Surficial Geology and Groundwater Hydrology of the Brookfield 7.5 Minute Quadrangle, Vermont[1]

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Executive Summary/Significant Findings

The surficial geology of the Brookfield 7.5-Minute Quadrangle was mapped during the summer of 2021 with field assistance from eight geology students at the University of Vermont. Considerable detail has been added to prior mapping done at a scale of 1:62,500 and later incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). A surficial geologic map, four geologic cross-sections, an overburden thickness map, water table contour and flow line map, well yield map, and recharge potential to surficial materials map are included with this report (Plates 1-5).

The Brookfield Quadrangle contains a variety of glacial landforms and sediments that formed as the Laurentide ice sheet first flowed across north-central Vermont and then thinned and retreated from the area. Glacial striations and elongate till ridges (crag and tail structures) are almost universally oriented north-south indicating that the last recorded direction of ice flow across this area was from north to south .

Till mantles all of the upland areas. Most is dense lodgment till, but some may be till remobilized as debris flows sourced from the steep mountain hillsides. Most of the till cover is thin, but extensive areas exist where the till is thick enough to completely mask the underlying bedrock topography. Most rocks occurring in the till are sourced locally from the Waits River or Gile Mountain formations. However, erratics sourced from areas to the northwest, are common. Very large erratics have been mapped. Distinctive white boulders of quartz, sourced from veins in the bedrock, are common in the till and are prominent where they have been used in the many stone walls outlining fields in the area.

During ice retreat sand and gravel was deposited in subglacial tunnels and in subaqueous fans, along the Second Branch and Stevens Branch valleys. These ice-contact sediments occur at the surface but are frequently overlain by younger glaciolacustrine sediments. They can host significant aquifers, both confined and unconfined.

The retreating ice sheet allowed the growth of two different glacial lakes. A long, thin, relatively shallow arm of Glacial Lake Hitchcock occupied the Second Branch valley and Glacial Lake Winooski grew northward in the Stevens Branch valley as soon as the ice sheet retreated north of the drainage divide between the two streams. Most of the glacial lake sediments mapped in these valleys consists of medium to fine sand, silt, and clay that accumulated in these lakes in ice distal environments. Deltas formed where tributary streams entered the lake. Remnants of a large delta mapped at the head of the Second Branch valley likely formed as the ice sheet retreated up the valley and by the outflow stream from Glacial Lake Winooski through Williamstown Gulf.

An array of large gravel bars and terraces comprised of very coarse gravel were mapped along the Second Branch valley where they were deposited directly on fine-grained Glacial Lake Hitchcock deposits. These likely formed as outflow from Glacial Lake Winooski eroded the earlier-deposited delta and deposited the bars in a braided river system following the drainage of Glacial Lake Hitchcock. Varved lake sediments are used to show that (1) the ice sheet was retreating across the area at ~300 m/yr and (2) Glacial Lake Winooski lasted ~375 years, beginning ~14,170 yr BP and ending ~13, 794 yr BP. The drainage of Glacial Lake Hitchcock from the Second Branch valley must have occurred during this time span.

Alluvial fans, large and small, are the only significant landforms to form in post-glacial times. The lack of abandoned fluvial terraces and channels in the Second Branch and Stevens Branch valleys suggest that streams in those valley have done little down-cutting during the last 14,000 years.

Well data was utilized to contour the overburden thickness. Similar to most valleys in Vermont, thick sections of surficial materials accumulated in the valleys in both glacial and glaciolacustrine environments whereas the high and steep mountain slopes are overlain by a discontinuous cover of till.

The water table across the map largely mimics the ground surface topography. Large-scale groundwater flow is towards the major rivers draining the area and the surface water divide separating the Winooski River Basin from the White River Basin is also a major groundwater divide.

Well yields vary widely across the quadrangle, but the vast majority of drilled wells provide yields adequate for homes and businesses. These yields, particularly in the till-covered uplands, indicate that groundwater recharge through the till is sufficient to replenish the bedrock aquifers. Coarse grained surficial materials in many of the valleys constitute both good areas for groundwater recharge and good surficial aquifers, both unconfined and confined.

Introduction

This report summarizes the results of mapping the surficial geology of the Brookfield 7.5-minute Quadrangle in north-central Vermont during the 2021 field season (Fig. 1). A companion report details the surficial geology of the Lincoln and Mt Ellen Quadrangles that were also mapped during the same 2021 field season (Fig. 1; Wright, 2022a, b). A principal objective of this work was to contribute to the effort to complete modern, detailed mapping of the entire Montpelier 1-degree sheet outlined in Figure 1.

A detailed surficial geologic map accompanies this report. This map and four geologic cross-sections present the bulk of the findings from this study. Additional maps completed for this project (1) contour the thickness of surficial materials, (2) show broad patterns of groundwater flow via contours of the water table and inferred flow lines, (3) infer the relative infiltration potential of the different mapped surficial materials, and (4) show the variation in well yields from private water wells.

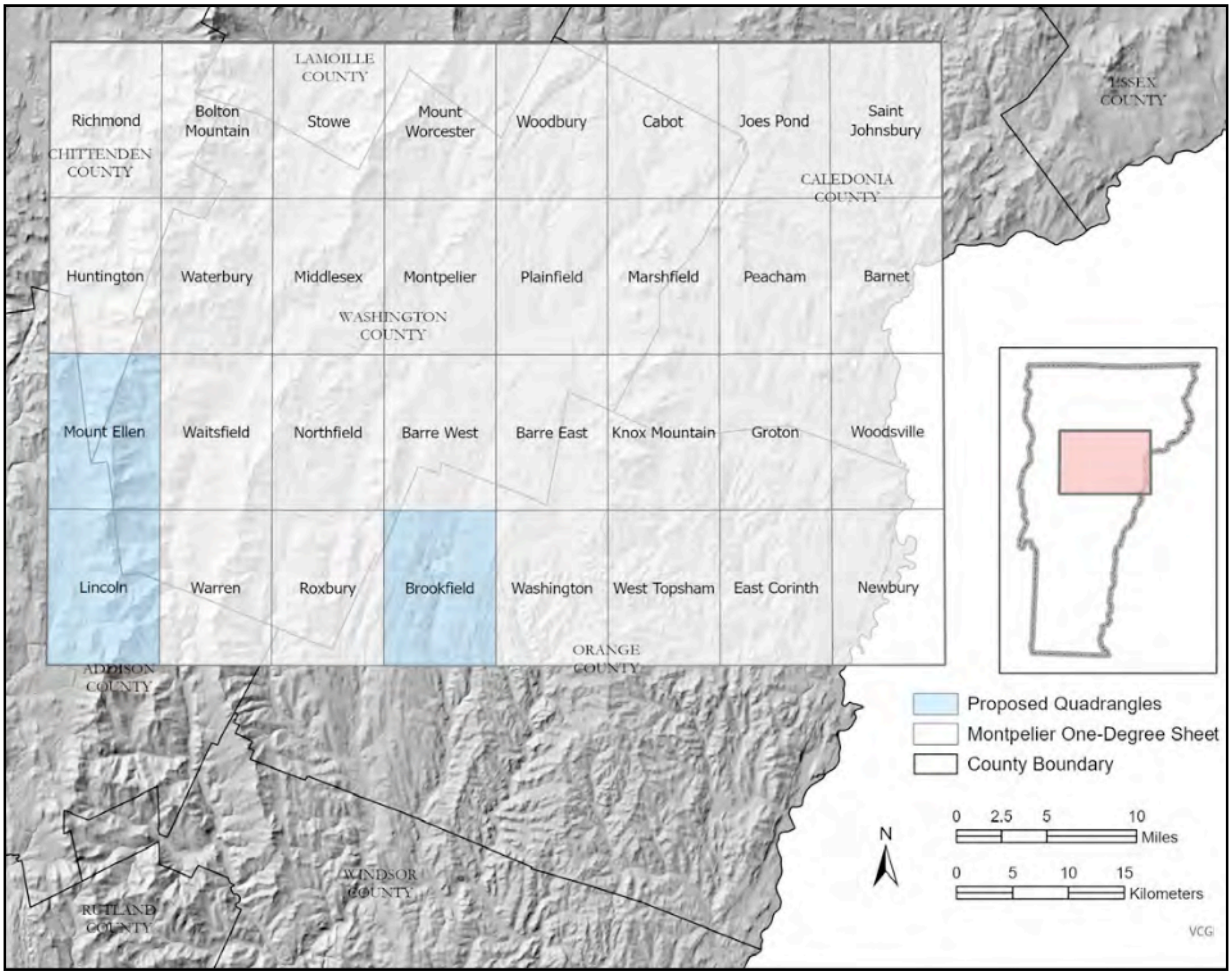


Figure 1: *Shaded relief map of north-central Vermont showing the locations of the Brookfield, Lincoln, and Mount Ellen Quadrangles. Map sourced from the RFP for this project prepared by the Vermont Geologic Survey.*

Location and Geologic Setting

The Brookfield Quadrangle is located in north-central Vermont in an area sometimes referred to as the Vermont Piedmont that lies between the Green/Northfield Mountains to the west and the Connecticut River valley to the east.. The landscape is rugged and largely forested, although significant areas of open farmland occur across the area. The most prominent physiographic feature in the quadrangle is a large north-south valley occupied by both the by the north-flowing Stevens Branch of the Winooski River and the south-flowing Second Branch of the White River (Fig. 2). The drainage divide separating the two streams and two major drainage basins cuts east-west across the quadrangle (Fig. 2).

The Brookfield Quadrangle is underlain by Silurian/ Devonian age metasedimentary rocks of the Waits River and Gile Mountain Formations (Fig. 2; Ratcliffe et al., 2011). Both formations consist of turbidites (sandstone, siltstone, shale sequences deposited during underwater landslides) that were later deformed and metamorphosed during the Acadian Orogeny. Sediments comprising the Waits River formation, particularly the meta-sandstone layers, contain a lot of clastic carbonate sediment. The solubility of these rocks, and clasts eroded from these rocks by glacial processes, makes them very susceptible to weathering. Bedding and major structures strike SSW-NNE forming a topographic grain that dominates the quadrangle on a wide range of scales (Fig. 3). Both formations are cut by quartz veins that are sometimes over a meter in width. A small number of Cretaceous dikes have also been mapped in the area.

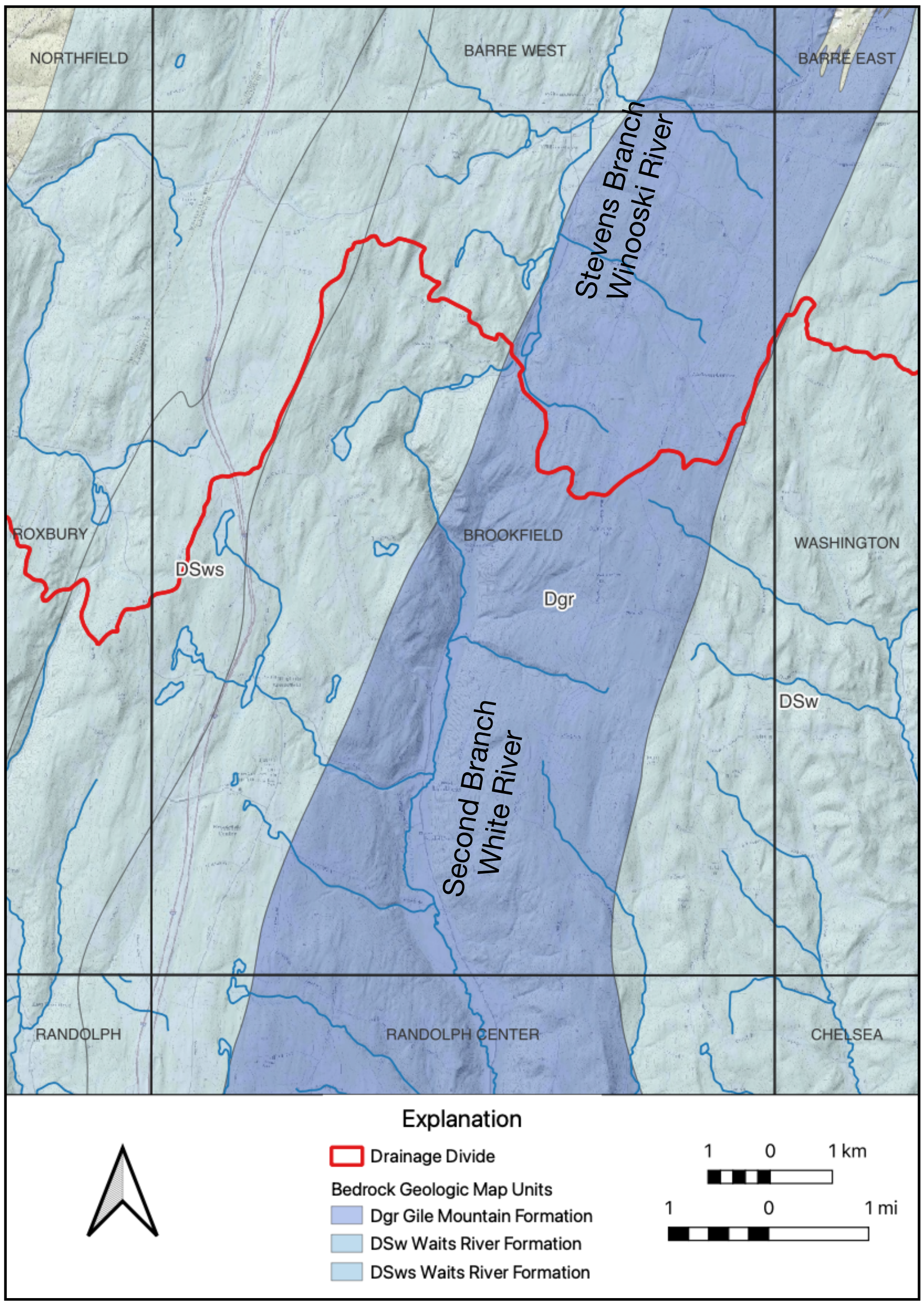


Figure 2: *Bedrock geologic map of the Brookfield Quadrangle (Ratcliffe et al., 2011) showing the area dominated by the Silurian/Devonian Waits River and Gile Mountain Formations. An east-west drainage divide separates water flowing north into the Winooski River Basin from water flowing south in the White River Basin.*

Prior Work

The Brookfield 7.5-minute quadrangle is the SE quadrant of the Barre 15-minute quadrangle which was mapped in reconnaissance fashion by Stewart (1956–1966). This mapped used the 1:62,500-scale topographic map as a base map and this open-file map was incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). Subsequent to this and other mapping conducted during the 1960's, the glacial geology of this part of Vermont was extensively updated by Larsen (1972, 1987). This work was supplemented by investigations of open pits in the Second Branch valley the results of which appear in Larsen and others (2003). Additionally, Wright (1999a, b) mapped the Barre West Quadrangle immediately north of the Brookfield Quadrangle and also mapped the Town of Randolph to the south (Wright, 2010). Additionally, as part of this work to the north, Wright extended his investigations into the northern part of the Brookfield Quadrangle.

A report outlining an investigation of groundwater contamination in the vicinity of the Williamstown landfill was completed following landfill closure (Stone Environmental, 2006). This work focuses on groundwater flow and quality in the vicinity of the landfill, but also includes logs recording the surficial materials encountered when monitoring wells were installed. While not directly related to this mapping proposal, extensive paleoecological work has occurred in several of ponds in the area, notably Twin Ponds (Grigg, 2019), and this work will be incorporated into interpretations derived from mapping this area.

Methods

Traditional field techniques and digital mapping were employed to generate a surficial geologic map of the area. Specifically, field observations and locations of different surficial materials, landforms, bedrock outcrops, glacial striations, kettles, landslides, and other geologic phenomena pertinent to this study were recorded using the Fulcrum App, a mobile mapping application. A stand-alone GPS allowed most field observations to be located with an accuracy of 3–5 m. Field mapping utilized LiDAR hillshade imagery with.4 m contours supplemented by traditional topographic maps and satellite imagery. In the valley bottom where relief was low 1 m topographic contours were generated to clarify the shape and extent of landforms. The locations and observations gathered in the field were imported into GIS software (QGIS) and utilized to draw geologic contacts between different surficial mapping units. Mapping units are consistent with those used on recently completed surficial geology maps within the Montpelier 1-degree sheet (e.g. Wright, 2020; Springston, 2019; Fig. 1) and conform to the unified set of mapping units developed by the Vermont Geological Survey.

Eight UVM undergraduate students assisted with the field mapping effort during June of 2021 as part of their Advanced Field Geology or Independent Geological Research class. The author gratefully acknowledges the work of Abby Baker, Evan Choquette, Jason Drebber, Caitlin Farkas, Remy Farrell, Cate Hogan, Ryan Mister, and Will Vanderlan.

Surficial Geologic Map of the Brookfield Quadrangle

The surficial geologic map that accompanies this report shows the aerial distribution of different types of surficial materials, landforms constructed of these materials, glacial striations, large erratics, landslides, and other geological phenomena. During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units which are utilized on the Stowe Surficial Geologic Map (Springston et al., 2018). The boundaries between these different materials are geologic contacts and are shown as solid lines on the geologic map. It's important to realize, however, that these contacts are non-planar 2-D surfaces that extend out-of-sight below Earth's surface and their extension above Earth's surface has eroded away. In some areas geologic contacts could be closely located in the field and these locations were recorded and used when constructing the map. However, in most areas the location of these contacts is interpreted from field observations, distinctive landforms, and aerial imagery. Every effort was made to make these contacts as accurate as possible, but there is an element of interpretation in the placement of these contacts.

Stratigraphic Framework/Surficial Geologic Mapping Units

The different surficial materials mapped within the quadrangle are described below, in stratigraphic order, from oldest to youngest. Most of the surficial materials in the area were initially deposited by or immediately adjacent to the Laurentide ice sheet as it flowed across and then gradually thinned and retreated across the area. A second group of surficial materials were deposited in glacial lakes that occupied the big north-south valley that cuts across the quadrangle. A third group of surficial materials largely consists of older glacial or lacustrine surficial materials that have been eroded and redeposited by processes occurring during the Holocene, the time span extending from ice sheet retreat to the present.

Bedrock Outcrops/Glacial Striations

Bedrock outcrops were mapped when they were encountered during field traverses. Additionally, most outcrops occurring along town roads and state highways were also mapped. No attempt was made to map all outcrops, especially in the upland areas where outcrops are numerous and closely spaced. Owing to the physically weak and soluble nature of the bedrock in the area, few of the mapped outcrops still retain a glacial polish or glacial striations. With one exception, the few striations mapped are all oriented approximately north-south (Plate 1).

Figure 3: *Waits River outcrop adjacent to Northfield road underpass beneath I-89. Near-vertical cleavage and sub-parallel bedding along with both vertical and horizontal joints give the outcrop its rectilinear pattern produced when blasted during construction of the Interstate. Joints and to a lesser extent the cleavage provide the secondary porosity through which groundwater flows in these rocks.*

Glacial Deposits

Glacial Till (Pt)

Glacial till directly overlies the bedrock in most areas. Within the quadrangle, till is the ubiquitous surficial material on the ground surface in areas above the valley bottoms. The freshest exposures are produced by stream erosion and also appear in landslides where the till is medium to dark gray and very dense (Fig. 4). Till in the area consists of angular to subrounded pebbles, cobbles, and boulders, many with striated surfaces) suspended in a fine clay/silt/sand matrix. In most areas the materials occurring in till consist of materials eroded, deformed, and deposited beneath the ice sheet. Frost heaving, plant roots, and animal borrows have loosened the till near the surface. Large glacially-transported boulders, some of which are erratics, are common and were mapped where encountered.

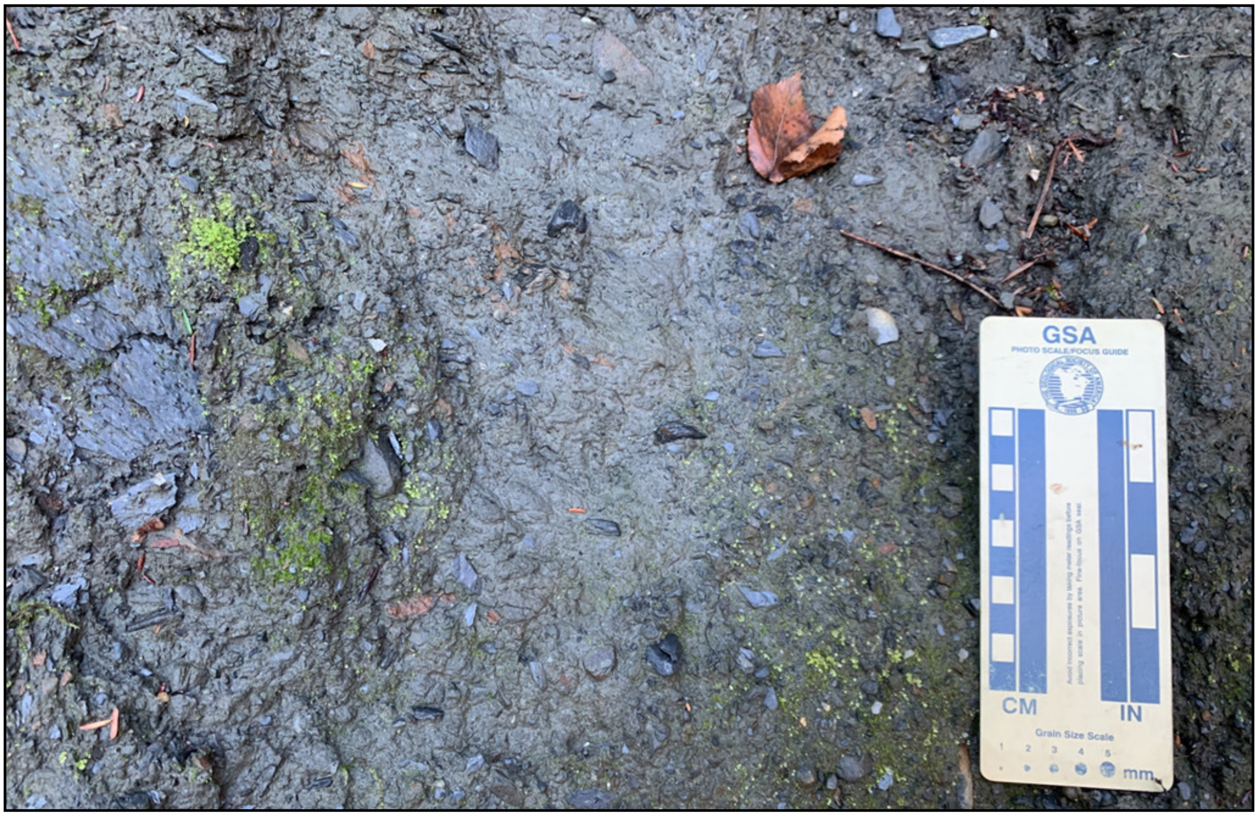


Figure 4: *Dense, grey glacial till exposed along south bank of Sunset Brook near East Brookfield. Most clasts visible in the photo are small and angular, but much larger boulder-size clasts are common.*

The thickness of till in the upland areas of the quadrangle varies considerably. In most areas, the till cover is thin (less than 2 to 3 meters) and abundant outcrops are present. However, in limited areas the till is sufficiently thick to completely bury the underlying bedrock.

Esker (Pie) and Ice-contact (Pi) Deposits

Ice-contact deposits largely consist of stream sediments deposited under, adjacent to, or in front of the retreating ice sheet. These streams are generally fast-moving and therefore carry and deposit coarse-grained sediment, dominantly sand and gravel. Sediments deposited in subglacial tunnels form ridges of sand and gravel (eskers) once the glacier melts away. An esker occurs in both the Second Branch and Stevens Branch valleys and earlier mapping shows this esker continues both north through Barre (Wright, 1999a,b) and south at least as far as South Randolph (Wright, 2010). Much of this esker has been quarried away, but an unquarried portion of the esker is well exposed ~3 km south of Williamstown, currently the site of Williamstown's solid waste transfer station (Fig. 5). Abundant water worn bedrock outcrops within the old gravel pit (green dots in Fig. 5) indicate that the subglacial stream that deposited the esker also eroded away any till overlying the bedrock. Indeed that till is the source of much of the sediment in the esker.

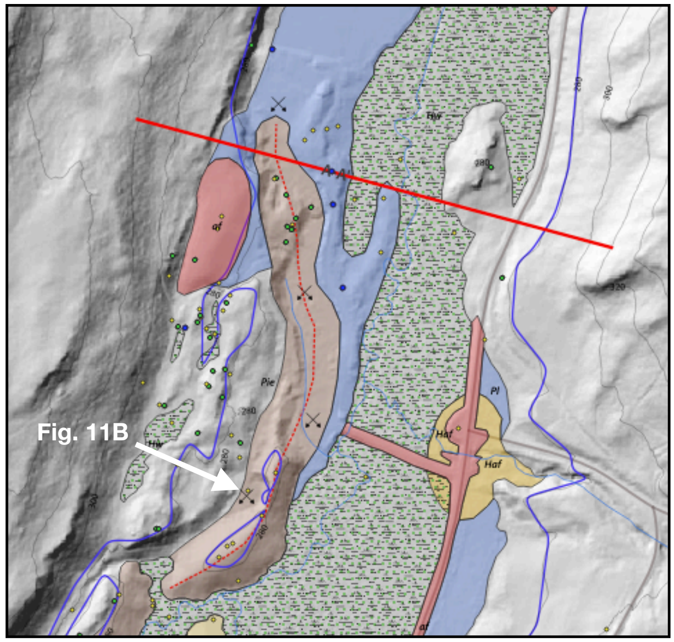


Figure 5: *Portion of the Brookfield geologic map ~3 km south of Williamstown showing an esker (Pie: brown color) extending along a portion of the Stevens Branch valley. Much of the esker has been quarried away revealing underlying waterworn bedrock outcrops (green dots).*

Most ice-contact sediments other than esker sediments mapped in the quadrangle are interpreted to be parts of subaqueous fans, i.e. sediments deposited under lake water at or close to the mouth of a subglacial tunnel. These sediments contain a wide-range of grain sizes that change abruptly in response to changing discharge in the subglacial tunnel, changing directions of outflow from the tunnel mouth, and distance from the tunnel mouth. These sediments grade into the undifferentiated lacustrine sediments described below. Generally, deposits dominated by gravel and coarse sand were mapped as ice contact sediments whereas deposits dominated by fine sand were mapped as undifferentiated lacustrine sediments. Cross-section A-A' (Fig. 6) depicts the distribution of both esker and lacustrine sediments across one part of the gravel pit shown in Fig. 5. Williamstown's closed landfill (the artificial fill—af—immediately south of the cross-section) is sited on lacustrine sediments.

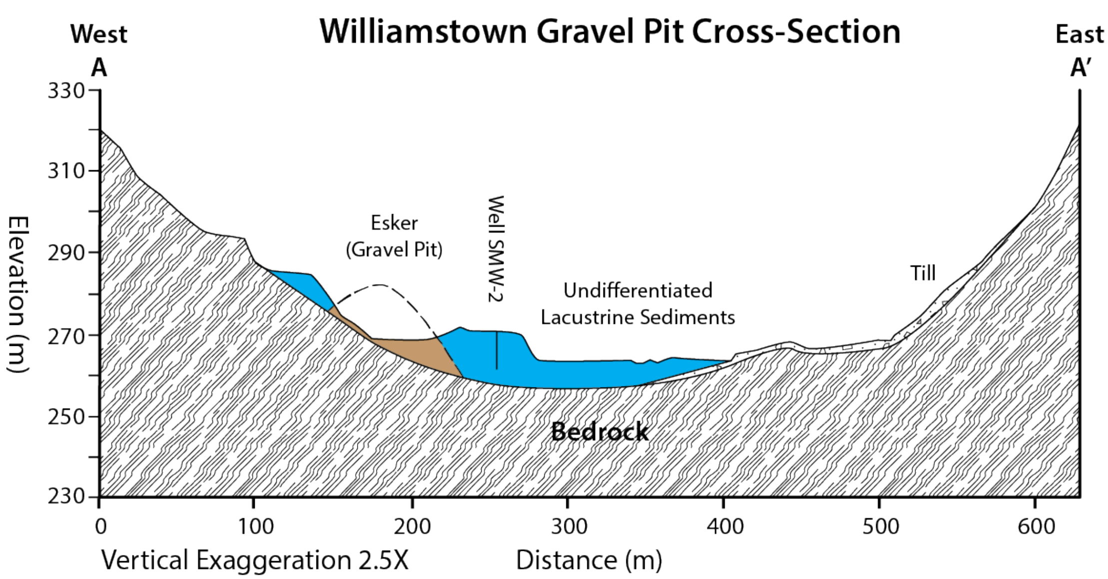


Figure 6: *Cross-section A-A' extends across the Steven's Branch valley ~3 km south of Williamstown (Fig. 5). Most of the esker gravel lying above the bedrock has been quarried away. Lacustrine sediments dominated by fine sand border the esker. Well SMW-2 is a monitoring well constructed to assess groundwater quality adjacent to the Williamstown's closed landfill (Stone Environmental, 2006). Depth to bedrock is estimated and thin wetlands sediments are not shown.*

Lacustrine Deposits

Lacustrine deposits are those that accumulated in either Glacial Lake Winooski (within the Steven's Branch valley north of Williamstown Gulf) or Glacial Lake Hitchcock (within the Second Branch valley south of Williamstown Gulf). The projected shorelines of these two lakes are shown on the geologic map (Plate 1). Sand/gravel deposits occurring at the mouths of tributary streams with terrace surfaces at or near the projected elevations of these lakes are mapped as deltas (Pldw—Glacial Lake Winooski Delta; Pldh—Glacial Lake Hitchcock Delta). In limited areas of the Second Branch valley fine-grained, quiet-water sediments were observed (silt/clay). However, most of the mapped lacustrine sediments mapped in the quadrangle vary greatly in grain size over short distances laterally and vertically and are mapped as Pl—Lacustrine Deposits, Undifferentiated. The variable grain size of these sediments results from (1) being deposited near the ice margin where the energy of water currents varies widely, (2) the shallow nature of both lakes, and (3) the narrow width of these lakes meaning that throughout their history most parts of the lake bottom were close to shore and close to tributary streams.

Glacial Flood Bars/Terraces (Pfb)

Along the Second Branch valley ovoid mounds and terraces of coarse pebble, cobble, boulder gravel lie in sharp contact with the underlying generally fine-grained lacustrine deposits (Fig. 7). These are interpreted to be bars and terraces deposited by high-energy stream water flowing out of Glacial Lake Winooski after Glacial Lake Hitchcock drained from the Second Branch valley. These sediments are far larger than those capable of being transported by the modern Second Branch of the White River in this very low-gradient valley.

Figure 7: *Coarse gravel mapped as Pfb exposed in a pit ~ 3 km north of East Brookfield in the center of the Second Branch valley. Abundant Waits River clasts are extremely susceptible to physical and chemical weathering and easily disintegrate whereas most erratic clasts remain competent.*

Holocene Deposits

Alluvial Fan (Haf) and Debris Flow Fan (Hdf) Deposits

Alluvial fans on a wide-range of scales are very abundant in both the Stevens Branch and Second Branch valleys. These form where sediments eroded from the valley sides, generally glacial till, have been carried downhill by tributary streams and deposited where the stream gradient abruptly lessens where it flows onto the valley bottom (Fig. 8). The apex of these fans frequently consists of debris flow deposits. One very large debris flow deposit occurring where Sunset Brook enters the Second Branch valley was mapped as a separate unit (Hdf). Farther down-fan sediments consist of lenses of sand/gravel that may fine to silt at their toes. In most cases these fans were deposited on the earlier deposited lacustrine and/or flood bar deposits. In many places these fans are large enough to extend almost completely across the valley and the courses of the Stevens Branch and Second Branch streams flow around the toes of these fans. Work on alluvial fans in northern Vermont suggests that fans have been episodically active throughout the Holocene and many received their most recent pulse of sediment following European land clearing in the late 18th and early 19th centuries (Bierman et al., 1997, Jennings et al, 2003). Related work by Noren et al. (2002) recording pulses of clastic sediment deposited in ponds and small lakes, indicates that pre-European settlement erosion has not been uniformly distributed throughout the Holocene and seems instead to be concentrated during periods of increased high-intensity storms. If climate shifts produce a greater frequency of high-intensity storms, further sedimentation on the area's alluvial fans seems likely.

Figure 8: *Large alluvial fan occurring on the west side of the Second Branch valley ~2 km south of East Brookfield (view looks west). This fan may have begun as a delta deposited by an unnamed brook flowing parallel to the Old Post Road where it entered Glacial Lake Hitchcock. The Second Branch of the White River flows from right to left and is bordered by modern alluvium (Ha).*

Modern Deltas (Hld)

Modern deltas were mapped in several areas where streams flow into ponds. These are generally small deposits of sand, gravel, and organics with marshy terraced surfaces at or close to the elevation of the pond.

Alluvium (Ha) and Alluvial Terrace (Hat) Deposits

Alluvium (Ha) refers to sediments deposited by modern rivers and streams. These sediments include sand and gravel deposited in river channels and point bars as well as sand and silt deposited on floodplains (Fig. 9). Organic materials are a frequent component of modern alluvium. These sediments were first deposited when streams began flowing across recently deglaciated valley sides and later when valleys occupied by glacial lakes drained. The thickness of alluvium corresponds to the depth of the modern stream channel. The two major streams in the quadrangle, the Stevens Branch of the Winooski River and the Second Branch of the White River are both quite small, low-discharge streams flowing down very low gradient valleys (former lake bottoms). Consequently, the extent and thickness of alluvium mapped in the quadrangle is relatively small and thin (Fig. 9).

Figure 9: *Narrow deposit of alluvium (Ha) along a reach of the Second Branch of the White River below Williamstown Gulf. The Second Branch is a very small stream here and the alluvial deposits consequently are thin. View looks downstream (southeast) with Vermont Route 14, built on artificial fill (af), at right.*

Alluvial terrace deposits (Hat) are stream sediments (alluvium) occurring on terraces above modern streams. As streams eroded channels more and more deeply through earlier-deposited sediments, older channels and adjacent flood plains were abandoned. Alluvial terraces are underlain by a veneer of sand and gravel corresponding in thickness to the depth of the stream channel that deposited the sediment.

Hw Wetlands Deposits

Wetland areas generally occupy closed basins and display varying amounts of open water depending on the season and the water table elevation. The dominant surficial material in wetland areas consists of both living and partially decayed organic materials but also includes inorganic fine-grained clastic sediment, “mud,” washed into these areas by streams and overland flow (Fig. 10). Another sediment occurring in these wetlands is marl, organically precipitated calcite ($CaCO_3$) that is a consequence of the very high calcite content of the underlying bedrock (Grigg, 2019). Most wetland areas in the uplands are underlain by till. Wetlands in the uplands,act as significant recharge areas for the underlying fractured bedrock aquifers (Fig. 10).

af Artificial Fill

Artificial fill was mapped where significant volumes of material were utilized for the construction of federal and state highways (Interstate-89 and VT Route 14) as well as dams. In most cases fill consists of sand and gravel (Fig 9).

Figure 10: *Wetlands sediments adjacent to Twin Ponds. View looks south from the shoreline of the western pond. A detailed history of changing climate in the region from ~14,000 years ago to the present has been interpreted from sediments in these ponds (Grigg, 2019).*

Results

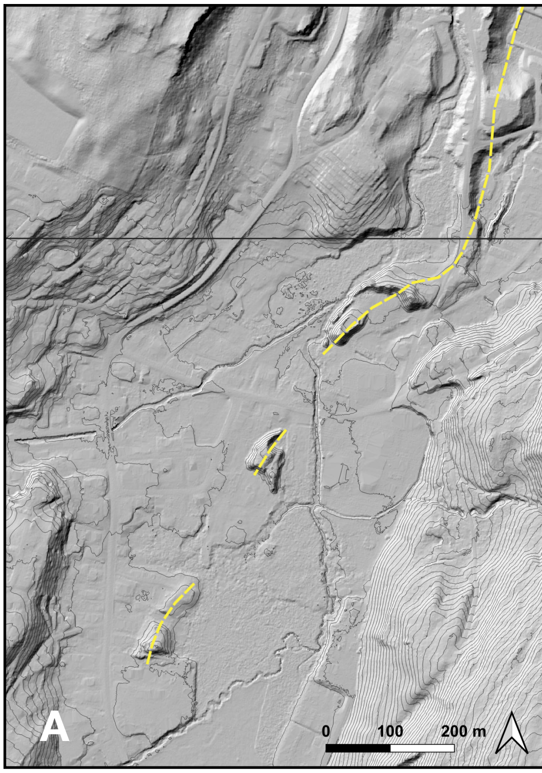
The surficial geologic materials and landforms mapped in the Brookfield Quadrangle provide the basis for the following interpretation of the glacial history of this area. This local history will be fit within our broader understanding of northern Vermont's glacial history based on earlier work.

Ice Flow History

The surficial geologic materials occurring in the region were predominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments existing during or shortly after the Laurentide ice sheet retreated across north-central Vermont ~14,000–13,500 years ago (Ridge et al., 2012; Corbett et al., 2018). Glacial till, erratics, and striations on the summits of the region's highest mountains indicate that the ice sheet in northern New England was sufficiently thick to completely cover the mountains. Striations on these high-standing peaks and ridge lines indicate that regional ice flow was from northwest to southeast across northern Vermont (Wright 2015a). Striations were rarely observed on bedrock exposures in the quadrangle and only one along I-89 records this NW to SE ice slow direction. All of the other striations are oriented north-south and were produced when the ice sheet had thinned sufficiently that it's flow was topographically controlled (Wright, 2015a). Crag and tail structures, visible on the LiDAR shaded relief imagery, are similarly oriented N-S and provide another line of evidence that the last ice flowing across the region was moving almost due south.

Ice Sheet Hydrology

A segmented esker was mapped along portions of the South Branch and Stevens Branch valleys and sedimentary structures observed in the esker indicate that water flow was to the south (Figs. 5. 11). This is consistent with southward ice flow as hydraulic gradients within the ice sheet would also be to the south, perpendicular to the south-sloping surface of the ice sheet. As noted earlier, prior mapping shows this esker continues both north through to North Barre (Wright, 1999a,b) and south at least as far as South Randolph (Wright, 2010). Reconnaissance work further indicates that this esker and the subglacial drainage system that deposited it likely continues along the Route 14 valley well north of Hardwick indicating that the north-south valley in the Brookfield Quadrangle and its extensions north and south served as a long-lasting, subglacial drainage conduit during ice



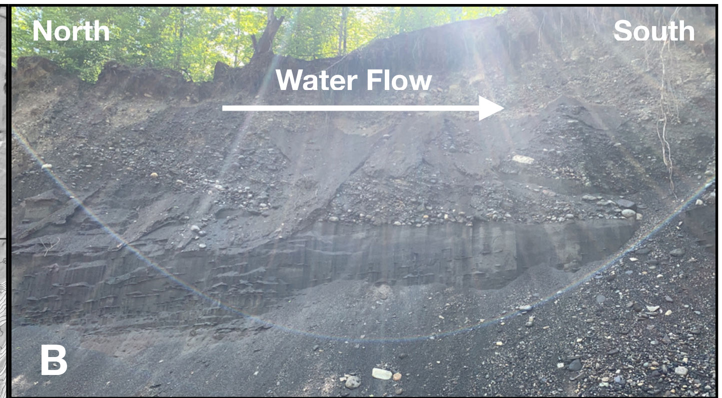


Figure 11: *(A) Shaded-relief LiDAR image of the Stevens Branch valley centered on the village of Williamstown. Beads of an esker (shown with yellow dashed line) rise above the alluvial fan that underlies Williamstown. The fan has formed where the unnamed brook flowing parallel to VT Rt 64 enters the Stevens Branch valley. The esker has, in most places been partially quarried for sand and gravel. The middle bead lies at the southern terminus of the railroad that used serve the granite sheds and grain elevators in Williamstown. (B) Sedimentary structures (large-sale cross-bedding) in esker indicates water flow to the south (see Fig. 5 for location).*

retreat (Fig. 12). Eskers are time-transgressive depositional landforms meaning that the esker wasn't being deposited along its entire length at the same time, but that at any one time net accumulation of sediments likely occurred only in the last several kilometers of the subglacial ice tunnel forming the esker. As the ice sheet retreated to the north, the locus of deposition in the subglacial tunnel also shifted to the north. In areas where no esker was mapped, it's unclear whether (1) an esker was never deposited in the subglacial tunnel in this location, (2) an esker was deposited but was later eroded away or fully excavated by human activities, or (3) the esker lies buried beneath younger sediments, e.g. lacustrine deposits.

In addition to being excellent sources of sand and gravel, the very porous and permeable nature of esker sediments mean that rainfall and snowmelt easily infiltrate the ground surface recharging both these surficial sediments and the underlying bedrock.

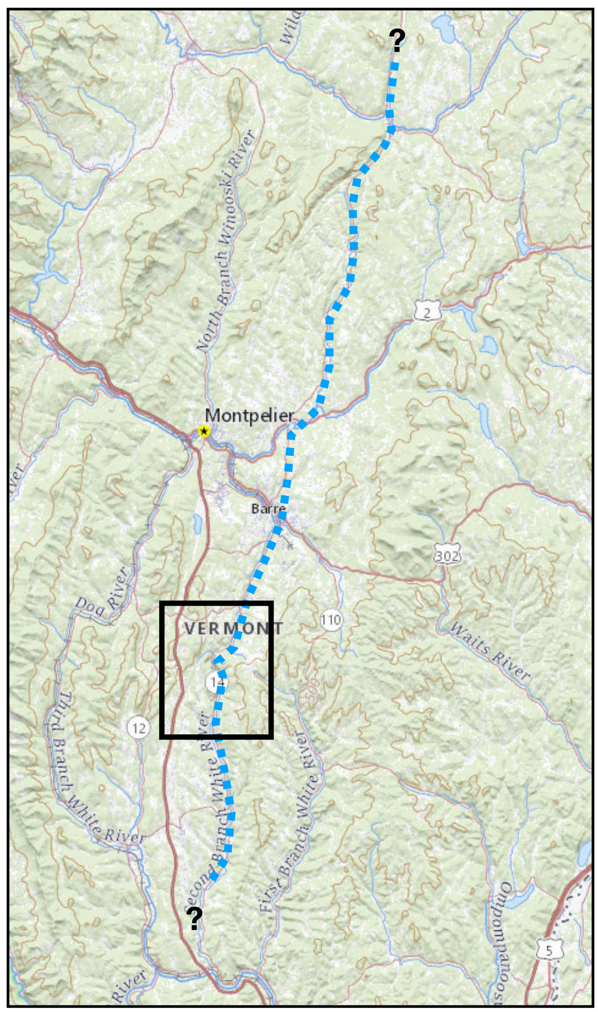


Figure 12: *Blue dashed line shows the currently known extent of the esker system that crosses the Brookfield Quadrangle (black rectangle).*

Glacial Lake History

A variety of glacial lake sediments were mapped in both the Stevens Branch and Second Branch valleys (Plate 1). These sediments were deposited in two large lakes that existed as the ice sheet retreated across the region. The Second Branch of the White River hosted a narrow arm of Glacial Lake Hitchcock which extended as far north as Williamstown Gulf (Fig. 13). This very extensive lake occupied the Connecticut River valley and it's tributaries north of the New Britain Spillway in central Connecticut. As the ice sheet retreated northwards from central Connecticut to northern Vermont/New Hampshire, this lake grew progressively larger over a period of more than 4,000 years (Stone et al., 2015; Ridge et al., 2012).

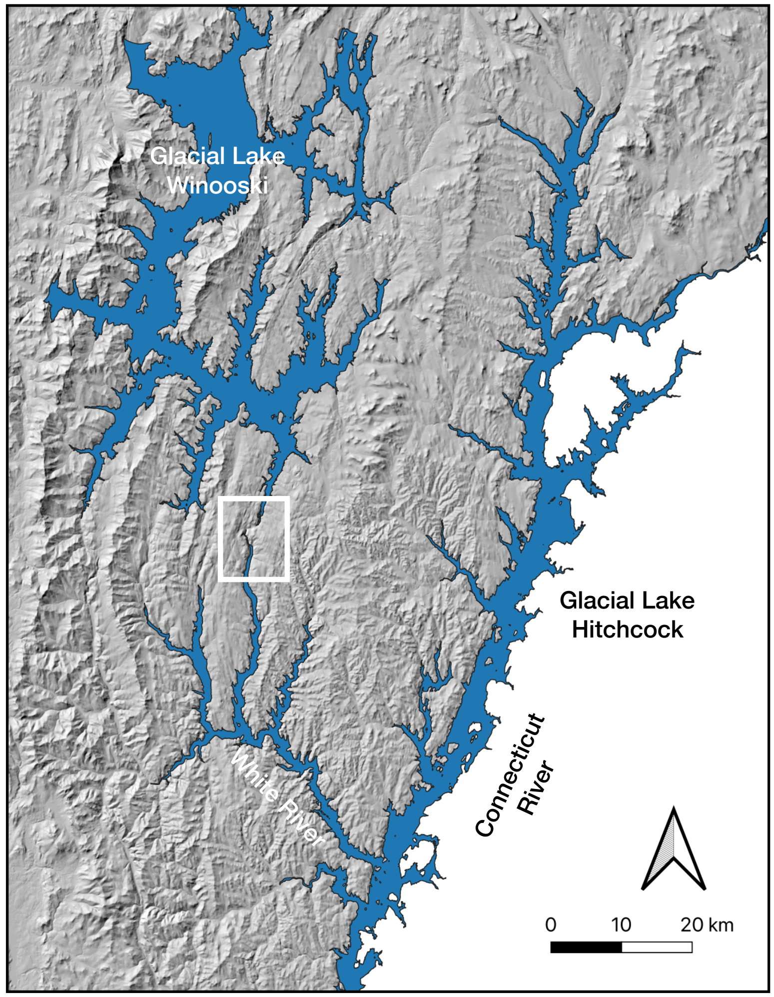


Figure 13: *Map of northeastern Vermont showing extent of Glacial Lake Hitchcock in the Connecticut and White River valleys and Glacial Lake Winooski in the Winooski and Lamoille River valleys. Brookfield Quadrangle is outlined in white.*

Within the Brookfield Quadrangle, as soon as the ice sheet retreated north of Williamstown Gulf and the drainage divide between the Second Branch of the White River and Stevens Branch of the Winooski River (Fig. 2), a second lake, Glacial Lake Winooski, began to grow as the ice sheet retreated north of this divide (Larsen 1972, 1987; Fig. 13). Continued retreat of the ice sheet allowed this lake to flood both the Winooski and Lamoille River valleys (Fig. 13).

During the lifetime of Glacial Lake Winooski outflow from the lake passed across the drainage divide, through Williamstown Gulf, and into the Second Branch valley (Fig. 14). The detailed map in Figure 14 clearly shows several north-south bedrock ridges that were the erosion-resistant structure of the drainage divide and likely formed the beginning of a series of rapids as water surged down through the Williamstown Gulf. Outflow discharge must have been quite high. In addition to all the meteoric water (rainfall, snowmelt) falling within the Lamoille and Winooski drainage basins that drained into the lake, this inflow was greatly increased by water from the rapidly melting ice sheet east of the Green Mountains during the summer ablation season.

At the south end of Williamstown Gulf several terraces consisting of sand and gravel occur along both sides of the Second Branch valley (Figs. 15, 16). The largest of these occurs on the northeast side of the valley and several other narrower terraces occur along the west side of the valley (Fig. 15). All of these terraces lie at approximately the same elevation (248—254 m, 814—833 ft; Fig. 16), close to but slightly above the projected elevation of Glacial Lake Hitchcock (~245 m, 804 ft). These terraces are most likely the eroded remnants of a delta that formed where outflow from Glacial Lake Winooski entered Glacial Lake Hitchcock. If this interpretation is correct, this delta consists of sediments from two possible sources: (1) From sediments emanating from the esker tunnel making this an ice-contact delta or (2) Sediments were eroded from Williamstown Gulf (largely earlier deposited glacial till and the

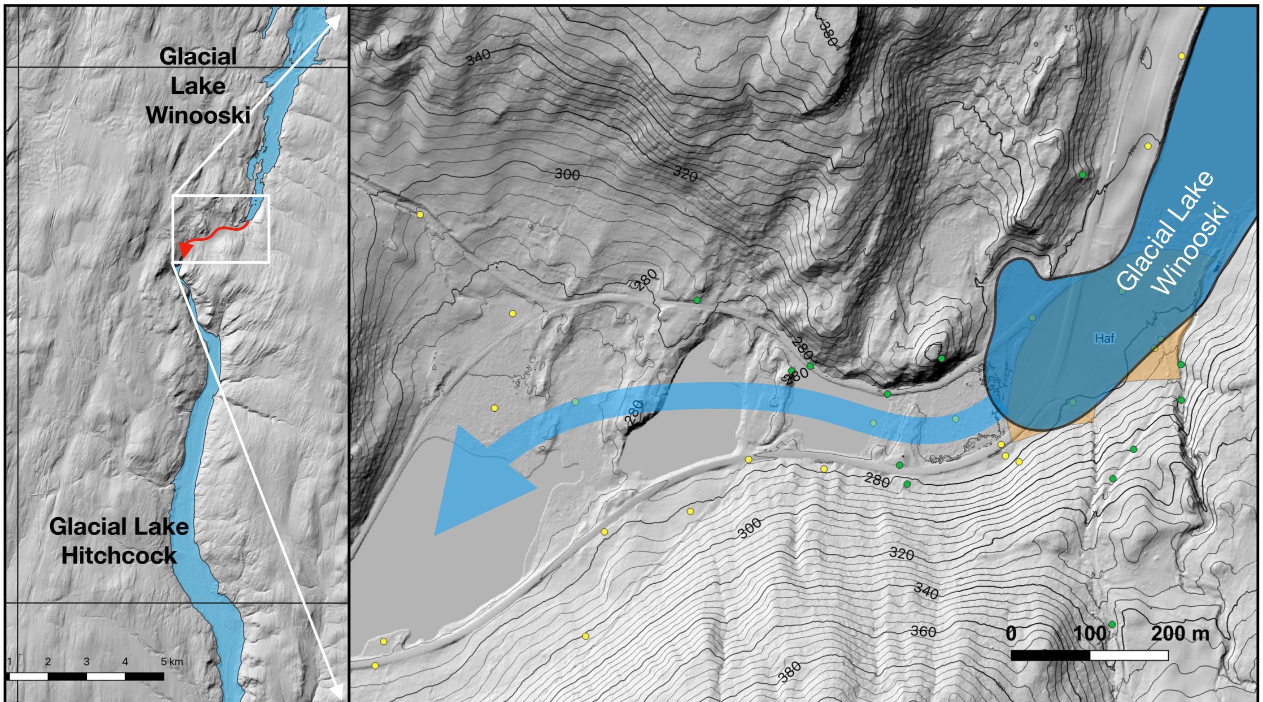


Figure 14: *Detailed map depicting most of the Brookfield Quadrangle (left) shows Glacial Lakes Hitchcock and Winooski. Red arrow shows the pathway outflow from Glacial Lake Winooski took through Williamstown Gulf to reach Glacial Lake Hitchcock. Detailed map at right clearly shows multiple north-south bedrock ridges that served to minimized the erosion of the outlet of Glacial Lake Winooski despite very high outflow discharges. Holocene alluvial fans (Haf) partially bury the outlet. Contours in meters.*

underlying bedrock occurring along this steep-sided, narrow valley) by the high-discharge outflow from Glacial Lake Winooski. It's very likely that the delta was comprised of sediment from both sources.

If not a delta, an alternative hypothesis is that these terraces are kame terraces deposited by an ice-marginal stream (Larsen, 1987; Larsen et

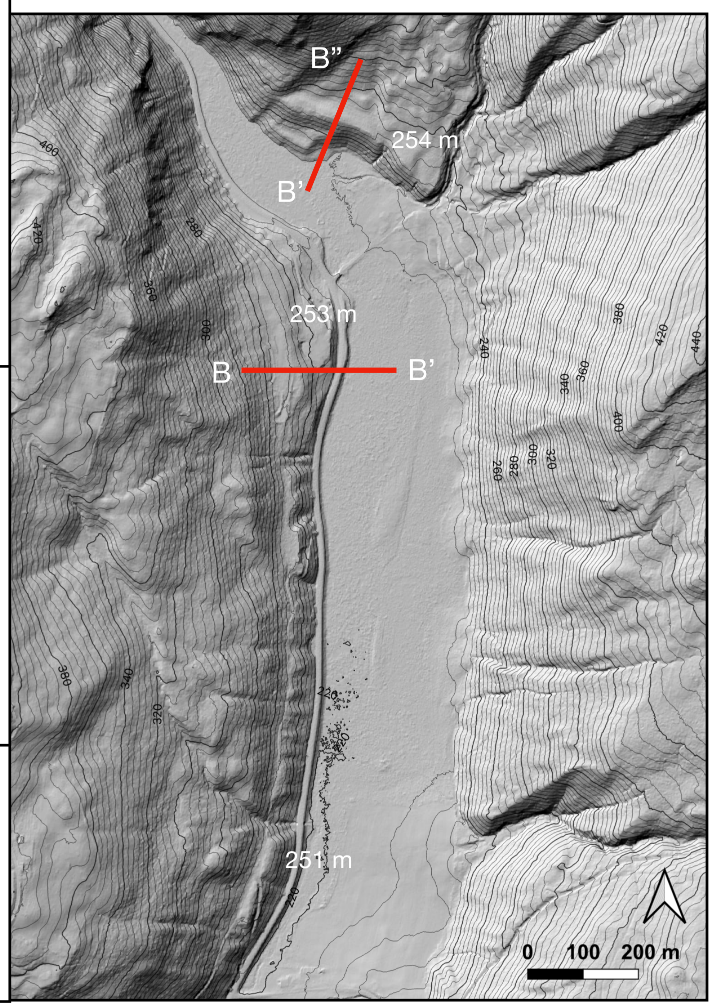


Figure 15: *Several sand and gravel terraces occur along both sides of the Second Branch valley immediately south of Williamstown Gulf. Terrace surfaces all lie close to the projected elevation of Glacial Lake Hitchcock. Contours outline several large alluvial fans built into the valley at the mouths of tributary streams. Contours in meters.*

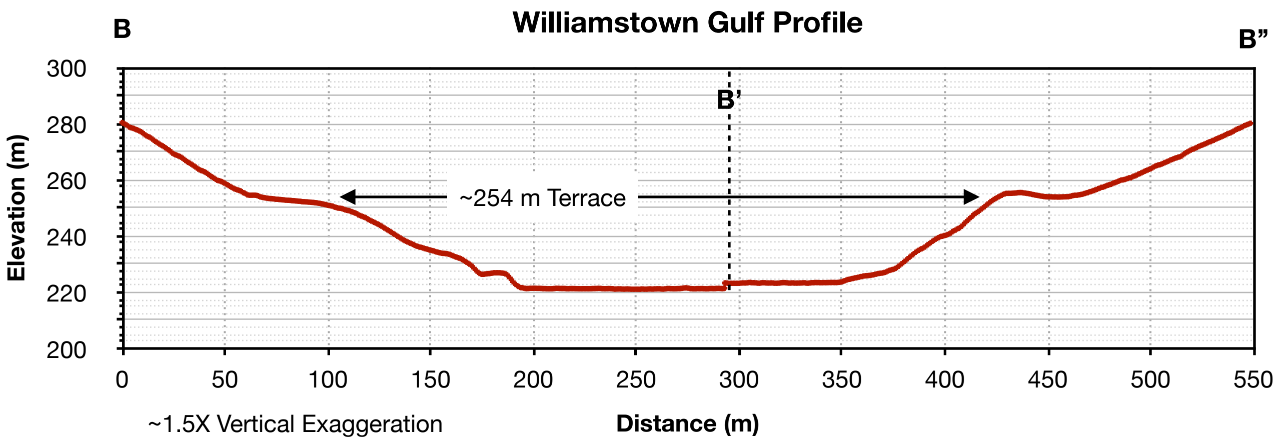


Figure 16: *Topographic profile across the lower end of Williamstown Gulf (see Fig. 15 for location of profile). Terraces composed of sand and gravel occur at the same elevation on both sides of the valley and are interpreted to be the eroded remnants of a delta that formed in Glacial Lake Hitchcock. Farther upstream, in the very narrow portions of Williamstown Gulf, the delta has been completely eroded away. Geologic Cross-section B-B” (Plate 1) shows the sediments and bedrock underlying this area.*

al. 2003). If so, this is the only place where they are preserved within the Brookfield Quadrangle and no ice-marginal stream terraces were mapped farther south in the town of Randolph or north in the Barre West Quadrangle (Wright, 1999a, b; 2010). The location of these terraces is exactly where one would expect a delta to occur and this seems a more likely interpretation.

By highlighting the internal sedimentary structures beneath these terraces a ground-penetrating-radar (GPR) survey might confirm their origin.

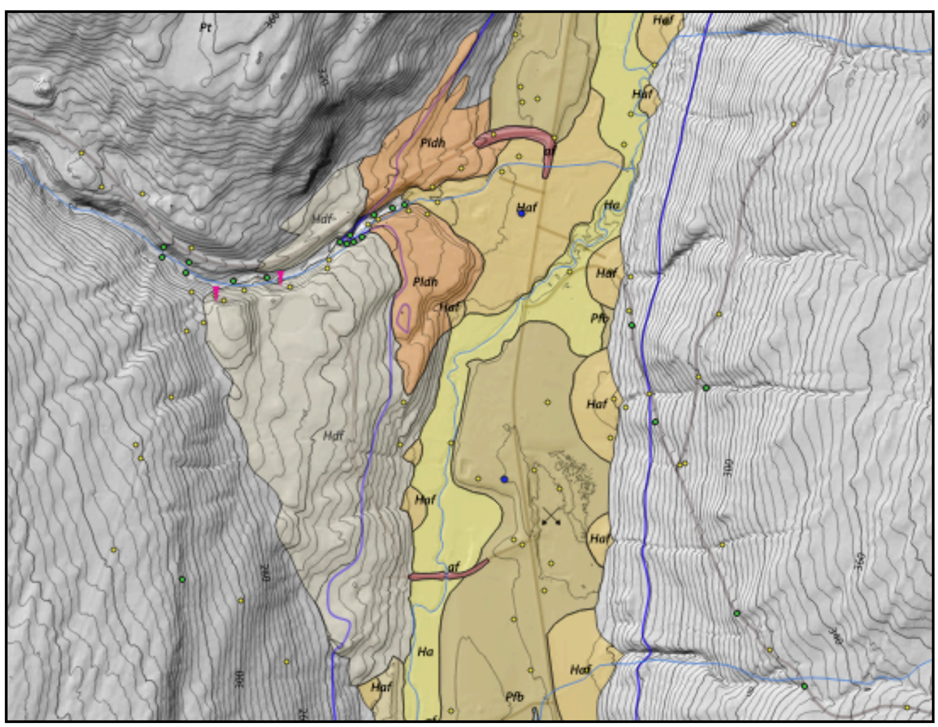


Figure 17: *Large debris fan (Hdf) has been deposited on and above a Glacial Lake Hitchcock delta (Pldh) above East Brookfield. The debris fan consists largely of glacial till that episodically slid down the Sunset Brook valley as a series of debris flows largely burying the earlier formed delta. Blue line shows the projected shoreline of Glacial lake Hitchcock.*

Remnants of other Glacial Lake Hitchcock deltas were mapped where tributary streams enter the Second Branch valley. Some have been largely buried by subsequent deposition of material on those deltas as alluvial fans or debris fans. A good example of this occurs above the confluence of Sunset Brook and the Second Branch in East Brookfield (Fig. 17).

In the Second Branch valley Glacial Lake Hitchcock expanded northward as the ice sheet retreated to the north. In addition to sediments transported by tributary streams, the bulk of the sediments deposited in the lake were transported by the same subglacial stream that deposited the esker. The subglacial stream exited the ice sheet at its base, well below the surface of Glacial Lake Hitchcock. Larger sediments being transported by that stream (sand/gravel) were deposited close to the mouth of the esker tunnel where that water slowed quickly. Finer sediments (silt/clay) remained in suspension and were transported much farther before settling in the quiet portions of the lake well away from the tunnel mouth. The same process occurred in Glacial Lake Winooski as the ice sheet retreated north of Williamstown Gulf. As the ice sheet retreated to the north, these depositional environments also migrated to the north. A consequence of this is that any one place in both valleys experienced a wide variety of depositional environments that changed relatively quickly with time. Consequently, a wide variety of glacial lake sediments (coarse sand/gravel deposited near the tunnel mouth to fine silt/clay deposited far from the ice margin) occur in close proximity in both the Second Branch and Stevens Branch valleys.

Most of the Second Branch valley-bottom is covered with elongate, low-amplitude mounds and terraces of very coarse gravel (Figs. 7, 18). Where exposed in a gravel pit ~3 km north of East Brookfield, the cobbles and boulders are imbricated (they dip to the north) indicating they were deposited by water currents moving from north to south (Fig. 18). A newly constructed manure pit on the Sprague farm shows that this gravel lies in abrupt contact with the underlying fine-grained glacial lake sediments (Fig. 19; Cross-section C-C’). The high-energy water flow necessary to transport this gravel is clear evidence that Glacial Lake Hitchcock had drained from the Second Branch valley before the gravel was deposited. The shape, distribution, and composition of these landforms suggest that they are bars deposited in a braided river system, a hypothesis first suggested by Larsen (1987), Larsen et al., 2003).

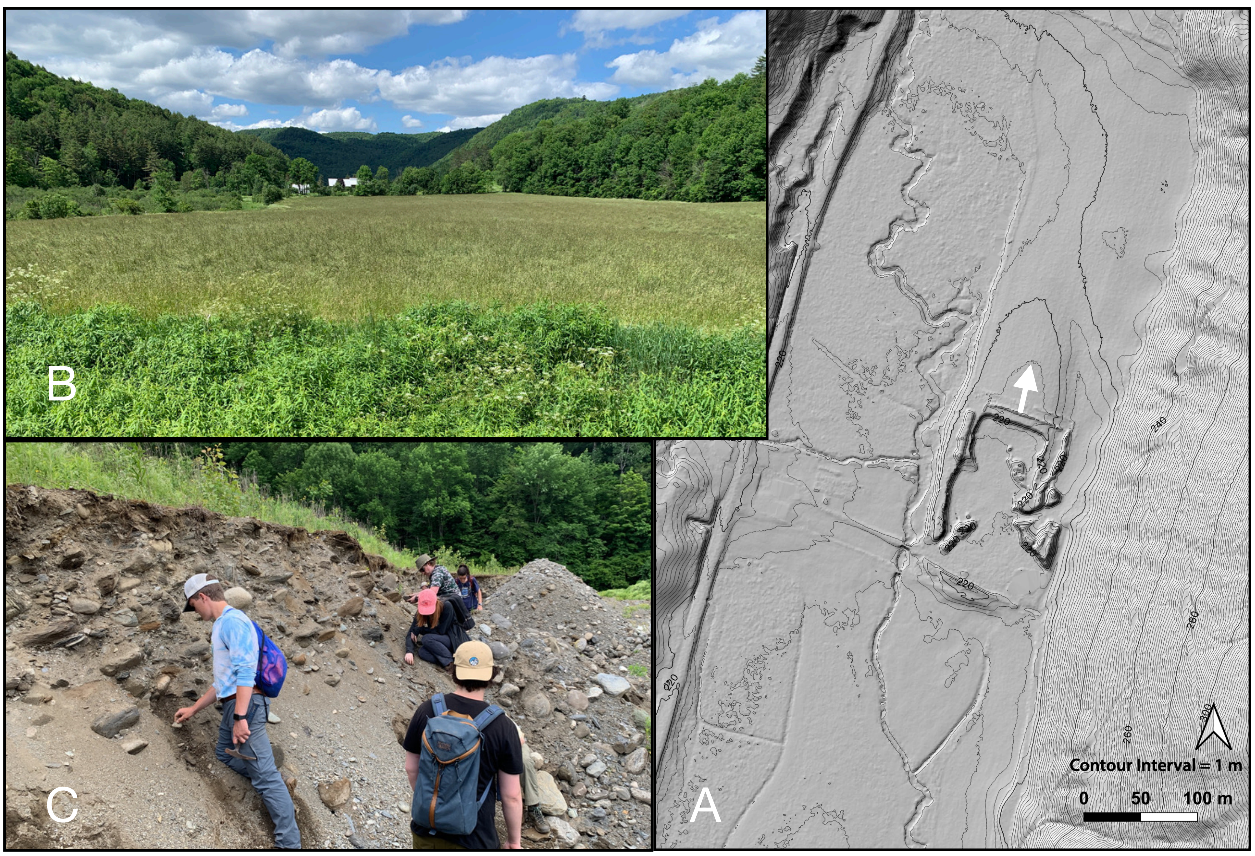


Figure 18: *(A) Shaded-relief LiDAR map (1 m contours) shows an elongate low-amplitude ridge (with large gravel pit) in the Second Branch valley approximately 3 km north of East Brookfield. (B) View north along the axis of the ridge (white arrow on map shows view angle). Coarse sand forms the matrix between imbricated cobbles and boulders along the north face of the pit. Imbrication indicates current flow was from north to south when this gravel was deposited.*

Figure 19: *Manure pit under construction at the Sprague Farm (East Brookfield) exposes the sharp contact between silt and clay deposited in Glacial Lake Hitchcock and the overlying coarse gravel. Contact has been smeared by construction. The high-energy water currents necessary to transport the gravel indicates that the lake had drained from the valley before the gravel was deposited. View looks south.*

The modern Second Branch of the White River is a very small discharge stream that flows in a very low gradient valley. Even in flood stage it lacks the competence to erode and transport the boulder/cobble gravel that comprises these bars. The most likely source of the coarse sand and gravel in these bars is the delta (Fig. 20). As soon as Glacial Lake Hitchcock drained from the Second Branch valley, outflow from Glacial Lake Winooski would have rapidly incised into the delta and distributed these sediments in a valley-wide braided river system (Fig. 20). As noted earlier, outflow from Glacial Lake Winooski consisted of both meteoric and glacial melt water gathered from a large geographic area. This outflow stream had discharges many orders of magnitude larger than the modern Second Branch of the White River, particularly during the summer melt season, and was capable transporting boulder-sized sediment and creating the myriad of bars and terraces preserved in the valley today.

The implication of this sequence of events is that Glacial Lake Winooski continued to exist after Glacial Lake Hitchcock drained or at least lowered sufficiently that its waters no longer flooded the upper Second Branch valley. The timing of this drainage event can be constrained by knowing when Glacial Lake Winooski existed, i.e. when, how long ago, it began and ended.

The best way to date Glacial Lake Winooski is by using distinctive annual layers of sediment deposited in the lake, glacial varves. Varves consist of couplets of sediment, most commonly silt layers and clay layers. In glacial lakes, both silt and clay-sized sediment are suspended in the water column and are dispersed throughout the lake by currents well away from where they enter the lake, typically from both surface streams flowing into the lake and especially from subglacial streams entering the lake. Consequently, the water in most glacial lakes is turbid (cloudy or muddy with suspended sediment) as opposed to clear. During the ice-free summer months wind-generated currents keep clay-sized sediment suspended in the water column, but the silt is large enough to settle to the bottom of the lake. Once the lake ices over, it's isolated from the wind, currents in the lake subside, and the clay

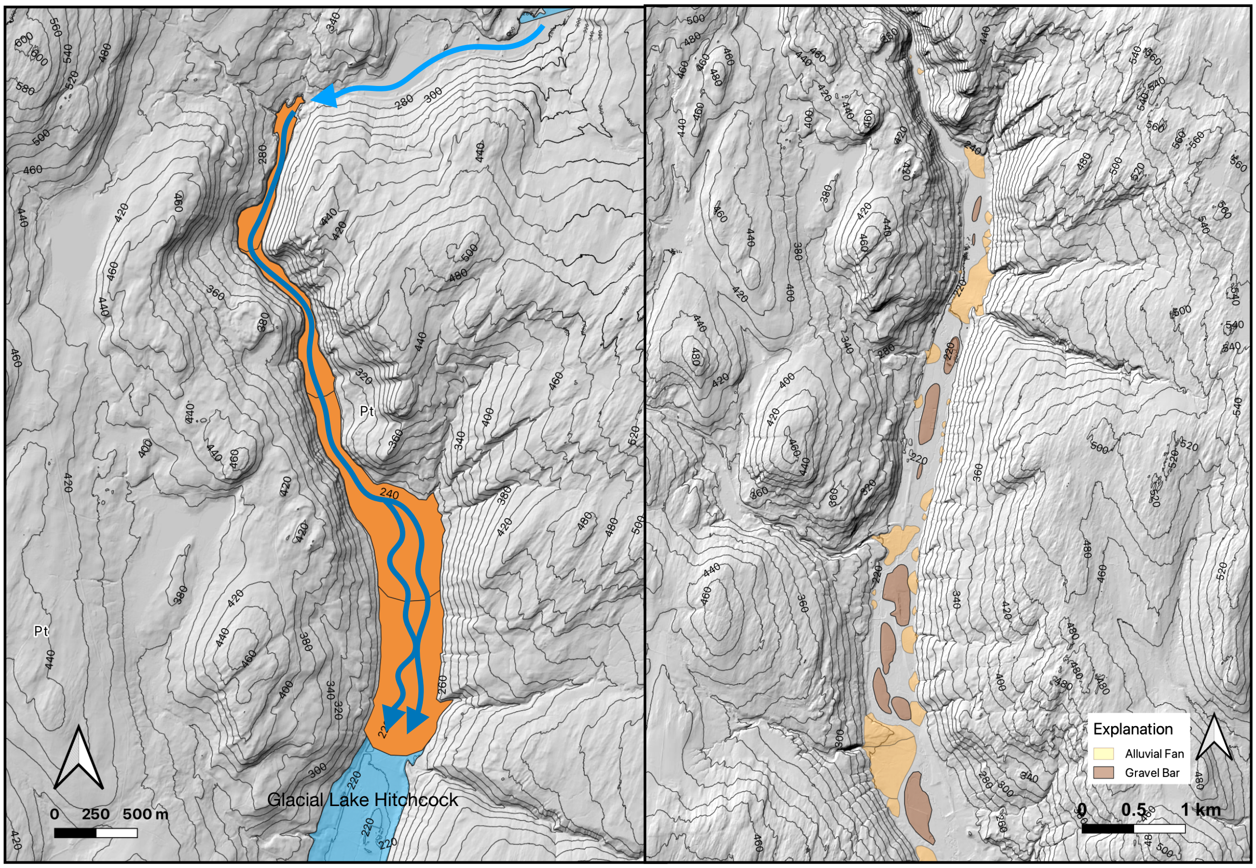
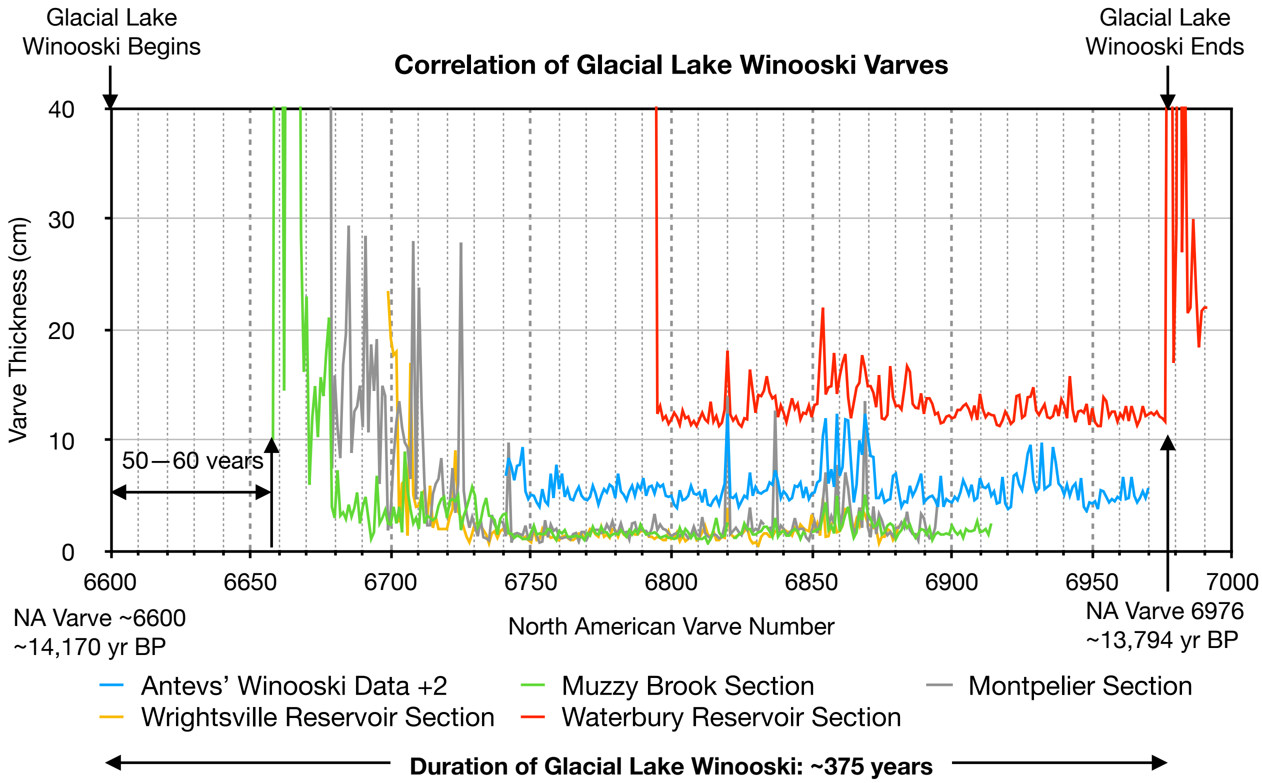


Figure 20: *Left-hand map shows the hypothesized full extent of the delta (orange) built into the northern end of Glacial Lake Hitchcock. Light blue arrow shows outflow stream from Glacial Lake Winooski and dark blue arrows show distributary channels flowing across the top of the delta. Right-hand map shows the distribution of landforms interpreted as gravel bars and younger alluvial fans in the Second Branch valley. Following drainage of Glacial Lake Hitchcock, the outflow from Glacial Lake Winooski eroded the earlier-formed delta and redistributed those sediments as bars and terraces (not shown) along the floor of the recently drained lake.*

sized sediment settles to the bottom. The process repeats year after year creating distinctive annual silt/clay layers. Similar to tree rings, these layers vary in thickness as a consequence of climate. In a relatively warm/wet year a lot of suspended sediment enters the lake and a relatively thick layers of silt is deposited during the summer months. During a relatively cold/dry year little suspended sediment enters the lake and a relatively thin layer of silt is deposited. Because the variations in climate that control varve thickness are regional, i.e. most of New England tends to experience a very similar climate, distinctive patterns of thin and thick varves are deposited both within the same lake and between different lakes in a region, e.g. both Glacial Lakes Hitchcock and Winooski.

The North American Varve Chronology is a year-by-year dated summation of variations in varve thickness largely compiled from the varve record preserved in Glacial Lake Hitchcock sediments up and down its length (Ridge et al., 2012). Antevs (1922) measured several sections of varved sediment deposited in Glacial Lake Winooski and his section has been correlated with the North American Varve Chronology (Ridge et al., 2012; Fig. 21, blue line). More recently, sections of Glacial Lake Winooski varves have been measured at the Waterbury Reservoir (Wright, in Larsen et al., 2003), Muzzy Brook (Larsen, unpublished data), Montpelier (Springston, unpublished data), and the Wrightsville Reservoir (Wright, unpublished data). Figure 21 correlates these different sections to the North American Varve Chronology.

The Waterbury Reservoir section (Fig. 21, red line) clearly records when Glacial Lake Winooski partially drained. An abrupt change from silt/clay varves to thick fine sand/silt layers occurs at North American Varve 6976 which was deposited ~13,794 yr BP. The increase in both grain size and layer thickness occurred when the ice dam in the Winooski Valley retreated far enough down-valley (WNW) for water in Glacial Lake Winooski to rapidly escape to the



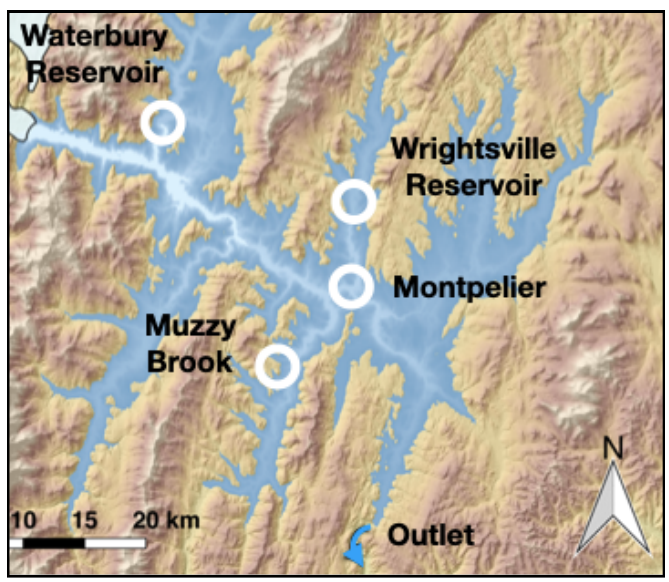


Figure 21: Varve correlation graph for four measured stratigraphic sections (see map at right for locations) and Antevs' Winooski Valley compilation (blue line) which has been correlated to the North American Varve Chronology (Ridge et al., 2012). Oldest and lowest part of each section is to the left (smaller North American Varve Number). Ice sheet retreat rates calculated from the Muzzy Brook, Montpelier, and Wrightsville Reservoir sections are ~300 m/year (Fig. 22). Based on this retreat rate, the ice sheet took ~50 years to retreat from the outlet of Glacial Lake Winooski to a position opposite Muzzy Brook in the Stevens Branch valley. Adding 50 to 60 years to the inception of sedimentation at Muzzy Brook indicates that Glacial Lake Winooski began ~NA Varve 6600 (~14,170 yr BP). The abrupt lowering of Glacial Lake Winooski occurs where sediment thickness abruptly thickens at the Waterbury Reservoir (red line) at NA Varve 6976 (~13,794 yr BP). Consequently, Glacial Lake Winooski lasted for ~375 years.

Champlain valley via a new outlet (the Hollow Brook valley) in Huntington, Vermont (Larsen, 1987; Larsen et al., 2003; Wright, 2018). The rapid drop in lake level associated with this breakout flood allowed much coarser sediment (derived from shore) to reach the site of the Waterbury Reservoir section.

The beginning of Glacial Lake Winooski is harder to date because no good sections of varved lake sediments have been found in the Stevens Branch valley, the valley hosting the lake during its earliest years. However, the varve records collected immediately northwest of the Stevens Branch allow a good estimate. All of the measured sections graphed in Figure 21 begin as soon as the ice sheet retreated north of these respective locations allowing sediments

Ice Margin Retreat Rates

		Distance (m)	Time (years)	Ice Retreat Rate (m/year)
A	**Muzzy Brook to Montpelier**	5,900	20	295
B	**Montpelier to Wrightsville Reservoir**	6,400	21	305
C	**Upper Connecticut River Valley (Ridge et al., 2012)**			300
D	**Estimated time for ice margin to retreat from Glacial Lake Winooski Outlet to Muzzy Brook if retreat rate was 300 m/year.**	15,000	50	300
E	**Estimated time for ice margin to retreat from Glacial Lake Winooski Outlet to Muzzy Brook if retreat rate was 250 m/year.**	15000	60	250

Figure 22: *(A,B) Calculated ice sheet retreat rates between Muzzy Brook and Montpelier and Montpelier and the Wrightsville Reservoir based on the time interval between the initiation of sedimentation at each site and the distance between these sites (Fig. 21). (C) Average ice sheet retreat rate in the upper Connecticut River valley (Ridge et al, 2012). (D,E) Calculated time necessary for the ice sheet to retreat from the outlet of Glacial Lake Winooski to a position in the Second Branch valley equivalent to Muzzy Brook based on a retreat rate of 300 m/year (D) and 250 m/year (E).*

to begin accumulating on the bottom of the lake. Each section begins with very thick varves deposited when the ice margin is very close. Varves thin and the sediment in those varves becomes finer over a span of 20 to 30 years as the ice sheet, the source of most of the sediment, retreats farther away. From the graph (Fig. 21) it's clear that sediments begin accumulating first at the southernmost section (Muzzy Brook, green line), begin next in Montpelier (grey line), and last at the northernmost section (Wrightsville Reservoir, orange line).

Ice margin retreat rates can be calculated between Muzzy Brook, Montpelier, and the Wrightsville Reservoir using the time interval between the start of sedimentation at each site and the distance between these sites (Fig. 22A,B). The calculated retreat rates between Muzzy Brook and Montpelier (295 m/year) and Montpelier and the Wrightsville Reservoir (305 m/year) are almost identical. Furthermore, Ridge and others (2012), using many more sections of varved lake sediments, calculate an identical retreat rate of ~300 m/year in the upper Connecticut River valley (the reach of the valley due east of the sections shown in Figure 21). If the ice retreated from the outlet of Glacial Lake Winooski to a position in the Second Branch valley equivalent to Muzzy Brook at 300 m/year it would have taken 50 years to retreat that distance (Fig. 22D). A similar calculation based on a more conservative retreat rate of 250 m/year increases the duration of that retreat to 60 years (Fig. 22E).

These calculations indicate that the ice margin retreated across the outlet of Glacial Lake Winooski 50 to 60 years before the ice retreated north of Muzzy Brook at North American Varve 6658 (~14,110 yr BP) putting the beginning of Glacial Lake Winooski at approximately North American Varve 6600 which corresponds to about 14,170 yr BP (Fig. 21). Therefore , Glacial Lake Winooski grew both north and west of its outlet for a span of ~375 years before the ice dam in the Winooski River valley retreated far enough west to uncover a lower outlet allowing water levels to fall and the outlet to be abandoned.

During the time Glacial Lake Winooski existed a substantial delta was deposited in Glacial Lake Hitchcock, the sediments of which were likely deposited by both the subglacial stream during ice retreat and the substantial stream flowing through Williamstown Gulf from the outlet of Glacial Lake Winooski (Fig. 20). Between ~14,170 and 13,794 yr BP the elevation of Glacial Lake Hitchcock lowered sufficiently to drain water from the Second Branch valley and the outlet stream from Glacial Lake Winooski eroded most of the delta and redeposited those coarse delta sediments in large gravel bars and terraces on top of fine-grained lake-bottom sediments. In the upper Connecticut River valley Ridge (1999) observed an abrupt increase in the thickness of Glacial Lake Hitchcock varves at Newbury, Vermont at 13,890 ±60 yr BP and suggested that this marked when the elevation of the lake lowered substantially. This time (North American Varve 6880) lies within the lifespan of Glacial Lake Winooski and may be the best estimate of when

Glacial Lake Hitchcock drained from the Second Branch valley and erosion of the delta and deposition of the gravel bars began.

Post-glacial History

The Holocene Epoch is the geologic period of time that generally encompasses Earth's history since the retreat of the ice sheets. That time epoch formally extends from 11,700 years ago to the present, but locally it's convenient to group those processes that have occurred since the ice receded from a particular area as being "post-glacial" a time interval that includes both the latest Pleistocene and the Holocene Epochs. In the Brookfield Quadrangle, the transition from full ice cover to fully ice-free extended across at least several hundred years, ~14,400 to ~14,100 years ago. Over these last ~14,000 years the landscape has changed considerably in response to an array of geologic processes augmented by changes in our climate and the populations of plants growing here. The post-glacial history of the Brookfield Quadrangle presented here is interpreted from the materials and landforms mapped within the quadrangle.

The most prominent landforms to form in the post-glacial period are alluvial fans. Virtually every tributary stream flowing down the steep hillsides along the Stevens Branch and Second Branch valleys has deposited an alluvial fan on the relatively flat valley bottom (Plate 1). The size of the alluvial fans is proportional to the size of the tributary stream. The largest alluvial fan in the valley lies above East Brookfield and was deposited by Sunset Brook (Fig. 17). Another large fan occurs at the mouth of an unnamed brook ~2 km south of East Brookfield (Figs 8, 23). As noted earlier, these fans have been active throughout the post-glacial period, albeit episodically (Bierman et al, 1997; Jennings et al. 2003; Noren et al, 2002). Erosion and subsequent sedimentation was likely rapid immediately following deglaciation when unvegetated till covered the hillslopes. Large storms, landslides, forest fires, and logging have also triggered sedimentation on alluvial fans.

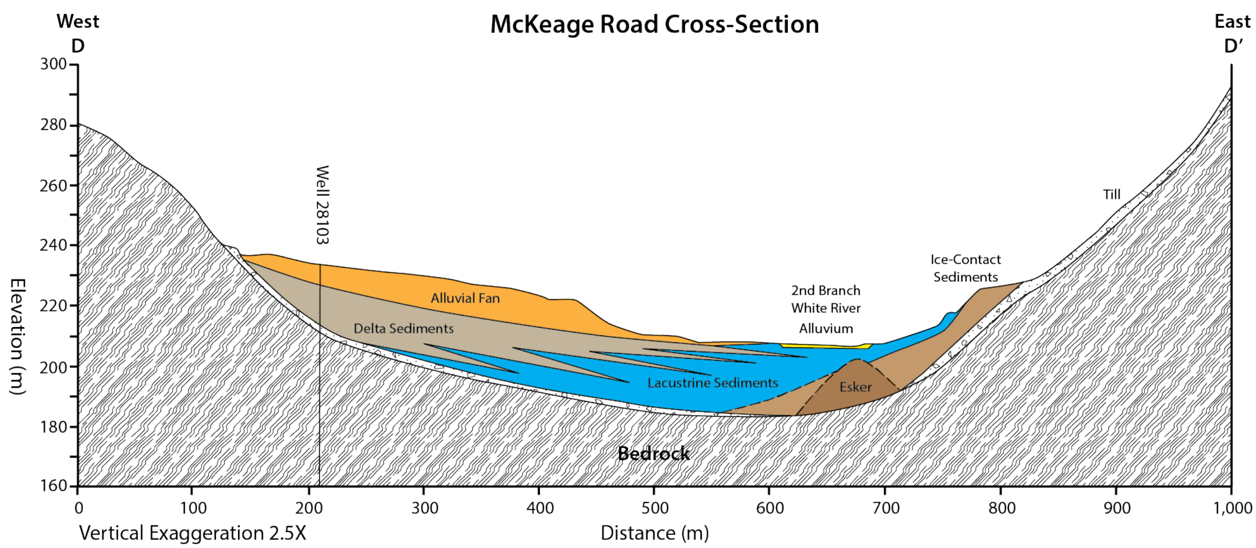


Figure 23: *Geologic Cross-section D-D' is drawn across the alluvial fan pictured in Figure 8 (see Plate 1 for exact location). The fan is interpreted to consist of both deltaic sediments, deposited when Glacial Lake Hitchcock occupied the valley, and alluvial fan sediments deposited on top of the delta both during and after the lake filled the valley. The deltaic sediments are shown inter fingering with lacustrine sediments (fine sand) which are in turn overlying older esker and ice-contact sediments.*

Across the Brookfield Quadrangle, both the Stevens Branch and the Second Branch rivers are small, low-gradient streams except for the short stretch through Williamstown Gulf. High-energy stream activity in the Second Branch valley, i.e. the braided river system, ended abruptly when Glacial Lake Winooski lowered and outflow water no longer entered Williamstown Gulf. At this point in time the Second Branch of the White River assumed its very low discharge from its relatively small drainage basin and its course has threaded between the earlier-deposited gravel bars and alluvial fans that have grown progressively larger throughout the Holocene (Fig. 20). Particularly in the upper part of the valley alluvial fans have largely dammed the Second Branch creating broad areas of wetlands (Fig. 24, Plate 1). In most other areas the extent of alluvium deposited by this stream is relatively small (Fig. 24, Plate 1).

The Stevens Branch north of Williamstown Gulf has similarly threaded its way between alluvial fans and older esker and ice-contact deposits (Plate 1). This stream are also dammed by alluvial fans creating extensive areas of wetland deposits. In neither valley were old channels mapped and abandoned alluvial terraces are rare. This indicates that in post-glacial times that (1) only minor downcutting through older sediments has occurred and (2) the stream channels have undergone only minor changes to their courses.

In addition to the wetland deposits associated with streams dammed by alluvial fans, abundant wetland deposits occur in low-lying areas, e.g. closed depressions, across the quadrangle. Many of these are small and many also border the open water of ponds. These wetland areas preserve an archive of sediments that have accumulated throughout post-glacial times. Detailed study of these sediments and the fossils occurring in them provides a way to understand many facets of the climate of this area and how that climate has changed during the last 14,000 years (Grigg, 2019).

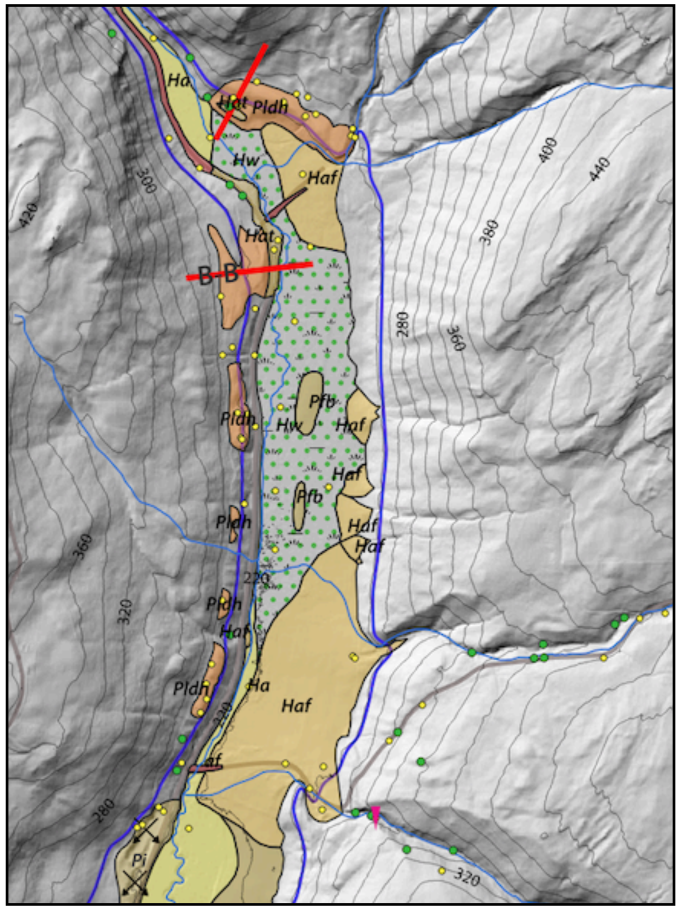


Figure 24: *A large area of wetlands (Hw) exists where the Second Branch is dammed by two large coalescing alluvial fans (Haf) deposited by tributary streams entering the valley from the east (Plate 1). Alluvium (Ha) borders the stream at the northern and southern boundaries of the map.*

Isopach Map of Surficial Materials (Overburden Thickness Map): Plate 3

The "Isopach Map of Surficial Materials" contours the thickness of surficial materials (overburden) within the quadrangle. The data used to generate this map are (1) mapped bedrock outcrops (Green dots, Plate 3) which indicate areas where surficial materials don't occur, (2) bedrock outcrops visible on the LiDAR shaded-relief imagery, and (3) records of overburden thickness from domestic water wells (Blue dots; Numbers indicate depth to bedrock, Plate 3). The well locations were not checked and errors, some significant misplacements of wells, occur which affect the accuracy of these contours. These data are contoured using 20, 50, and 100-foot contours. Contouring algorithms applied to the overburden thickness data produced geologically unrealistic contours, so these data were contoured by hand. In general, isolated wells reporting thick surficial materials were ignored, i.e. bullseyes were not drawn around these isolated wells.

Generally, areas of thick surficial materials are restricted to the Second Branch valley and to t lesser extent, the Stevens Branch valley neither of which expose any bedrock except in Williamstown Gulf (Plate 3; see also the geologic cross-sections presented on Plate 1 and described earlier in this report). The valleys have accumulated not only the till that's also present in the uplands, but all of the ice-contact (e.g. esker) and glacial lake sediments that accumulated as the ice sheet was retreating across this area. In many parts of these valleys sediment fill exceeds 100 feet indicating that preglacial erosion was substantial and the preglacial bedrock valleys are largely hidden by the glacial sediments that currently fill them.

Groundwater Hydrology of the Brookfield Quadrangle

Within the Brookfield Quadrangle, most homes utilize private wells for their drinking water supply. Surficial aquifers are utilized by some residents (shallow dug wells or deeper drilled wells in surficial materials), however drilled wells extending variable depths into bedrock are much more common.

Several different types of bedrock underlie the quadrangle (Fig. 2). While they differ in their mineralogy and texture, they are all metamorphic rocks and have no primary porosity, meaning there is no open space between the mineral grains in these rocks to store water. Consequently, groundwater in these rocks is located in fractures and any drilled well in bedrock gets its water from fractures intersected by that well. Generally, the volume of groundwater in fractured bedrock aquifers depends on the density of fractures but is typically less than 1% of the rock volume. On the other hand, most surficial materials have a lot of primary porosity, i.e. a high percentage of open space between individual sediment grains, typically 15–45% of the volume of the sediments. The usefulness of water in those pore spaces depends on how easily water can move through these surficial materials to reach a well, i.e. how permeable these sediments are. Generally, groundwater moves very slowly through fine-grained materials and much more quickly through coarse-grained materials.

The largest useful groundwater aquifers occurring in the quadrangle are found in the coarse-grained surficial materials (sand and gravel) where those materials extend below the water table. The largest surficial aquifer in the quadrangle consists of ice-contact sediments (eskers or subaqueous fans), particularly where the sand and gravel comprising these landforms lies buried beneath fine-grained glacial lake sediments (see geologic cross-sections presented on Plate 1 and earlier in this report). These sediments, while buried and only discoverable via drilling or geophysical work, are confined and consequently isolated from contamination from human and agricultural sources.

Water Table Contour Map with Flow Lines (Plate 2)

A map contouring the elevation of the water table is included with this report (Plate 2). The data used to construct these contours comes from the topographic map of the area and domestic water wells where the depth to the water table was recorded. Specifically, groundwater discharges to the surface in streams, ponds, lakes, and wetlands so these are areas where the elevation of the ground surface and the elevation of the water table are equal. In areas between these groundwater discharge points the water table is, by definition, at an elevation below the ground surface. Streams are common in the upland areas implying that even in these areas the water table is relatively close to the ground surface. For the groundwater wells, the water table elevation was calculated by taking the surface elevation of the well (garnered from the LiDAR DEM) and subtracting the depth to the static water table. Note: not all wells record the depth to the water table. The calculated water table elevation (in feet above sea level) is labeled adjacent to each well (Plate 2).

Drainage basin boundaries were downloaded from the VCGI database and denote both surface water and groundwater divides (Plate 2). As noted earlier, the major water basin divide in the area cuts east-west across the quadrangle and separates water flowing north and west into the Winooski River and eventually into Lake Champlain and onwards to the Gulf of St Lawrence from water flowing south and east into the White River and eventually into the Connecticut River and Long Island Sound. In this mountainous terrain the water table was contoured using a 500-foot contour interval (Plate 2). The elevation of the water table varies seasonally; it's generally highest in the early spring when groundwater is recharged by melting snow and rain and generally lowest at the end of the summer/early fall when the combination of lower summer rainfall and very high evapotranspiration rates from plants limits recharge. Consequently, water table contour lines on a map shift seasonally, moving up in the spring and down during the summer months. This is why many streams at higher elevations flow in the spring, but go dry during the summer.

Groundwater flows down-gradient (downhill) perpendicular to groundwater contour lines. Interpretive groundwater flow lines (arrows) are drawn on the map showing the approximate directions of groundwater flow across the area. In general, most of these flow lines begin in the upland areas and end at streams where groundwater discharges to the surface. The flow lines can be used to understand the pathways groundwater has taken to reach domestic water wells. The flow lines can also be used to interpret the different types of bedrock and surficial material groundwater has flowed through. These different types of rock and surficial material are the sources of all the naturally-occurring dissolved ions in groundwater. For groundwater contaminated with human/domestic animal waste or other toxic chemicals, the flow lines can be used to search areas up-gradient from the contaminated groundwater for potential sources. Note however that the detailed groundwater flow paths needed to show point sources of groundwater contamination cannot be deciphered from this map.

Well Yield Map (Plate 4)

The reported yields for private wells (gallons per minute) are generally measured during well construction and determine when drilling can cease. The Well Yield Map (Plate 4) scales the size of the well symbol to the well yield as well as displaying the measured well yield. Most private wells are constructed with casing that extends into the underlying bedrock ensuring that water flowing into the well is coming from the bedrock and not the overlying surficial materials. Of the 861 private wells shown on the map, 850 are bedrock wells; only 11 tap surficial aquifers (gravel wells). The map does not distinguish between these two well types.

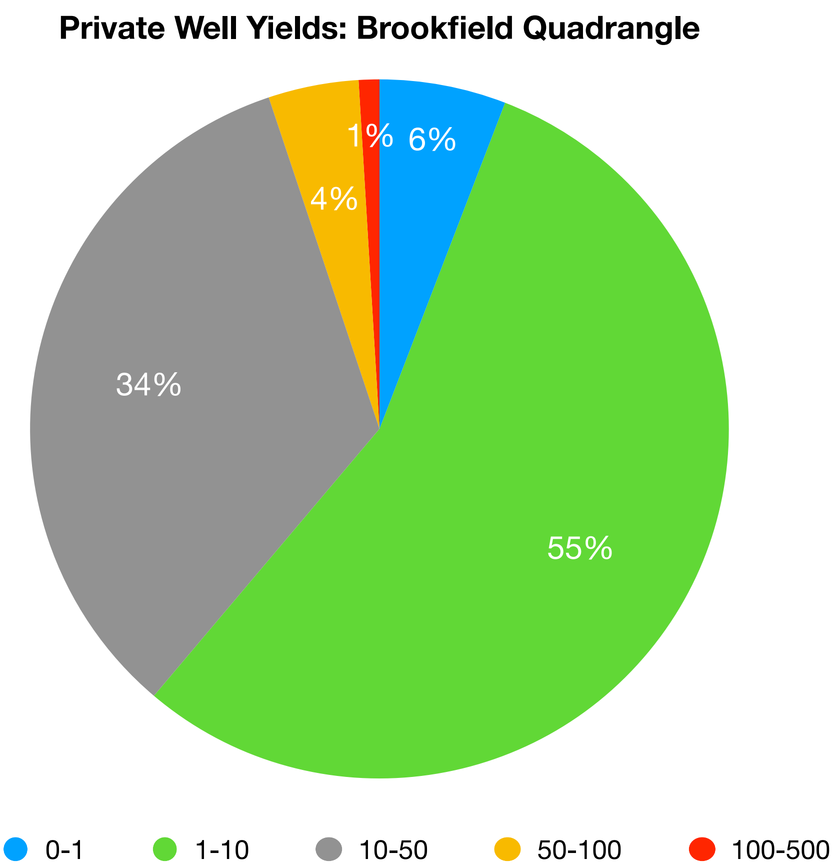


Figure 25: *Pie chart categorizes the yields of private wells within the Brookfield Quadrangle (n = 861 wells). Almost 90% of drilled wells in the area have yields between 1 and 50 gallons per minute (gpm), more than sufficient for most private dwellings.*

Figure 25 categorizes well yields from private wells within the quadrangle. Relatively few (6%) have yields of less than 1 gallon per minute (gpm). Most have significantly higher yields indicating that groundwater in the underlying rocks is both available and flows with some ease to drilled wells. As noted earlier, the metamorphic rocks underlying this area have no primary porosity and water occurring in these rocks occupies fractures that have formed when the rocks were brittle, well after they were deformed during the Acadian Orogeny. The very high-yield wells likely intersect rock that is highly fractured and that increased fracture density most commonly results from faults or closely spaced joint sets.

<u>Recharge Potential to Surficial Materials Map (Plate 5)</u>

Groundwater recharge depends on (1) how easily rainfall and snow melt can infiltrate the ground surface, (2) the rate at which water can move through the surficial material or rock it infiltrates into—its permeability, (3) the amount of time that water is available to enter different groundwater systems. Infiltration is enhanced when the ground surface is permeable and rainfall and snow melt can linger on the ground surface. Coarse-grained surficial materials on level ground provide the best infiltration whereas steep bedrock surfaces surfaces covered with impermeable materials, e.g. asphalt, provide the worst. Vegetation, burrowing animals, and frost heaving usually enhances infiltration by increasing the permeability of soils and providing a myriad of small depressions where surface water can linger and infiltrate. Fine-grained surficial materials usually have a low permeability. Even if vegetation allows water to infiltrate, the rate at which it can percolate (seep) through the material may be far slower than the rate at which new water from rainfall or snow melt is available. However, fine-grained materials with low permeability, e.g. many tills and lacustrine sediments, a significant amount of water can move though these materials if enough time is available.

The recharge potential map included with this report groups surficial materials into 1) those with high porosity and high to moderately high permeabilities and 2) those with low permeabilities.

High Recharge Potential to Surficial and Bedrock Aquifers
Alluvium, alluvial Fan sediments, fluvial Terrace sediments, ice-contact sediments, deltaic sediments, and wetlands are all materials that readily absorb surface water. They all consist of coarse-grained surficial materials and lie in valleys where slopes are gentle. Where these materials overlie moderate- to low-permeability materials, e.g. till, they have the capacity of soak up surface water allowing it to slowly seep into these underlying surficial materials. With the exception of the wetlands areas, these materials make excellent surficial aquifers where they extend below the water table. Wetlands uniquely serve as good recharge sites because they occur in closed depressions where surface water collects. Even if the surficial materials underlying wetland have a low permeability, they will have a near constant flow of well-filtered surface water through them into the underlying groundwater system.

Low to Moderate Recharge Potential to Surficial and Bedrock Aquifers
Lacustrine very fine/fine sand, silt, most till, and artificial fill (commonly covered with pavement) all have moderate to low permeabilities. Till mantles most upland areas and usually directly overlies bedrock, so till itself is the surficial aquifer that's being recharged. As noted earlier, animals, vegetation, and frost heaving enhance near surface infiltration and dug wells utilizing groundwater from till are common. Lacustrine fine sand, silt, and clay occurs in the valley bottoms where slopes are gentle which enhances its ability to absorb water. Slow movement of water through these materials can recharge coarse-grained surficial aquifer materials or bedrock, albeit slowly.

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