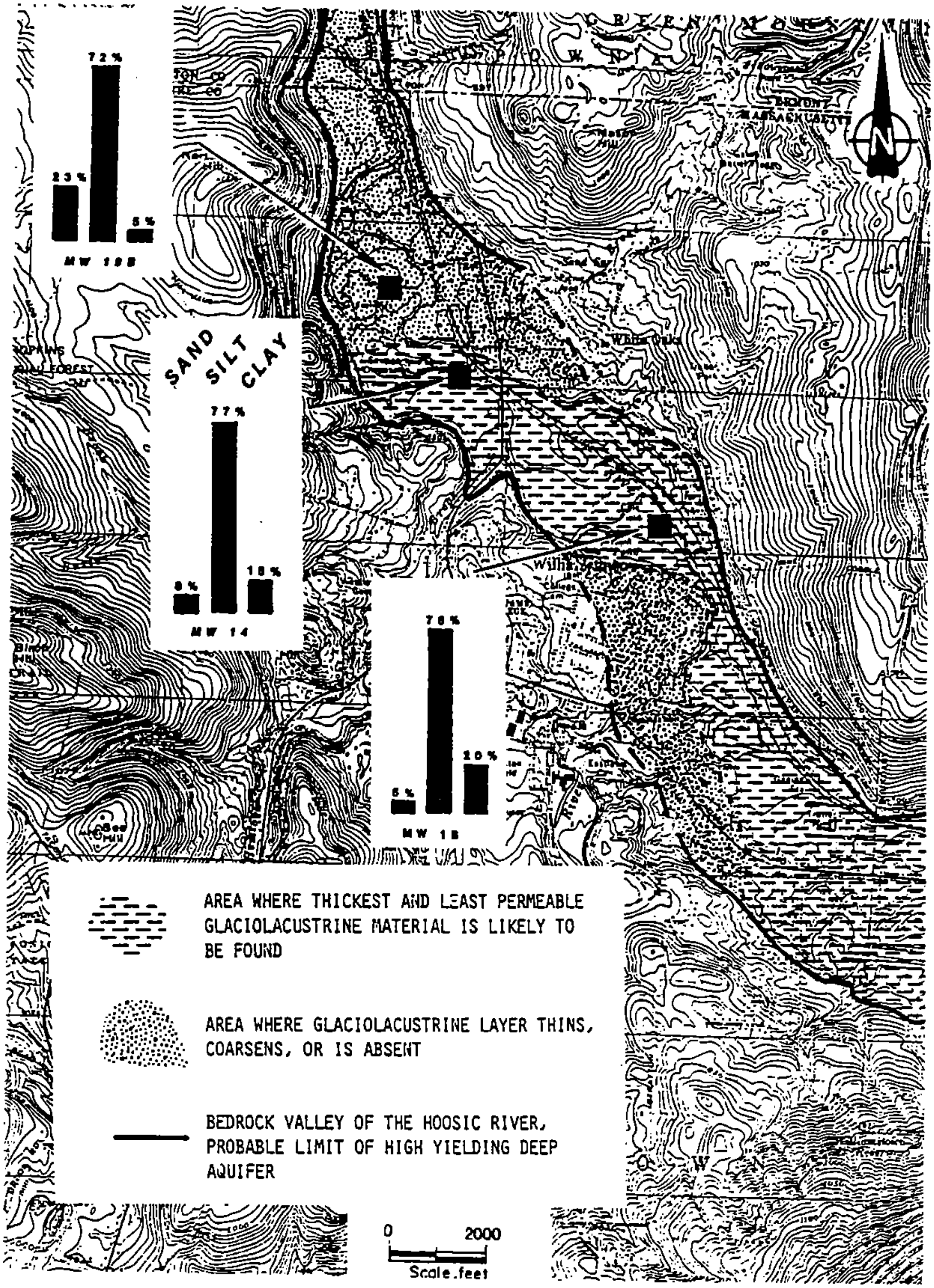


FIGURE 9 AVERAGE GRAIN SIZE DISTRIBUTION FOR SAMPLES TAKEN FROM THE GLACIOLACUSTRINE SILT/CLAY UNIT. BASE IS USGS 1:24,000 WILLIAMSTOWN QUADRANGLE (1973).

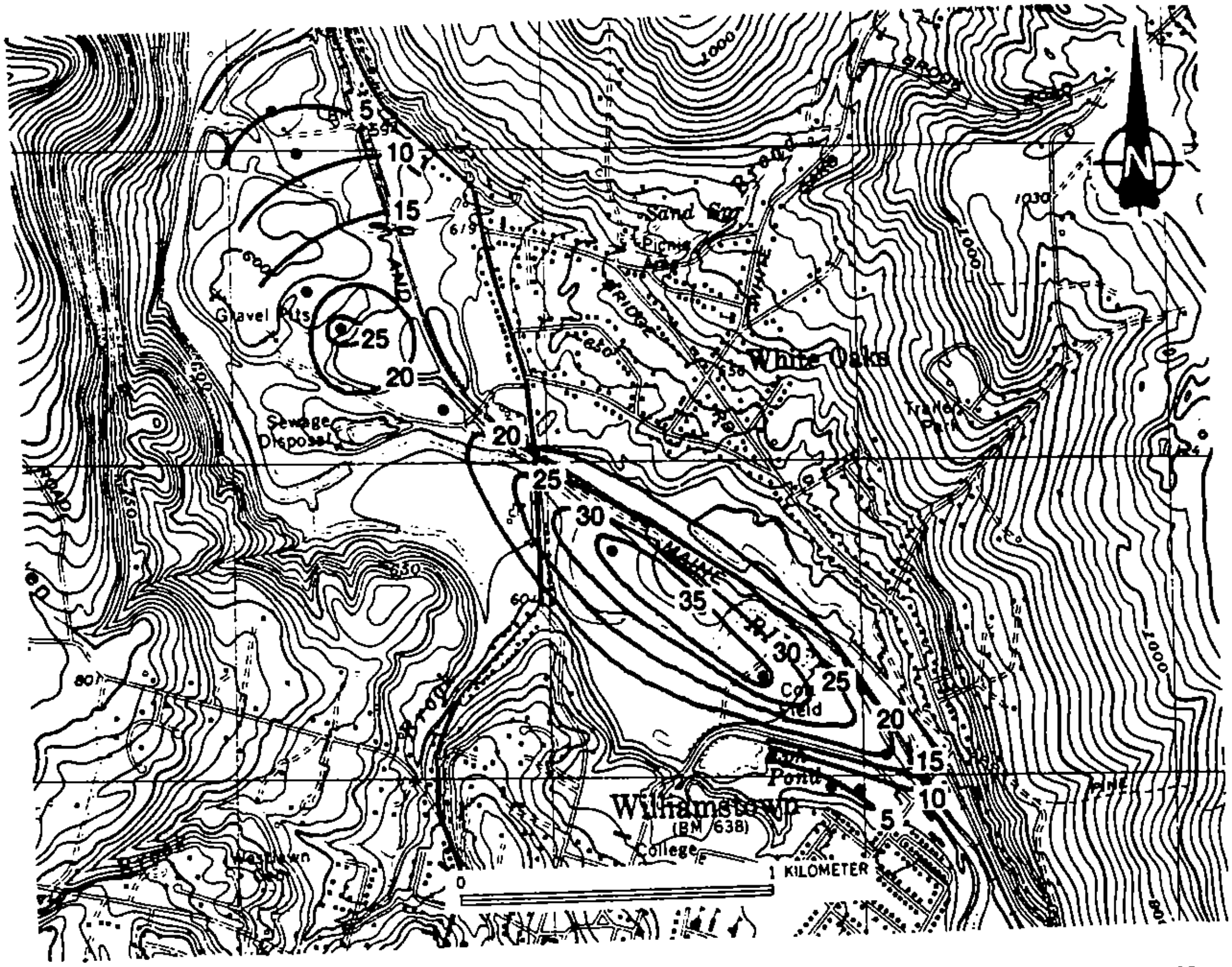


FIGURE 10 THICKNESS (METERS) OF GLACIOLACUSTRINE SILT/CLAY UNIT. BASE IS USGS 1:24,000 WILLIAMSTOWN QUADRANGLE (1973).

Unconfined aquifer -- The unconfined aquifer is located in alluvium of the Hoosic River and its tributaries. Depth to the water table is about 3m (10') in most areas, but is about 14m (45') below the top of the active Phase I landfill; the greatest saturated thickness is 9m (29').

The unconfined aquifer is recharged episodically by precipitation and continuously by several ponds. Except during floods, ground water in the unconfined aquifer flows toward the Hoosic River (Figure 11). In most areas the water table surface parallels topography. Horizontal head gradients range between 0.001 to 0.01. Wells screened in alluvium have sustainable pumping rates from less than 5.5m^3/day (1gpm) to 110m^3/day (20gpm).

Water quality in the unconfined aquifer has been impacted by human activities (Figure 12). The average chloride content is 23 ppm, twenty times higher than the average value in the confined aquifer. Conductivity, which in our samples correlates with chloride content, averages 900 micro-mhos. Water samples from a significant number of wells screened in the alluvium exceeded the drinking water standards for arsenic, barium, chromium, and lead.

Confined aquifer -- The confined aquifer occurs in glaciofluvial gravel. Wells screened in this gravel, with the exception of those in the northern part of the study area, are flowing artesian with up to 107kpa (15.5 psi) of head at the ground surface. The confined aquifer ranges in thickness from 5.8m (19') to at least 12m (40'). The confined aquifer is recharged through exposures of permeable sediment on the lower valley walls and through fractured bedrock in the highlands.

Total head in the confined aquifer decreases down valley (Figure 13). Horizontal head gradients range from 0.0016 to 0.0038 but steepen ten-fold in the northern part of the study area. Natural, short-term, flow from artesian wells screened in the glaciofluvial sand and gravel ranges from about $82m^3$/day (15 gpm) to over $2700m^3$/day (500 gpm). Individual wells pumping water from the confined aquifer withdraw up to $6500m^3$/day (1200 gpm). From the observed distance-drawdown relationship, we calculated a transmissivity for the aquifer of $322m^3$pd/m (26,000gpd/ft). Transmissivities at individual observation wells range from $248m^3$pd/m (20,000gpd/ft) to $1120m^3$pd/m (90,000gpd/ft). Hydraulic conductivity for the confined aquifer is between 10^2 and 10^1 m/day. Our analyses yielded a coefficient of storage on the order of 10^{-4}.

Water quality in the confined aquifer is excellent (Figure 12). Average chloride content is less than 2ppm and conductivity is less than 300 micro-mhos. Water from the confined aquifer meets all drinking water standards.

<u>Aquitard</u> -- An aquitard of glaciolacustrine clay, silt, and fine sand limits flow between the confined and unconfined aquifers. The thickness of the aquitard varies from 4.5m (15') to 37m (120'). The aquitard coarsens to the north and west; it generally thins in the northern part of the study area and near the valley margins.

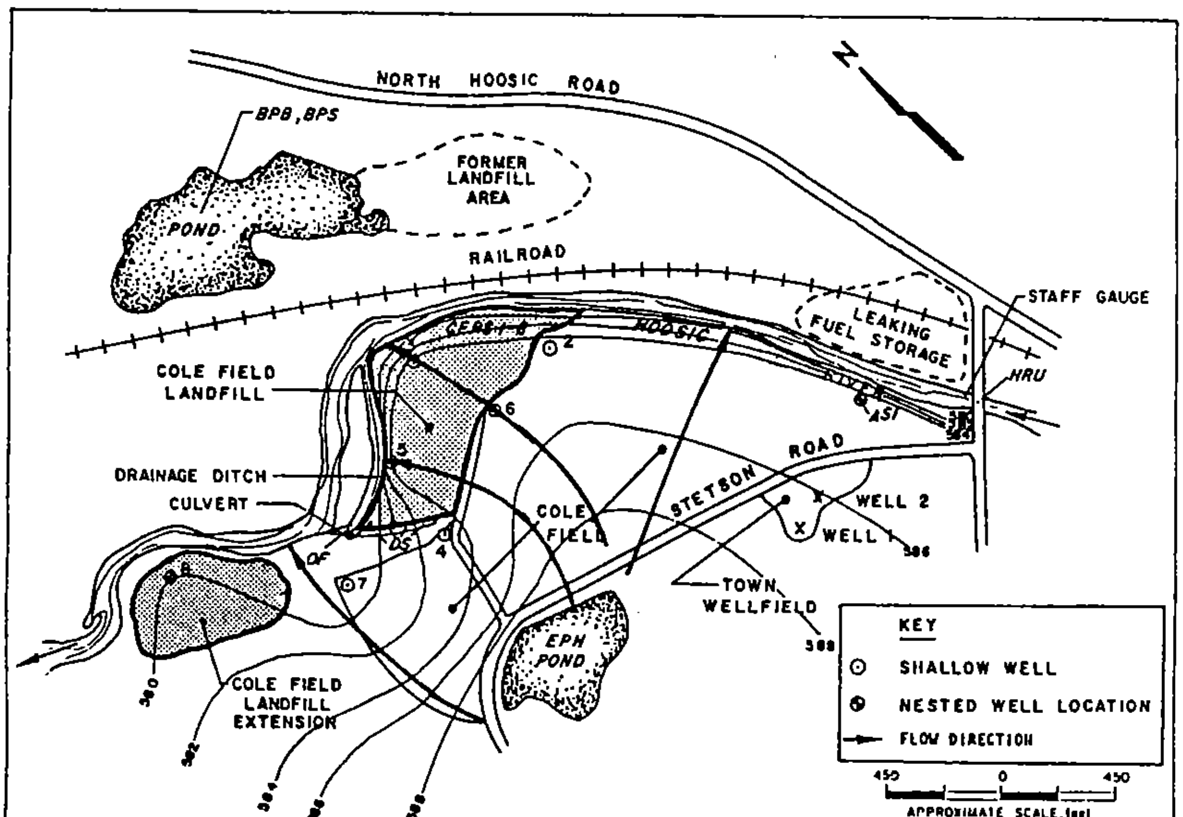


FIGURE 11 HEAD DISTRIBUTION AND GROUND WATER FLOW DIRECTIONS IN THE UNCONFINED AQUIFER AT THE COLE FIELD LANDFILL. WATER TABLE ELEVATIONS IN FEET ABOVE MSL. MAP TRACED FROM AERIAL PHOTOGRAPHS TAKEN IN 1986.

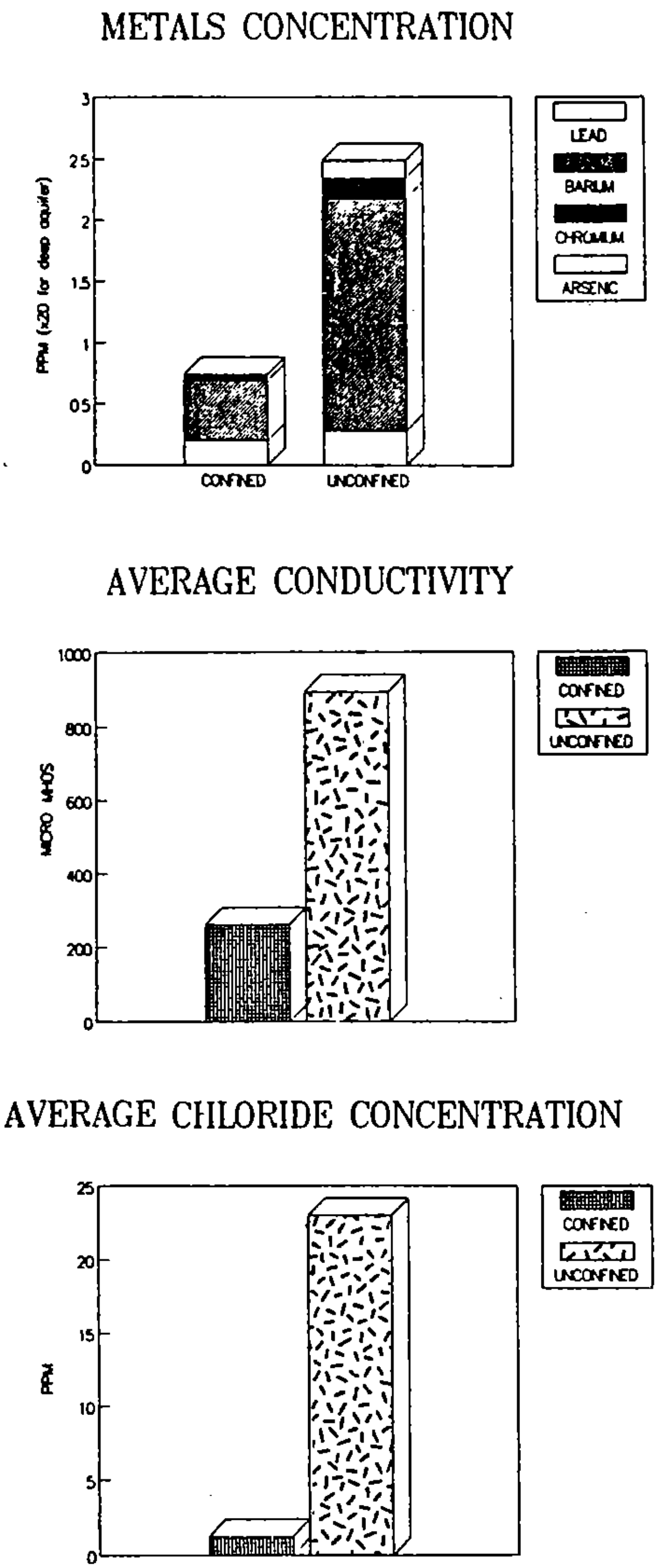


FIGURE 12 CONDUCTIVITY AND AVERAGE CONCENTRATION OF CHLORIDE AND FOUR METALS IN SAMPLES COLLECTED FROM 20 WELLS IN THE UNCONFINED AQUIFER AND 6 WELLS IN THE CONFINED AQUIFER.

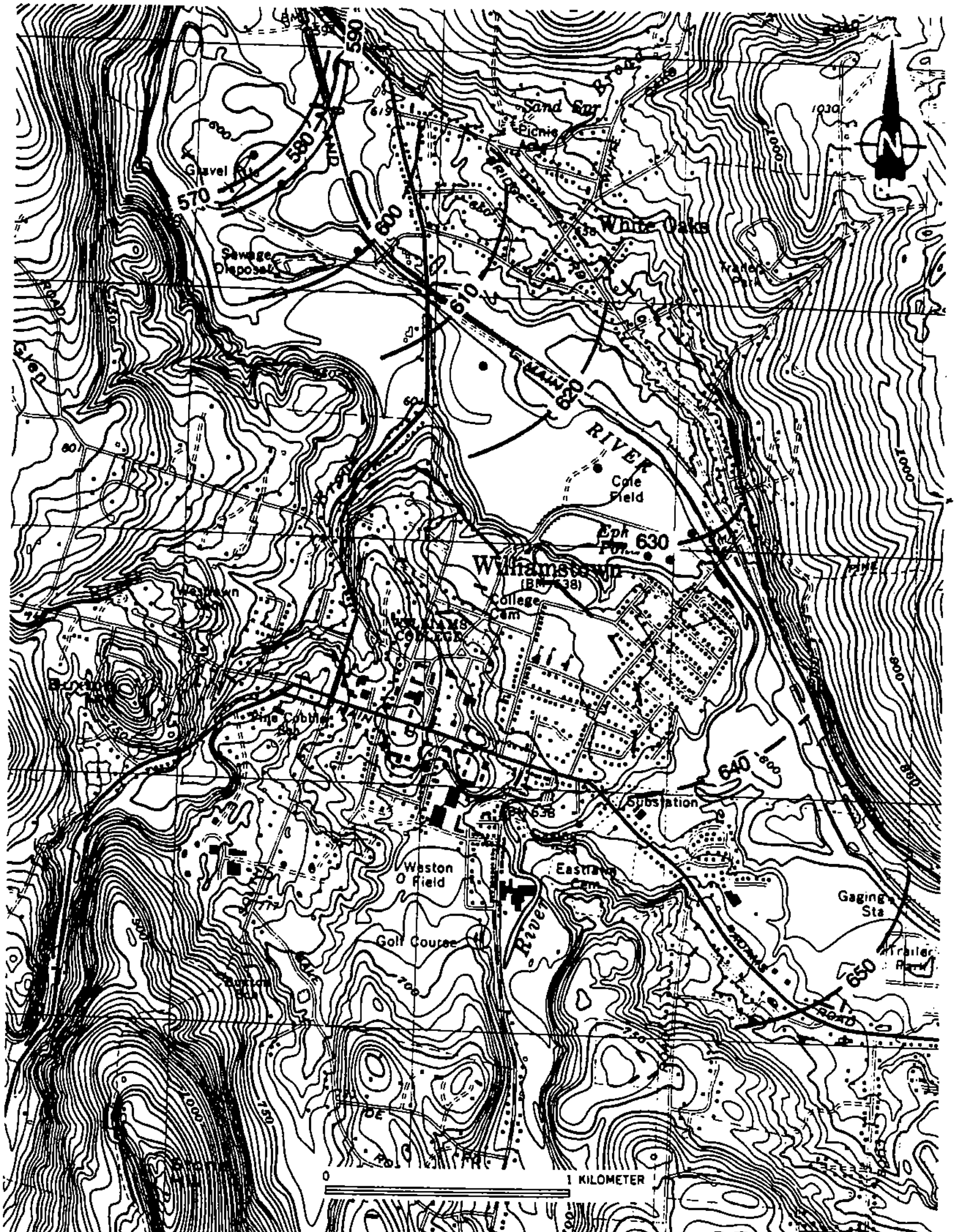


FIGURE 13 POTENTIOMETRIC SURFACE OF CONFINED AQUIFER IN FEET ABOVE MSL. HEAD MEASUREMENTS MADE AFTER TOWN WELLS HAD BEEN SHUT DOWN FOR 38 HOURS. BASE IS USGS 1:24,000 WILLIAMSTOWN QUADRANGLE (1973).

Laboratory measurements indicate that the hydraulic conductivity of the silt and clay (the fine-grained portion of the aquitard) is between 10^{-4}m/day and 10^{-5}m/day. Coarser sections of the aquitard yield small amounts of water to monitoring wells but we measured sustainable pumping rates of less than 5.5m^3/day (1 gpm). Vertical gradients between the confined and unconfined aquifers range between 0.345 and -0.275. Vertical gradients are upward throughout the study area except in the northernmost section.

Surface Morphology

Several tributary drainages enter the Hoosic River Valley near Williamstown: Broad Brook, Hemlock Brook, and the Green River. There is a dissected fanform feature at the mouth of Broad Brook. This fan and several other surfaces in the Hoosic River Valley near Williamstown are graded to a level of about 183m (600'). Gravel mining and landfilling have disturbed the fan and several of the surfaces (Figure 14).

There is a large deposit of sorted sediment along the Hoosic River north of Williamstown. The sediment extends to an elevation of about 275m (900'). We suspect that this deposit of glaciofluvial sediment represents a head of subaqueous outwash, the ice-proximal portion of a morphosequence.

DISCUSSION

Hoosic River Valley

A predictable spatial and textural distribution of glaciofluvial, glaciolacustrine, and alluvial sediment control the occurrence of ground water in the Hoosic River Valley. We identified two sand and gravel aquifers, separated over most of the study area by a silt and clay aquitard. The process of deglaciation and the location of sediment sources to glacial Lake Bascom determined the character of these hydrogeologic units.

Koteff and Pessl (1981) suggest that during the deglaciation of New England, flowing ice (a significant sediment source) was restricted to valleys between exposed highlands. Bierman (1985) provides field evidence and ice surface profiles from the Hoosic River Valley indicating that narrow ice tongues bordered Lake Bascom directly. During the deposition of glaciofluvial sediment, Lake Bascom was probably more than 150m (500') deep in Williamstown. Because the lake was too deep for ice-contact deltas to build to the lake surface, coarse-grained glaciofluvial sediment was probably deposited in a series of subaqueous fans. Fine-grained, glaciolacustrine sediment settled onto these fans during and after their deposition. Even after the level of Lake Bascom dropped with the opening of spillways in New York, water in Williamstown was about 90m (300') deep -- deep enough so that continued deposition of lacustrine sediment confined most of the glaciofluvial sand and gravel.

The distribution of glaciogenic sediment found by our study is consistent with the above interpretations because:

- o glaciofluvial sand and gravel predominate in the valley bottom and do not crop out extensively at higher elevations. This pattern of deposition indicates that ice (the sediment source) was restricted to lower elevations in the Hoosic River Valley during deglaciation;

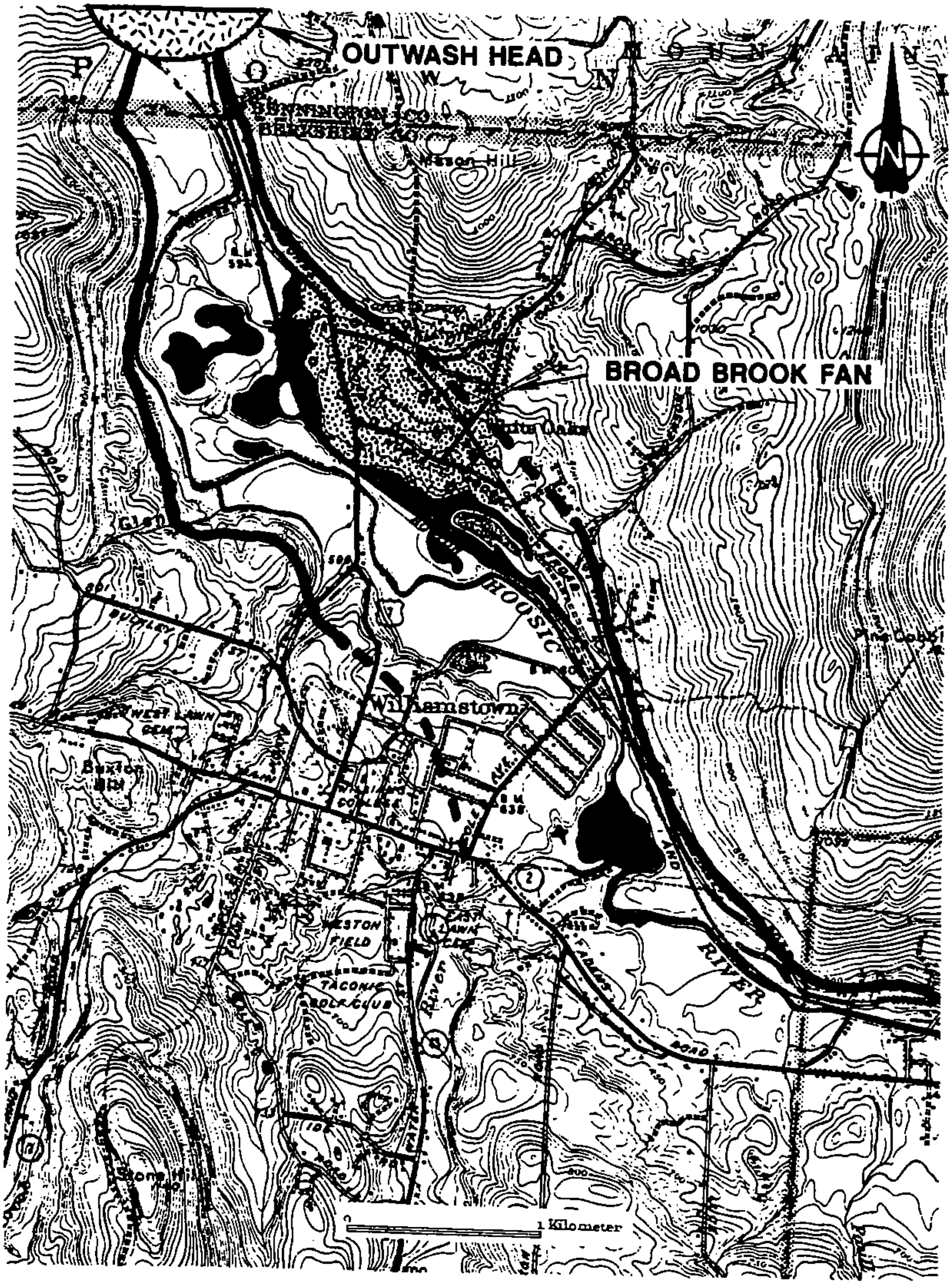


FIGURE 14 SURFACES GRADED TO LEVELS OF LAKE BASCOM BETWEEN 600' AND 610' ARE SHADED. FAN BUILT BY BROAD BROOK IS SHOWN BY STIPPLING. MARGINS OF THE HOOSIC RIVER BEDROCK CHANNEL ARE INDICATED BY HEAVY LINE. BASE IS USGS 1:31,680 WILLIAMSTOWN QUADRANGLE (1947).

- every boring advanced through the glaciolacustrine strata encountered lithologically and texturally similar glaciofluvial gravel. The pumping test indicated that this glaciofluvial gravel (or the underlying fractured bedrock) is hydraulically continuous. This evidence suggests that a large volume of sorted sediment was deposited in the valley bottom;

- glaciolacustrine sediment directly overlies glaciofluvial sediment and the latter deposit contains over 15% fines. This implies that Lake Bascom bordered the retreating ice margin;

- the upper surface of the glaciofluvial unit rises near the valley walls, reflecting the deposition of glaciofluvial sediment in subaqueous ice marginal drainages;

- the upper surface of the glaciofluvial unit rises to the north, possibly reflecting the presence of an outwash head which crops out in southern Vermont.

Because every boring installed during this study encountered glaciolacustrine sediment and because confined conditions exist throughout the study area, we believe that the aquitard is laterally continuous. However, the thickness of the aquitard is quite variable. The glaciolacustrine sediment thins in the northern part of the study area and near the valley margins because this unit drapes the surface of the underlying glaciofluvial deposits. The glaciolacustrine unit coarsens to the North reflecting the input of sediment from Broad Brook or the outwash head in southern Vermont. The thinning and coarsening of the aquitard may allow water to leak into or out of the confined aquifer.

The thickness and texture of the overlying alluvium are highly variable, indicating that the channel of the Hoosic River has migrated considerably since deposition of lacustrine sediment ceased. Surfaces graded to approximately 183m (600') probably represent deposits of tributary drainages (Broad Brook) and of the Hoosic River graded to lower levels of Lake Bascom. The existence of these features suggests that a large proportion of the alluvium may have been deposited when or just after Lake Bascom drained.

The style of deglaciation, the depth of Lake Bascom, and Berkshire geography dictate Hoosic River Valley hydrogeology. Retreat of an active ice margin deposited the thick, permeable, and presumably continuous section of glaciofluvial gravel. The presence of a sufficiently integral glaciolacustrine aquitard maintains confined conditions in the glaciofluvial sediment and the underlying bedrock. Flowing artesian conditions exist because the confined aquifer is recharged through fractured bedrock and through outcrops of permeable sediment on the valley walls. The distribution and texture of alluvium determine the occurrence of ground water in the unconfined aquifer.

The confined aquifer is a valuable ground water resource. Steep upward gradients between the two aquifers throughout most of the study area prevent the migration of contaminants from the uppermost aquifer to the confined system. Most recharge to the confined aquifer occurs in the relatively undeveloped uplands. Water quality in the confined aquifer is excellent. Monitoring wells screened in the unconfined aquifer yield only small amounts of lower quality water. On-going releases, in addition to flood plain sediment contaminated by industrial, agricultural, and waste disposal practices over the past 200 years, degrade water quality in the unconfined aquifer.

General Model

Our study suggests that a specific sequence of unconsolidated sediment is present in upland valleys where glacial lakes existed. We propose a generalized hydrogeologic stratigraphy constrained by our understanding of glacial processes and our investigation in the Hoosic River Valley (Table 1).

A varying thickness of low permeability basal till overlies bedrock. The till may be discontinuous (a leaky aquitard) if localized erosion by meltwater accompanied deposition of glaciofluvial sediment. If the underlying bedrock is sufficiently permeable, it may provide large quantities of ground water.

Because active ice is restricted to valleys during deglaciation, the greatest thickness of glaciofluvial sediment is deposited along the lower valley walls in ice marginal drainages or along the valley bottom in subaqueous fans and ice contact deltas. If the glacial lake were sufficiently deep or if retreat occurred rapidly, most of the glaciofluvial unit (with the possible exception of the outwash head) would be buried by glaciolacustrine sediment. If the lake were shallow or if retreat were slow, less fine-grained glaciolacustrine sediment would be deposited and a greater proportion of the glaciofluvial unit would crop out. Glaciofluvial sediment of sufficient thickness is relatively transmissive and can supply large quantities of ground water. The upper surface of the glaciofluvial unit generally slopes away from the outwash head.

The thickness of glaciolacustrine sediment is proportional to sediment flux, lake longevity, and water depth. Thickness is inversely proportional to the intensity of post-depositional erosion. Least permeable (smallest grain size) glaciolacustrine sediment is deposited in areas isolated from outwash heads, tributary mouths, and the sides of the lake. Water in the underlying bedrock and glaciofluvial sediment is most effectively confined where the glaciolacustrine unit is thickest and finest-grained. Head distribution in the confined aquifer is a function of glaciofluvial sediment texture and thickness, valley topography, location of recharge and discharge boundaries, and the integrity of the confining layer. If the glaciofluvial sediment is well-confined and sufficient recharge is supplied by the surrounding highlands, the upward vertical head gradients prevent potentially contaminated shallow ground water from moving downward. Water quality in the confined aquifer should be good if recharge zones have not been contaminated.

The thickness, distribution, and character of alluvium depend on fluvial activity during and after drainage of the lake. Alluvium is thickest near the mouths of tributary drainages or where the trunk stream built deltas into lower level lakes. A variable quantity of water is available from wells screened in the alluvium. Because the alluvial aquifer is not confined, near-surface contamination can readily degrade ground water quality.

Suggestions for Other Investigators

A thorough literature review and file search usually provide an investigator in New England with geologic information. Much data is unpublished and may be available only through universities or government offices. If sufficient information cannot be compiled from the literature, field reconnaissance and analysis of topographic maps can guide initial investigation. We recommend:

- researching <u>basin history</u>. Was the basin occupied by a glacial lake? If it was occupied by a lake, what were the lake levels and where were the spillways? How long did the lake persist and how deep was the lake in the area being investigated? The best sources for this information are USGS publications and open file reports, journal articles, field trip guides, and geology departments at local colleges and universities;

TABLE 1. GENERALIZED HYDROGEOLOGIC STRATIGRAPHY FOR AN UPLAND VALLEY PREVIOUSLY OCCUPIED BY A GLACIAL LAKE.

GEOLOGIC UNIT	DEPOSITIONAL PROCESSES	DESCRIPTION	THICKNESS	HYDRAULIC CONDUCTIVITY	WATER QUALITY
ALLUVIUM	1. Fluvial - Channel and overbank deposits 2. Deltaic - deposits in low level glacial lakes	Stratified sand, gravel, and silt Unconfined aquifer	Thickest near tributaries and location of low level deltas built by trunk stream	K = 1 to 0.001 m/day May be less conductive at base because of reworked fine-grain lacustrine sediment	Readily degraded by surface contamination
GLACIO LACUSTRINE	1. Deposition from density currents 2. Settling from suspension 3. Debris flows	Thin bedded or laminated silt, clay, and fine sand May be an aquitard	Thins near outwash heads and valley walls. Thickness depends on upper surface of underlying unit and amount of post-depositional incision	K = 10^{-3} to 10^{-5} m/day Highest conductivity where coarsest: near lake margins, tributaries, and outwash heads	Not applicable
GLACIO FLUVIAL	1. Ice marginal and englacial drainages 2. Ice contact deltas and subaqueous fans 3. Debris flows	Stratified sand and gravel Aquifer may be confined	Thickest near outwash heads and valley walls	K = 100 to 1m day	Good, if aquifer is confined and recharge zone is not contaminated
TILL	Emplaced at base of ice	Unstratified, poorly sorted mixture of sand, silt, clay, and gravel May be an aquitard	Depends on original thickness and subsequent erosion by meltwater streams	K = 1 to 0.0001 m/day Generally low but variable	Not applicable

- identifying the location of outwash heads and morphosequences. If the quadrangle has been mapped by a geological survey or a professional geologist, this information is available through libraries, geology departments, and Federal and State government agencies. If mapping has not been performed, analysis of topographic maps, aerial photographs, and surficial exposures will be necessary;

- determining the sources of lacustrine sediment. Topographic maps indicate the location of surface drainages and fan/delta complexes. In some cases, sediment is supplied by drainage of an adjacent glacial lake.

- identifying the location, extent, and character of bedrock outcrops. Bedrock geometry may control lake morphology and patterns of ground water recharge. Lithologic maps, survey reports, and unpublished academic studies may provide information. Surficial geologic maps may identify bedrock outcrops. With the aid of aerial photographs, field reconnaissance can quickly determine the approximate extent of exposed bedrock.

CONCLUSIONS

Our research suggests that a predictable sequence of hydrogeologic units exists in upland valleys once occupied by glacial lakes. Permeable glaciofluvial gravel overlies till and bedrock. Glaciofluvial sediment may crop out at the margins of the lake or at outwash heads. The top of a glaciofluvial unit dips away from the former ice margin (outwash head). Depending on the depth and longevity of the lake, sufficient low permeability glaciolacustrine sediment may have accumulated to confine water in the glaciofluvial gravel. Lake level, paleotopography, and post-depositional incision determine the integrity of the confining layer. An unconfined aquifer exists in the overlying alluvium.

Large amounts of high quality ground water should be found in confined glaciofluvial sediment. The yield and quality of ground water from unconfined alluvium are usually lower. If the glaciofluvial sediment is not confined, yield may still be high but ground water quality may be adversely impacted by contaminants introduced at the surface.

REFERENCES CITED

Bierman, P., 1985, The deglaciation of northwestern Massachusetts: Unpublished thesis, Williams College, 143 p.

__________ and Dethier, D, 1986, Lake Bascom and the deglaciation of northwestern Massachusetts: Northeastern Geology, v. 8, nos 1/2, 1986, p. 32-43.

Dale, T. N., 1906, The geological history of Mt. Greylock: Press of the Sun Printing Co., Pittsfield, 17 p.

Drewry, D., 1986, Glacial geologic processes, Edward Arnold, London, 276 p.

Hansen, B. P., Gay, F. B., and Toler, L. G., 1973, Hydrology and water resources of the Hoosic River Basin, Massachusetts: United States Geological Survey Hydrologic Investigation, HA-481.

__________, 1974, Hydrologic data of the Hoosic River Basin, Massachusetts: Massachusetts hydrologic data report no. 15, United States Geological Survey, 33 p.

Jopling, A. and McDonald, B., 1975, Glaciofluvial and glaciolacustrine sedimentation, SEPM Special Publication No. 23, Tulsa, 320 p.

Koteff, C. and Pessl, F., 1981, Systematic ice retreat in New England: United States Geological Survey Professional Paper 1179, 20 p.

Mathews, W. H., 1974, Surface profiles of the Laurentide ice sheet in its marginal areas: Journal of Glaciology, v. 13, p. 37-43.

Motts, W. and MacFadyen, J., 1983, Hydrogeology and aquifer protection study of Williamstown, Massachusetts: Berkshire Regional Planning Commission.

Nye, J. F., 1952, A method of calculating the thickness of ice sheets: Nature, v. 169, p. 529-530.

Zen, E. et al, 1983, Bedrock geologic map of Massachusetts: Department of Public Works, Commonwealth of Massachusetts and United States Geological Survey.

ACKNOWLEDGEMENTS

The authors would like to thank numerous individuals who contributed to the success of this investigation. Many officials of Williamstown government aided our inquiry. In particular we are indebted to the Water Department, the Town Manager's Office, and the Highway Department. David Dethier of the Williams College Geology Department provided valuable commentary, a helpful review of this paper, grain size analyses, and a number of eager student assistants. Michael Retelle, Bates College, performed the sedigraph analyses. Many staff members of Alliance Technologies and Hydro Group took part in this project. Our strong appreciation goes to Dottie Sheahan and Jennifer Elmassian who spent long days and weekends producing numerous technical illustrations some of which we have used in this paper. We would like to thank Susan Perkins and Kathleen Campbell of the University of Washington for their thorough reviews. Any errors or omissions remain the responsibility of the authors.

BIOGRAPHICAL SKETCHES

Mr. Bierman is presently pursuing a graduate degree in geomorphology at the University of Washington. His research interests include glacial processes, hillslope evolution, and ground water hydrology. Before coming to Seattle, Mr. Bierman was employed as a hydrogeologist by Alliance Technologies. He directed field investigation at several hazardous waste sites in glaciated terrains and managed the Williamstown Landfill Study. Mr. Bierman graduated from Williams College where he mapped surficial geology and prepared a thesis entitled, Lake Bascom and the Deglaciation of Northwestern Massachusetts.

Ms. Marler is a hydrologist with Ground Water Associates. In addition to numerous water supply projects, she is supervising field investigation at a Superfund site in eastern Massachusetts. Prior to joining Ground Water Associates, Ms. Marler was a hydrologist with Alliance Technologies. At Alliance, she oversaw ground water remediation at a Superfund site, helped develop EPA guidelines for RCRA Facility Investigations, and performed hydrologic analyses for the Williamstown Landfill Study. Ms. Marler graduated from the University of New Hampshire with a degree in hydrology.

Mr. Martin is a hydrogeologist with Ground Water Associates. He oversees numerous projects involving the design, installation, and sampling of monitoring well networks and public water supplies. Mr. Martin has managed ground water remediation projects and has been responsible for the hydrogeologic aspects of a Remedial Investigation/ Feasibility study at a Superfund site in eastern Massachusetts. Mr. Martin graduated from Williams College with a combined degree in Geology and Economics.