<u>Grant</u> EPA/LCBP 2019 TMDL Implementation

<u>Final Report:</u>

How Does Groundwater from the Fractured Bedrock and Surficial Aquifers Affect Nutrient Levels (i.e., Phosphorus and Nitrate) in Surface Waters from the Lake Carmi Watershed?

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ABSTRACT

In 2020, the Environmental Protection Agency (EPA) and Lake Champlain Basin Program (LCBP) awarded a 2019 TMDL Implementation Grant to the Vermont Geological Survey to investigate the role that groundwater from the bedrock and surficial aquifers plays in phosphorus levels in surface water (tributaries and the lake) from the Lake Carmi Watershed. Lake Carmi is a small (~1400 acre and shallow (maximum depth = 33') eutrophic lake in northern Vermont that has had severe cyanobacteria blooms over decades from phosphorus (P) input. The purposes of this study are to first resolve whether the source(s) of nutrients such as phosphorus and nitrate reaching to Lake Carmi likely are: 1) surface water, 2) groundwater or 3) groundwater - surface water interaction and, secondly, to determine the spatial variation in these sources in the watershed and potential sources. This study has physical and chemical hydrogeology parts.

The **physical** hydrogeology part of the study consists of bedrock geologic mapping; surficial geologic mapping; the spatial analysis of well driller's reports/logs to construct derivative hydrogeologic maps (isopach, bedrock surface contour, and static water level (potentiometric surface) maps for the Lake Carmi Watershed area. The ***chemical*** hydrogeology part is comprised of sampling and analyzing the groundwater from shallow (surficial) and deep (bedrock) wells surrounding Lake Carmi and the surface water from tributaries and the lake for major and trace element chemistry, stable isotopes (deuterium and ^{18}O), and groundwater recharge-ages (tritium; CFC-11, 12, 113; and SF_6). The compilation of physical hydrogeology maps generates a 3-D geologic framework in which to integrate the chemical hydrogeology portion and produce a conceptual site model for phosphorous and nitrate and other chemical tracers.

Some major points from the conceptual site model include: 1) Groundwater from the surficial and bedrock aquifers and surface water from tributaries flows from the surrounding highlands toward the Lake Carmi basin; 2) Groundwater from the bedrock and surficial aquifers and surface water can interact and mix on the way to or at the lake; 3) Bedrock islands in Lake Carmi show the same structures as the surrounding rock formations and may connect the bedrock aquifer to the lake; 4) Groundwater from the bedrock and surficial aquifers average ~10 ppb and ~20 ppb P, respectively- a separate study of monitoring wells installed around Lake Carmi yields average P levels of ~50 ppb; 5) The chemistry of groundwater from the surficial and bedrock aquifers is consistent with that of the surficial deposits and bedrock formations, indicating a natural component of P; 6) Surface water from Lake Carmi tributaries has the highest average P (~85 ppb), but a significant component of this is likely groundwater from baseflow during the 2020-2021 drought, 7) With the exception of groundwater from one well, no other shallow or deep wells exceeded either chloride (250 ppm) or nitrate (10 ppm) drinking water standards. All other groundwater and surface water samples had low nitrate (<1.5 ppm) and chloride (<20 ppm), suggesting that input from anthropogenic contamination sources is currently low.

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1. Introduction

Lake Carmi (the Lake) is a small (~1400 acre, 568 hectare) and relatively shallow (maximum depth = 33 ft, 11 m) eutrophic lake in northern Vermont that has had severe cyanobacteria blooms over decades from excessive phosphorus (P) input (**Figure 1**) (e.g. VTANR, 2008; Gearhardt, 2018). Lake Carmi has a small (~7700 acres, 3117 hectare) watershed that is comprised primarily of both tilled and untilled farmland from dairy farms (44 %) and woods or wetland (45 %). For decades, elevated P levels in Lake Carmi have contributed to summer algae blooms and resultant reductions in water clarity. Since the mid-1970s, algae blooms, which occur during the summer months, have contained significant cyanobacteria. Because of the deterioration in water quality in Lake Carmi from increasing nutrient levels and algae blooms that increase in frequency seasonally, a Total Maximum Daily Load (TMDL) was established in 2008 for P levels (e.g., VTANR, 2008; Gearhardt, 2018) that seeks to reduce its input into the lake, so that P concentrations will attain 22 parts/billion (ppb) in the lake. Average annual P concentrations in the lake were 28 ppb, prior to the TMDL establishment. Following the establishment of the TMDL, an alliance of local citizens and officials, farmers, non-government organizations and state and federal agencies collaborated to reduce the influx of P to Lake Carmi (VTANR, 2008; Gearhardt, 2018; State of Vermont, 2020). Specific tasks were undertaken to reduce the P input to Lake Carmi, such as the implementation of agricultural best management practices, protection efforts for shoreland, and stormwater runoff control (State of Vermont, 2020).

Phosphorus loading to Lake Carmi is thought to occur from external anthropogenic sources within the watershed, such as agricultural practices and stormwater runoff from impervious surfaces, and also from internal sources, such as from lake bottom sediments that release P to lake water during spring turnover (VTANR, 2008; Gearhardt, 2018; State of Vermont, 2020). From 2015-2017, moderate to high P concentrations were found in 5/19 tributaries that flow into Lake Carmi (Gearhardt, 2018). Although groundwater is currently not thought to play a role in the transport of P to Lake Carmi, recent publications suggest that it should not be overlooked (e.g., Brookfield et al., 2021; Safaie et al., 2021)

1.1 Phosphorus and Groundwater

Domagalski and Johnson (2012) summarize that: 1) the source of P in natural environments can be derived from the breakdown of P-bearing minerals (e.g. apatite, fluoroapatite, monazite, and autunite, (Reimann and de Caritat, 1998)) in the bedrock and overlying soils/surficial materials; this P is utilized for plant growth and is returned to the soil through animal feces or the breakdown of animal or plant remains, 2) P can be added to soils by agricultural nutrient management practices, which include the spreading of industrial fertilizer and manure, 3) Once soils exceed their limited ability to adsorb P, the excess P will mobilize to a stream through surface water runoff or eluviate downward to groundwater in the surficial and/or bedrock aquifer, 4) Once the P reaches streams or lakes, it can contribute to algae growth and eutrophication, which starve water bodies of oxygen and lead to eutrophication.

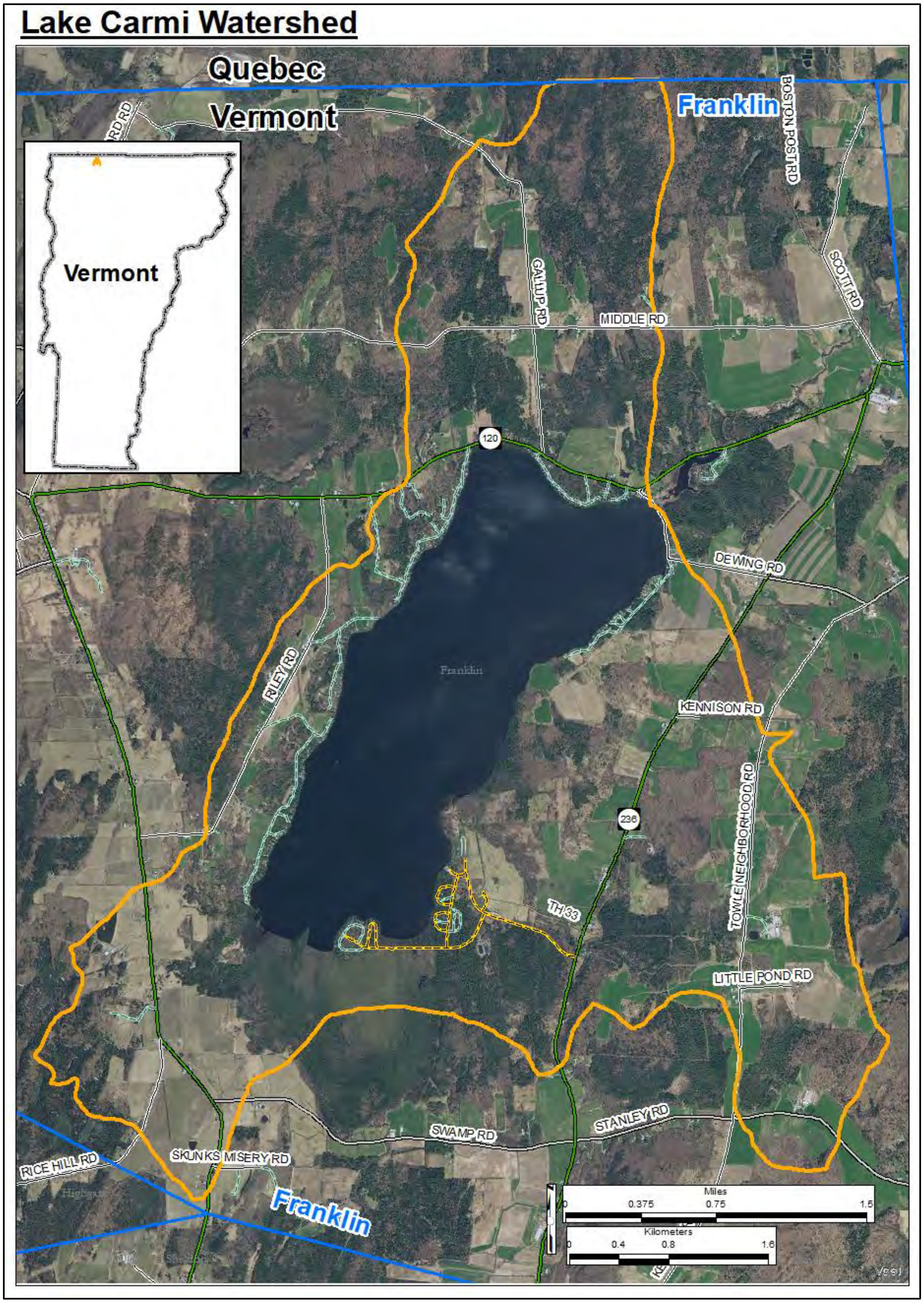


Figure 1- Lake Carmi Watershed base map.

Meinkmann et al. (2013; 2015) suggest that lake eutrophication and cyanobacteria blooms are mainly correlated with P that is delivered by overland flow, in particulate or dissolved form. The role that lacustrine groundwater discharge (LCD) plays in nutrient transport to lakes is frequently overlooked because it is difficult to quantify and because naturally-occurring, dissolved P is thought to be A) immobile in groundwater and B) adsorbed into the soil/sediment matrix in the saturated zone. Significant findings from Meinkmann et al. (2013; 2015) on a German lake indicate that groundwater may carry significant nutrient loads (up to 50 % of the total P) and that these loads may enter the lake along specific segments of the shoreline. Determining the spatial distribution of P in lacustrine groundwater discharge was crucial to understanding the total P balance in this lake. The possible contamination of groundwater by wastewater and/or agricultural practices that flows to a lake is also important, in addition to natural sources of P. The determination of P concentrations in groundwater from domestic and monitoring wells surrounding a lake is necessary to map the spatial influx of P from groundwater sources and discriminate them from surface water sources.

As summarized by Alley et al. (2002), groundwater and surface water constitute a system that needs to be studied holistically. Groundwater may enter a stream from the underlying surficial or bedrock aquifers and increase its flow (gaining stream) and/or surface water may leak from a stream into the underlying aquifer(s) (losing stream). Since cyanobacteria blooms in lakes are strongly influenced by P and possibly nitrate in the water column, it is important to know whether groundwater, surface water, or both are responsible for the transport of nutrients from their respective source areas.

Existing studies suggest that the sources of P to Lake Carmi are external, dominantly agricultural and runoff from impervious sources that are delivered via surface water, and internal, derived from lake sediments (e.g., VTANR, 2008; Gearhardt, 2018; State of Vermont, 2020). Loewald (2020; 2021), Kim et al. (2022), and Memeger (2022) suggest that other external sources of P also be considered, such as natural sources of P from bedrock and surficial materials, and other shoreline development sources (septic systems). The purposes of this study are to first resolve whether the source(s) of nutrients such as P and nitrate reaching to Lake Carmi likely are: 1) surface water, 2) groundwater or 3) groundwater - surface water interaction and, secondly, to determine the spatial variation in these sources in the watershed and potential sources. This study has physical and chemical hydrogeology parts, which will be integrated to construct a conceptual site model.

The ***physical*** hydrogeology part of the study consists of bedrock mapping; surficial mapping; the spatial analysis of well driller's reports/logs to construct derivative hydrogeologic maps (isopach, bedrock surface contour, and static water level (potentiometric surface) maps for the Lake Carmi Watershed area (Figure 1). The ***chemical*** hydrogeology part is comprised of sampling and analyzing the groundwater from shallow (surficial) and deep (bedrock) wells surrounding Lake Carmi and the surface water from tributaries and the lake for major and trace element chemistry, stable isotopes (deuterium and ^{18}O), and groundwater recharge-ages (tritium; CFC-11, 12, 113; and SF6). The physical hydrogeology portion results in the construction of a 3-D geologic framework in which to integrate the chemical hydrogeology portion and ultimately produce a conceptual site model for phosphorous and other chemical tracers. A temporal component can be derived from the groundwater recharge ages.

2.0 Major Activity Summary and Methods

The following is general summary of major activities for this LCBP/EPA 2019 Lake Champlain TMDL Implementation Grant, which was awarded to the Vermont Geological Survey in January 2020:

1) Development of a Quality Assurance Performance Plan (QAPP), which was approved on September 8, 2020,
2) Field work tasks began in the fall of 2020 and continued during the summer and fall of 2021. As described in semi-annual progress reports, Covid-19 restrictions, staff shortages, and other factors hindered progress and delayed the completion of field work by one year.
3) Preparation of Separate Outputs (submitted with #4)
    A) 3-D geological framework for the Lake Carmi watershed.
    B) GIS maps that show the spatial distribution of chemical parameters (including P and nitrate) in groundwater and surface water throughout the watershed.
    C) A Conceptual Site Model (CSM) that integrates the 3-D framework with the chemical data.
4) A final report documenting major activities conducted, and outputs and outcomes achieved by June 30, 2022.

3.0 Results of Major Activities

3.1 Physical Hydrogeology

3.1.1 Bedrock Geology (Task A)

The bedrock geology of the Lake Carmi Watershed is predominantly Precambrian metamorphic rocks of the Fairfield Pond and Pinnacle formations, with small areas of the early Cambrian Cheshire Formation to the west; all of these rocks are phyllitic ("shaly") quartzites **(Figure 2)**. These rocks comprise the bedrock aquifer. Mapping by Dennis (1964) and this study show that the dominant foliation ("layering") is moderately to steeply east dipping, as shown by the cross sections A-A' and B-B' in **Figure 3**. The locations for these cross sections are shown on **Figure 2**. The folding that influenced these formations occurred during the Taconian (Ordovician) and Acadian (Devonian) mountain-building events (orogenies).

The long axis of Lake Carmi is exactly parallel to strike of the dominant foliation described above and formed a zone of weakness for erosion and excavation by the latest Pleistocene glaciation (Wisconsin). The bedrock geologic map (**Figure 2**) also shows a topographic "grain" that is parallel to this foliation, particularly on the west side of Lake Carmi. The foliation and fracture data are plotted on the rose diagram and equal area stereonet in **Figure 4**. The dominant foliation is shown as a NNE-striking pink petal on the rose diagram and as a pink field (moderately to steeply east-dipping) on the equal area net. Fractures that were measured in this study are shown as black petals on the rose diagram and as gray and black fields on the equal area net (**Figure 4**). The dominant fracture set strikes WNW, dips steeply, and is ~perpendicular to the dominant foliation, and explains the orientations of the north and south coastlines of Lake Carmi.

In addition to the fact that bedrock structures control the shape of Lake Carmi, they likely also act as pathways for groundwater to flow in the bedrock aquifer. The chemical composition of the host bedrock aquifer strongly influences the chemistry of groundwater, which will be shown in the Chemical Hydrogeology section.

3.1.2 Surficial Geology (Task B)

Stephen Wright (University of Vermont) was contracted to map the surficial geology of the Lake Carmi Watershed (Wright, 2021). The effective porosity and permeability of surficial deposits determine how readily rainfall, surface water (and nutrients such as phosphorus or nitrate) infiltrate downward from the ground surface through the vadose zone to the saturated zone/surficial aquifer and on to the bedrock aquifer below. The distribution and thicknesses of the surficial geologic units (and soils) influence the pathway(s) that nutrients take to the surficial and bedrock aquifers.

Wright (2021) determined that the most abundant surficial materials in the Lake Carmi Watershed are glacial till and stratified diamict (**Figure 5**), which is till that was eroded and redeposited in glacial water bodies, such as Lake Vermont and the Champlain Sea, and interlayered with deposits from these fresh and marine water bodies, respectively. The glacial till and stratified diamict deposits were judged by Wright (2021) to be relatively impermeable to downward percolating surface water or groundwater overall, but may be more permeable at the ground surface where disrupted by physical processes (i.e., frost heaving, roots, and burrowing. The minor alluvial deposits with relatively high permeability are isolated to one location in the Lake Carmi Watershed.

Cross sections by Wright (2021) (**Figure 6**) show surficial deposits that vary greatly in thickness (primarily stratified diamict and till) from ~0-65 ft (20 m) at the northern end of Lake Carmi. These thick surficial deposits could be a host for persistent surficial aquifers.

3.1.3 Well Driller Reports (Task C)

The critical third dimension of the Lake Carmi Watershed was determined through the analysis of well driller reports from the State of Vermont database. These reports are correlated with Global Positioning System (GPS) or Enhanced 911 Address (E911) well locations, so that information such as well depth, overburden thickness, well yield, casing depth, and static water level can be mapped across the Lake Carmi Watershed using Geographic Information System (GIS) software. See **Figure 7** for the locations of wells (and bedrock outcrops) used to make maps in this study. This type of GIS well report analysis was used to generate the surficial geology cross sections in **Figure 6** and were used to produce the general hydrogeologic maps, such as isopach, bedrock surface contour, and static water level maps provided in the following sections.

3.1.4 General Hydrogeologic Maps (Task D)

3.1.4.1 Isopach Map

Isopach maps, which are constructed in GIS from the "depth to bedrock" data in well driller reports, indicate the thickness of overburden throughout the Lake Carmi Watershed area as contoured surfaces. Isopach maps complement the surficial geologic maps and cross sections prepared by Wright (2021) and are important for delineating zones where surficial aquifers may be located and where nutrients could take longer to infiltrate downward through the surficial deposits. An important observation from the surficial geologic isopach map (**Figure 8**) is that the thickness of overburden is much greater on the NNE end of Lake Carmi, ranging from 20-80 ft (6-24 m), making this general part of the study area more favorable for a persistent surficial aquifer(s). Surficial deposits at the southern end of the lake might also be favorable, however the exact thickness of deposits there is less certain due to sparse wells.

3.1.4.2 Bedrock Surface Contour Map

Bedrock surface contour maps are constructed from the "depth to bedrock" indicated in well completion reports and ground surface elevation data from airborne Light Detection and Ranging (LiDAR) surveys. The bedrock surface contour map provided as **Figure 9** shows the geometry (shape) of the bedrock surface, which is controlled by bedrock structures including foliations and fractures as described in Section 3.1.1. The bedrock surface makes a strong permeability contrast with the overlying surficial materials and groundwater may flow along this surface towards Lake Carmi. In addition, these maps may show underlying channels in the bedrock that predated the last glaciation and may influence groundwater flow. **Figure 9** shows that A) Lake Carmi lies in a bedrock-floored basin and that surface water and groundwater would be expected to flow towards this basin, and B) the low-elevation areas to the north and south of the Lake Carmi bedrock basin likely are pre-glacial bedrock channels that were later filled in with thick surficial deposits during the Pleistocene and Holocene.

3.1.4.3 Static Water Level Map

In order to determine the general directions that groundwater flows in an aquifer, static water-level (potentiometric surface) contour maps were made in GIS from the static water level ("water table") data contained in driller's logs coupled with LiDAR ground surface elevations. By taking the static water level for each well location and referencing it to its elevation above sea level, the static water level was contoured for all wells in the Lake Carmi Watershed area. Because the vast majority of wells in this area are bedrock wells, only a static water-level contour map of the bedrock aquifer was constructed in GIS. Groundwater flows from higher static water-level elevation toward lower static water-level elevations; as indicated in **Figure 10**, it is apparent that, at the scale of this map, groundwater in the bedrock aquifer flows towards the Lake Carmi basin from the highlands in all directions.

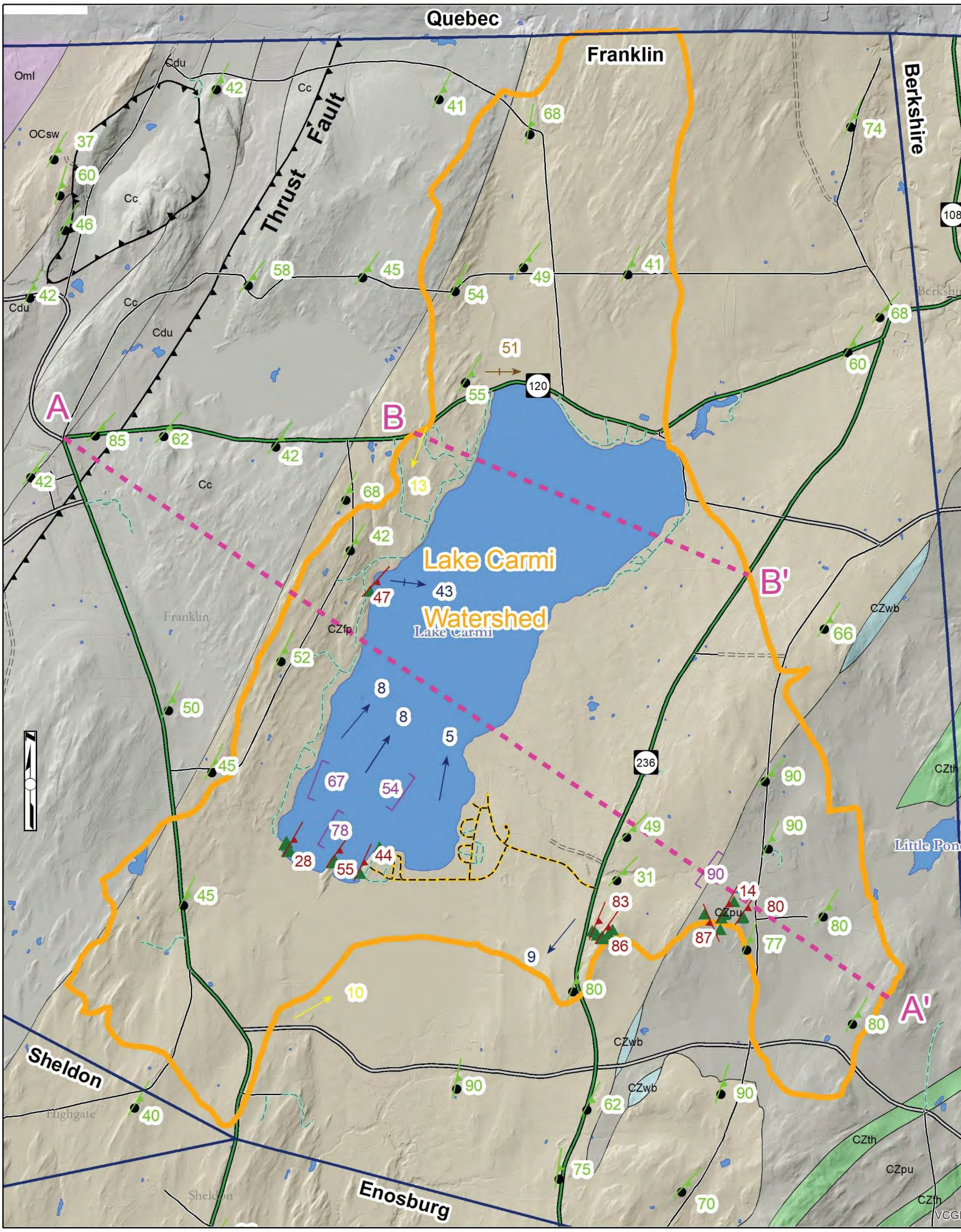


Figure 2- Bedrock geologic map of the Lake Carmi Watershed area modified from Ratcliffe et al. (2011) with structural data from this study and from Dennis (1964). See cross sections in Figure 3.

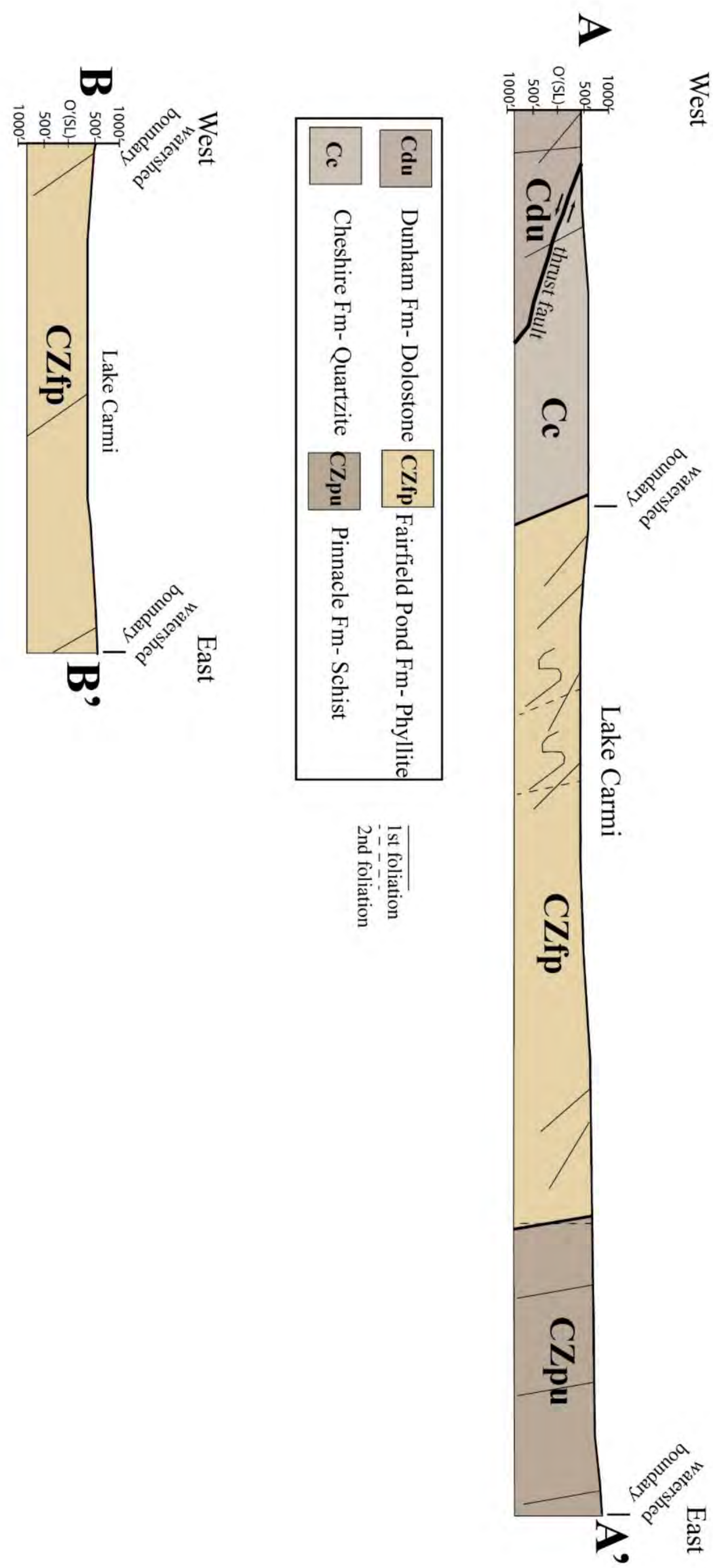


Figure 3- Cross sections A - A' and B - B' . See Figure 2 for locations.

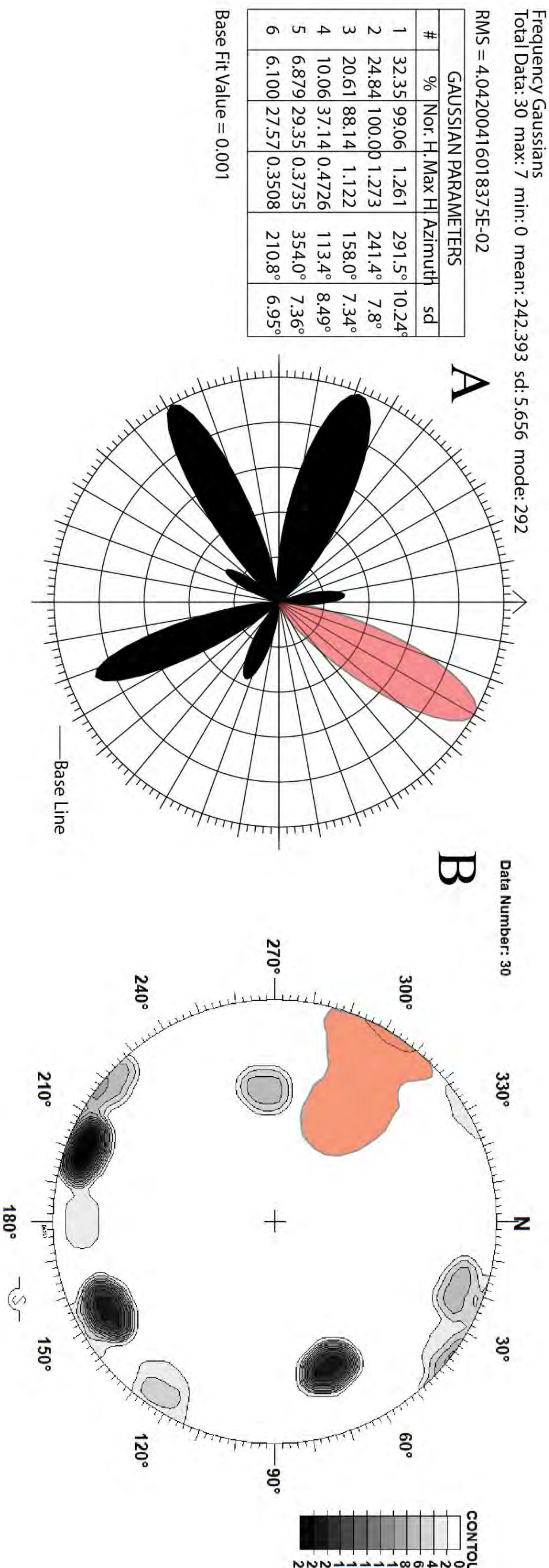


Figure 4- Fractures (black and gray) from this study and foliations (light red) from this study and Dennis (1964) plotted on rose diagram and equal area net (Salvini et al., 1999) See text for explanation.

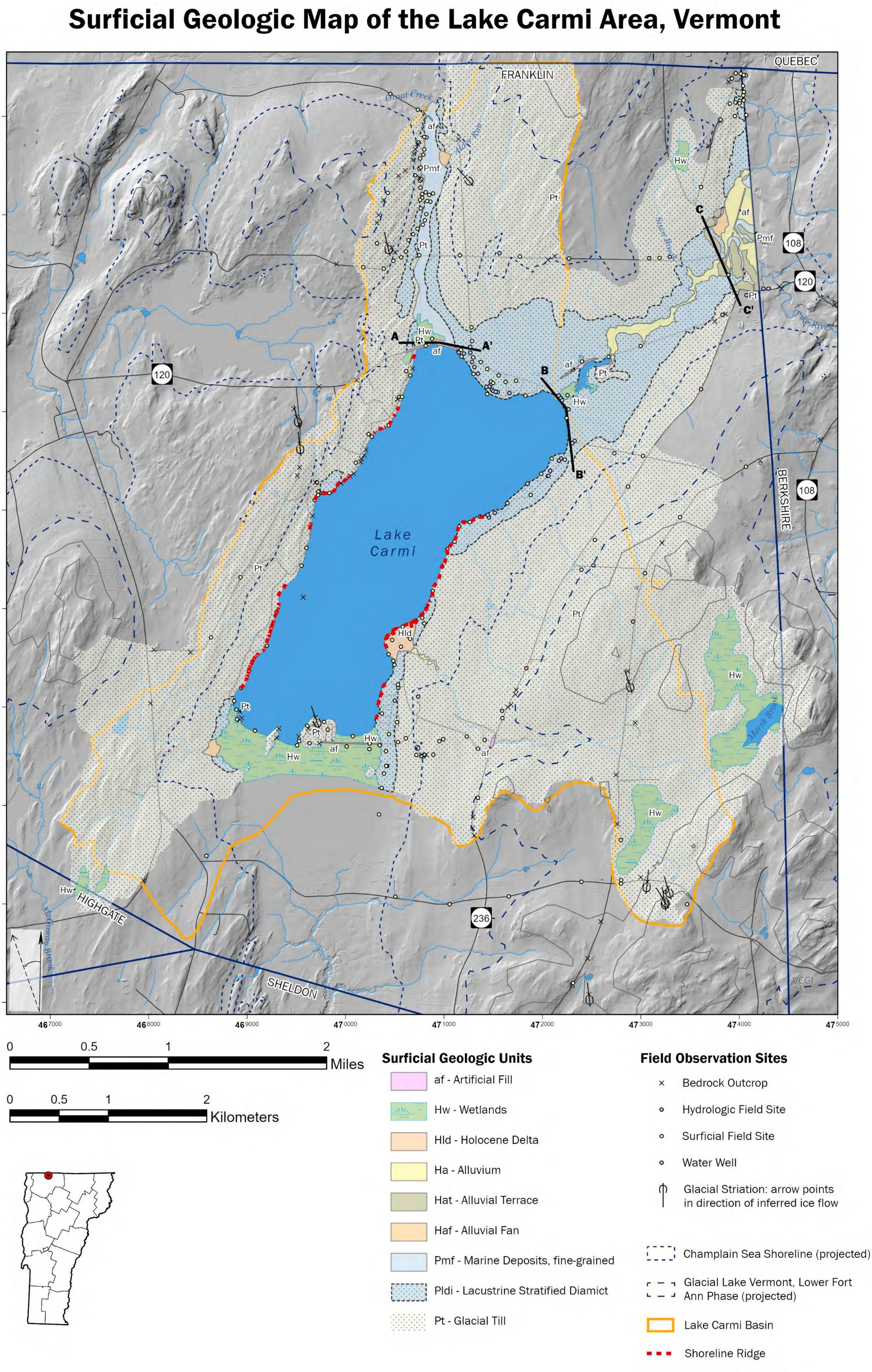
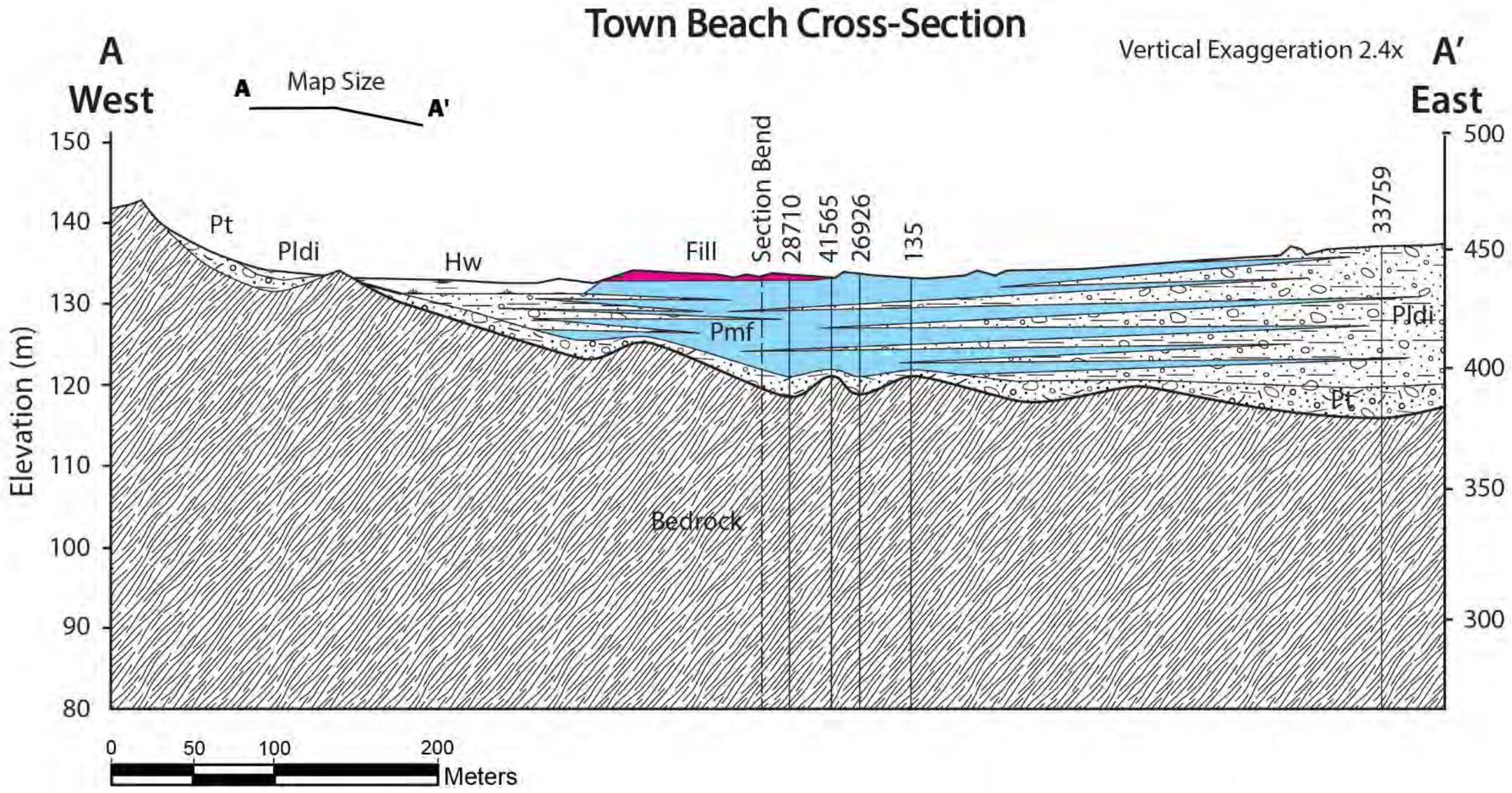
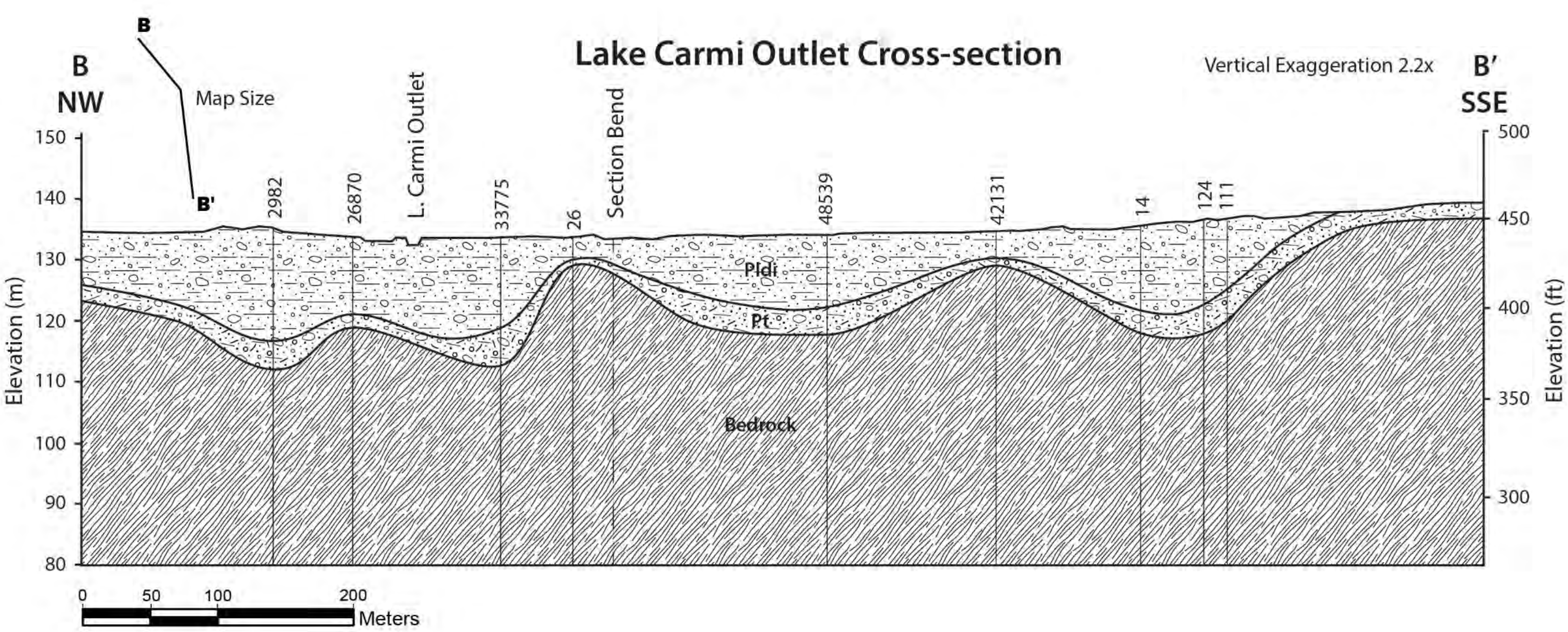


Figure 5- Surficial geologic map of the Lake Carmi area modified from Wright (2021).

Surficial Geologic Cross Sections





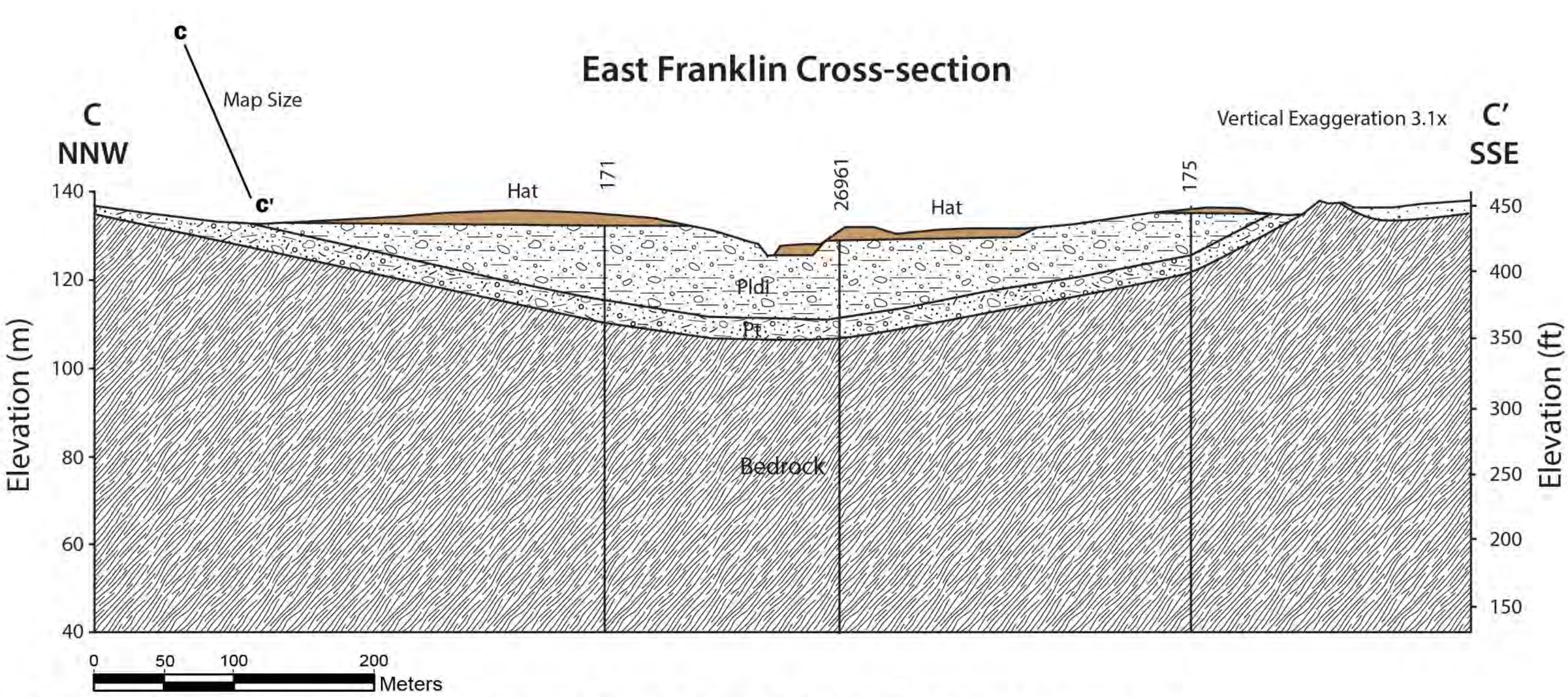


Figure 6- Cross sections from surficial geologic map of Wright (2021). See Figure 5 for locations.

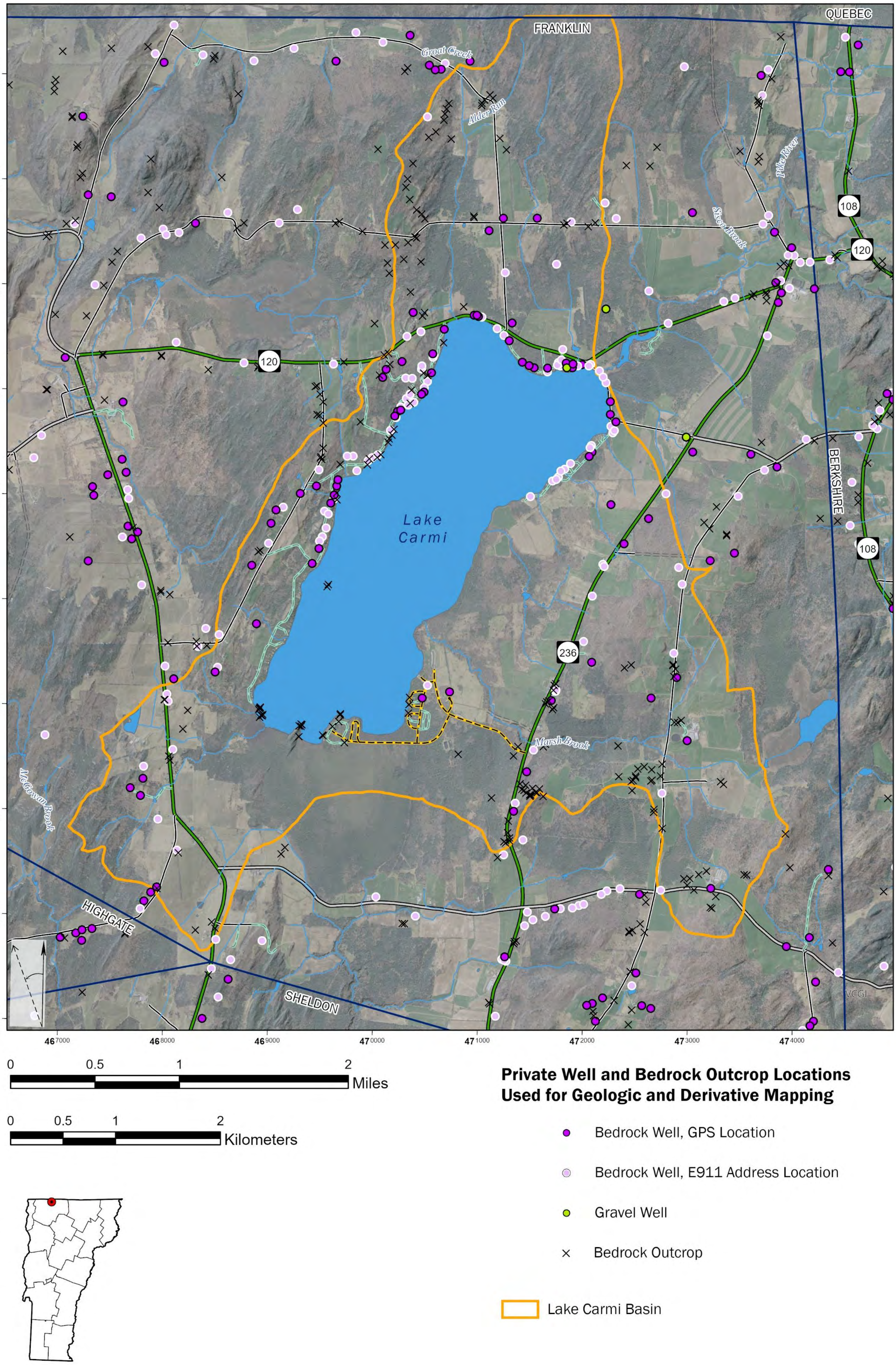


Figure 7- Locations of bedrock wells and bedrock outcrops used to make the "General Hydrogeology Maps" in the following sections, including isopach, bedrock surface contour, and static water level maps. The sparse number of gravel (surficial) well locations are also shown.

Depth to Bedrock Map of the Lake Carmi Area, Vermont

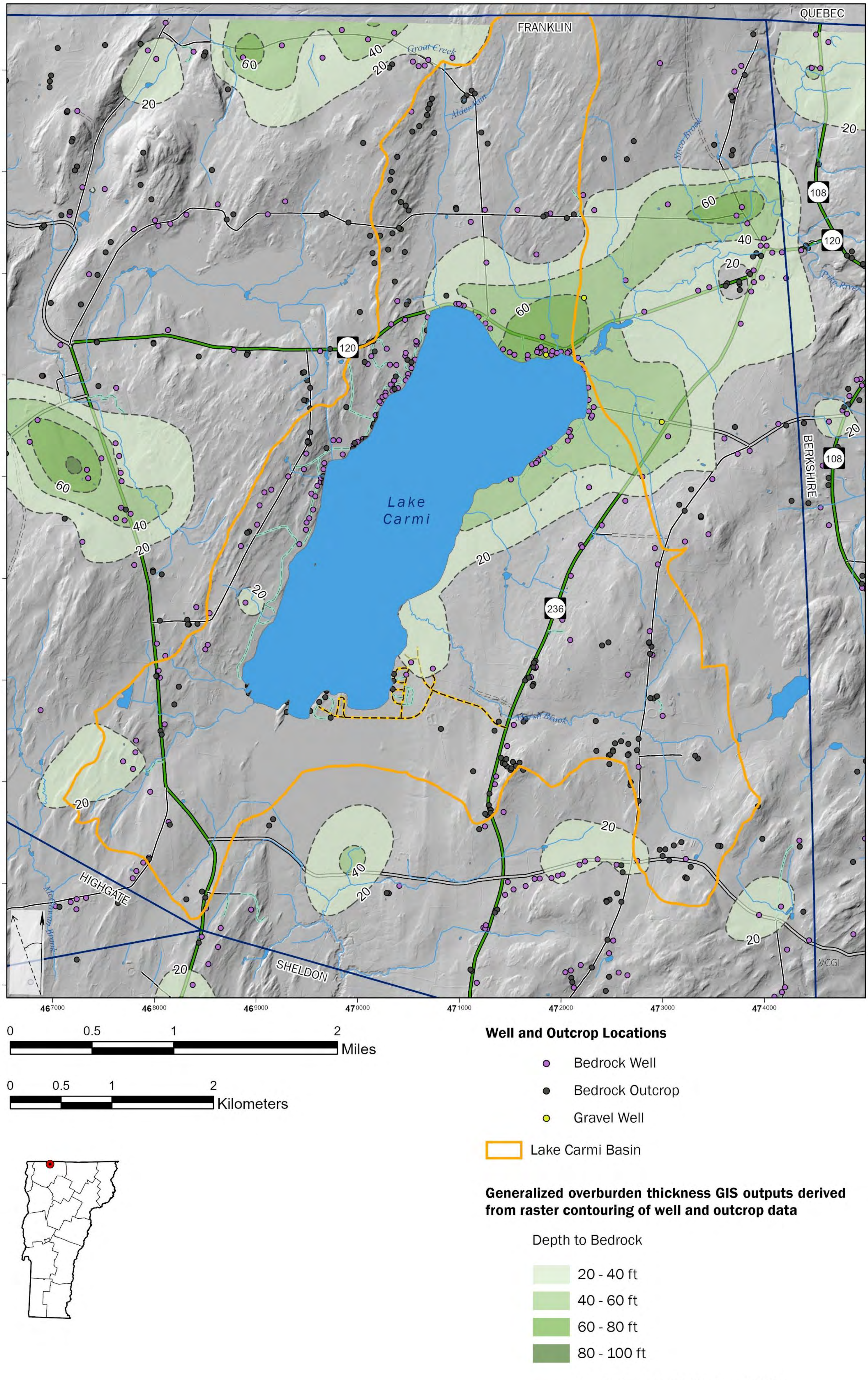
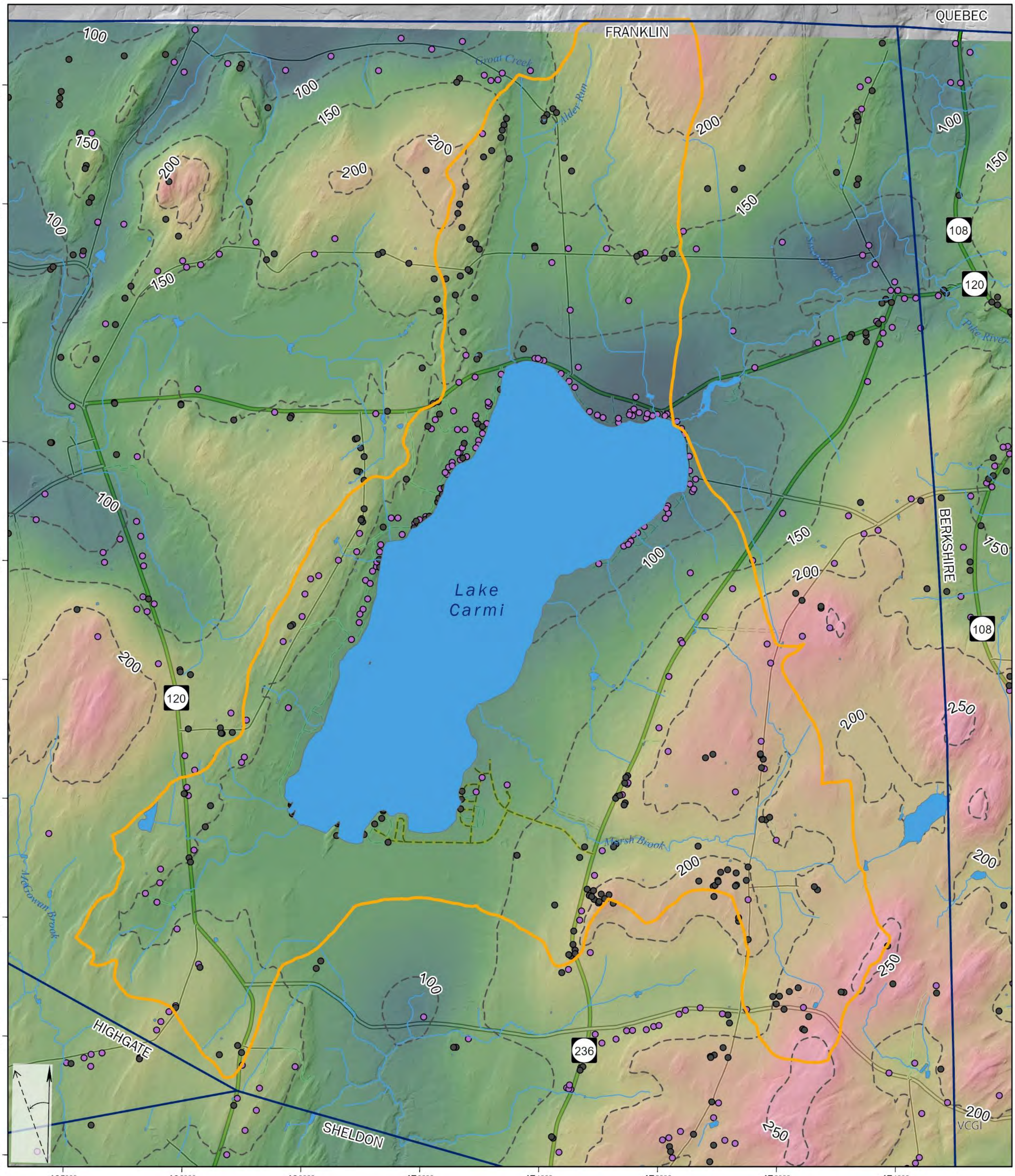


Figure 8- Isopach map of overburden thickness in the Lake Carmi area. See text for explanation.

Bedrock Surface Contour Map of the Lake Carmi Area, Vermont



0 0.5 1 2 Miles

0 0.5 1 2 Kilometers

Well and Outcrop Locations

- Bedrock Well
- Bedrock Outcrop

Lake Carmi Basin

Generalized bedrock surface elevation GIS outputs derived from raster contouring of well and outcrop data

Bedrock Surface Elevation

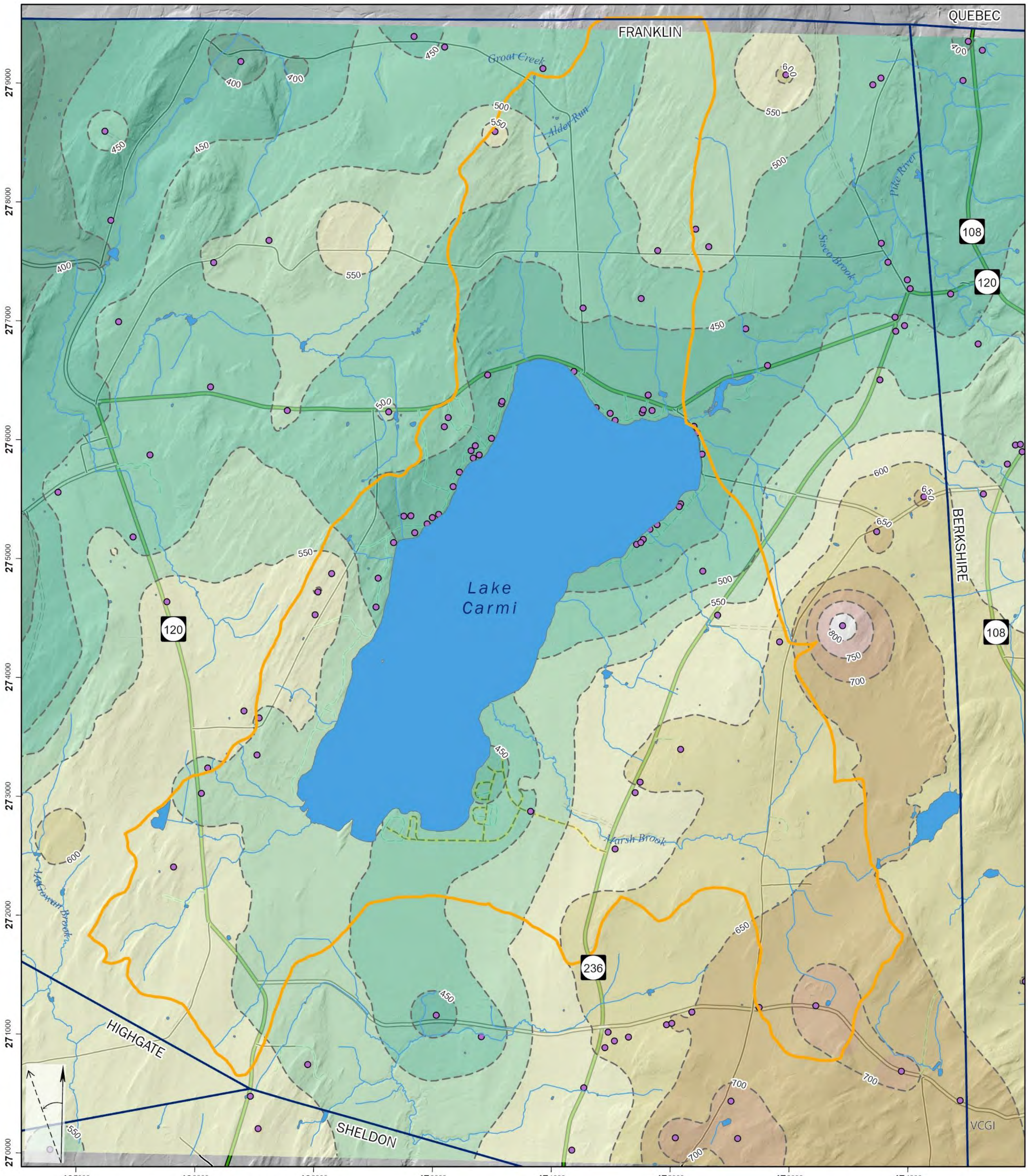
895 ft

141 ft

Bedrock Surface Contour (50 ft)

Figure 9- Bedrock surface contour map for the Lake Carmi area. See text for explanation.

Potentiometric Surface (Static Water Level) of the Bedrock Aquifer
Lake Carmi Area, Vermont



0 0.5 1 2 Miles

0 0.5 1 2 Kilometers

Bedrock Well

Lake Carmi Basin

Generalized static water level elevation GIS outputs derived from raster contouring of well data

Static Water Level

850 ft

300 ft

Static Water Level Contour (50 ft)

Figure 10- Static water level map for the bedrock aquifer in the Lake Carmi area. This type of map is formally called a potentiometric sufrace contour map. See text for explantion.

3.2 Chemical Hydrogeology

A total of 45 groundwater and surface water samples were taken for chemical analysis for Task E (Major and Trace Elements) (33 parameters including P, Nitrate (NO_x), Alkalinity, Total Carbonate Hardness (TCH), Cl, F, SO_4, SiO_2, Al, Sb, As, Ba, Be, Cd, Ca, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Ni, K, Se, Ag, Na, Sr, Tl, U, V, and Zn) at the Vermont Agricultural and Environmental Laboratory (VAEL) and for Task F (Stable Isotopes ^{2}H and ^{18}O) during 2020 and 2021 at the Middlebury College Department of Geology. Eight groundwater samples were taken for recharge-age dating (Task G) in 2021 and analyzed for CFC-11, CFC-12, CFC-113, and SF_6 at the Tritium Laboratory.

In terms of water sample types, 19 groundwater samples were taken from "Bedrock Wells" and 6 from shallow "Dug + Surficial Wells", and 7 surface water samples were taken from "Tributaries" and 10 from Lake Carmi (**Figure 11**). Samples were taken from the same 3 lake sites in 2020 and 2021 for temporal comparison purposes, but only the 2020 samples were counted in the water sample type total. **Figures 12-20** provide mapped abundances of each selected chemical parameter (P, NO_x, Cl, Na, TCH, Sr, Ba, SiO_2, and SO_4) and box-and-whisker plots for "Bedrock Wells", "Dug + Surficial Wells", "Tributaries", and "Lake" samples. The average and median for each water sample type is labeled above each box and whisker plot.

3.2.1 Groundwater and Surface Water Chemistry- Major and Trace Elements (Task E)

Selected major, trace, and anion data (P, NO_x, Cl, Na, TCH, Sr, Ba, SiO_2, and SO_4) are shown on maps of the Lake Carmi Watershed and are accompanied by box-and-whisker plots below.

3.2.1.1 Phosphorus (P)

Figure 12 presents the concentrations of P from water sampling. Groundwater from bedrock wells averages P concentrations of 9.7 ppb (median = 8.6 ppb) and that from dug and surficial wells averages 20.3 ppb (median = 13.6 ppb). Surface water samples from tributaries average P concentrations of 86.5 ppb (median = 88.2 ppb) and Lake Carmi samples average P concentrations of 50.7 ppb (median = 45.7 ppb). There is overlap between the lake sample "box" (represents 50 % of samples and contains the lower quartile, upper quartile and median) and the minimum range of tributary samples and maximum range of dug and surficial wells. There is also overlap between the maximum range of bedrock wells and the dug and surficial wells box.

3.2.1.2 Nitrate (NO_x)

Figure 13 presents the concentrations of NO_x from water sampling. Groundwater from bedrock wells averages NO_x concentrations of 0.18 ppm (median = 0.03 ppm) and that from dug and surficial wells averages 0.26 ppm (median = 0.21 ppm). Surface water samples from tributaries average NO_x concentrations of 0.15 ppm (median = 0.13 ppm) and Lake Carmi samples average NO_x concentrations of 0.03 ppm, the equivalent of not being detected (median = 0.03 ppm). For groundwater, the maximum contaminant level for nitrate is 10 ppm, and all the well samples are significantly below this. Although there are no surface-water standards for nitrate, the surface-water nitrate levels are lower than those in the groundwater samples. Lake Carmi had "non-detect" nitrate concentrations throughout this study.

3.2.1.3 Chloride (Cl)

Figure 14 presents the concentrations of Cl from water sampling. Groundwater from bedrock wells averages Cl concentrations of 4.5 ppm (median = 3.4 ppm) and that from dug and surficial wells averages 5.6 ppm (median = 2.5 ppm). Surface water samples from tributaries average Cl concentrations of 5.0 ppm (median = 4.2 ppm) and Lake Carmi samples average P concentrations of 8.4 ppm (median = 8.5 ppm). For groundwater, the EPA secondary contaminant level (odor, taste, color) is 250 ppm, and only one well sample exceeds this. Although there are no surface water-standards for chloride, the surface water chloride levels in this study are in the same low range as the groundwater samples. Cl levels in Lake Carmi during this study were uniform at ~8 ppm.

3.2.1.4 Sodium (Na)

Figure 15 presents the concentrations of Na from water sampling. Groundwater from bedrock wells averages Na concentrations of 39.7 ppm (median = 22.2 ppm) and that from dug and surficial wells averages 4.1 ppm (median = 2.6 ppm). Surface water samples from tributaries average Cl concentrations of 3.3 ppm (median = 3.1 ppm) and Lake Carmi samples average P concentrations of 5.3 ppm (median = 5.3 ppm). For groundwater, the EPA advises that people on a low sodium diet not ingest > 20 ppm in their drinking water (https://www.epa.gov/sites/default/files/2014-09/documents/support_cc1_sodium_dwreport.pdf), (https://www.cambridgema.gov/-/media/Files/waterdepartment/Distribution/ChloridesEnviroFactSheet.pdf). One bedrock well from this study has elevated Na (303 ppm), which is the same well with high Cl (448 ppm), likely indicating NaCl as the source. Although this single bedrock well increases the Na and Cl averages for this sample group, Na concentrations are higher overall for bedrock wells, without commensurate Cl that would be indicative of a NaCl source. The Dug + Surficial Wells, Tributaries, and Lake samples have much lower levels of Na. Lake Carmi had uniform Na levels of ~5 ppm during this study.

3.2.1.5 Total Carbonate Hardness (TCH)

Figure 16 presents the concentrations of TCH from water sampling. Groundwater from bedrock wells averages TCH concentrations of 95.3 ppm (median = 94.7 ppm) and that from dug and surficial wells averages 184.9 ppm (median = 163.0 ppm). Surface water samples from tributaries average TCH concentrations of 57.5 ppm (median = 58.9 ppm) and Lake Carmi samples average TCH concentrations of 46.8 ppm (median = 47.0 ppm). Based on the USGS Water Hardness classification, bedrock well water is moderately hard (61-120 ppm), dug and surficial well water very hard (>180 ppm), and tributary and lake water are soft (0- 60 ppm) (https://www.usgs.gov/special-topics/water-science-school/science/hardness-water). The large difference in average hardness between the dug and surficial wells suggests that the shallow surficial aquifer is relatively enriched with calcium carbonate compared with the bedrock aquifer. In spite of the high TCH content of the dug and surficial wells, the lake has much lower hardness levels and virtually no spatial variation over the duration of this study.

3.2.1.6 Strontium (Sr)

Figure 17 presents the concentrations of Sr from water sampling. Groundwater from bedrock wells averages Sr concentrations of 3136 ppb (median = 3030 ppb); dug and surficial well water averages 560 ppb (median = 519 ppb). Surface-water samples from tributaries average Sr concentrations of 154 ppb (median = 151 ppb) and Lake Carmi samples average Sr concentrations of 113 ppb (median = 113 ppb). The bedrock aquifer is clearly the source of the most Sr, with a big drop to the surficial aquifer (dug and surficial wells). The surface water samples only have a fraction of the Sr observed in groundwater. The Sr in Lake Carmi has a uniform spatial distribution.

3.2.1.7 Barium (Ba)

Figure 18 presents the concentrations of Ba from water sampling. Groundwater from bedrock wells averages Ba concentrations of 41.8 ppb (median = 14.2 ppb) and that from dug and surficial wells averages 20.6 ppb (median = 21.1 ppb). Surface-water samples from tributaries average Ba concentrations of 154 ppb (median = 151 ppb) and Lake Carmi samples average Ba concentrations of 18.7 ppb (median = 21.6 ppb). The bedrock aquifer is clearly the source of the most Ba, dug and surficial wells and tributaries having similar amounts, with a large drop in Ba for lake samples. The wells with the most Ba are those with the most Sr also. The Ba in Lake Carmi has a uniform spatial distribution.

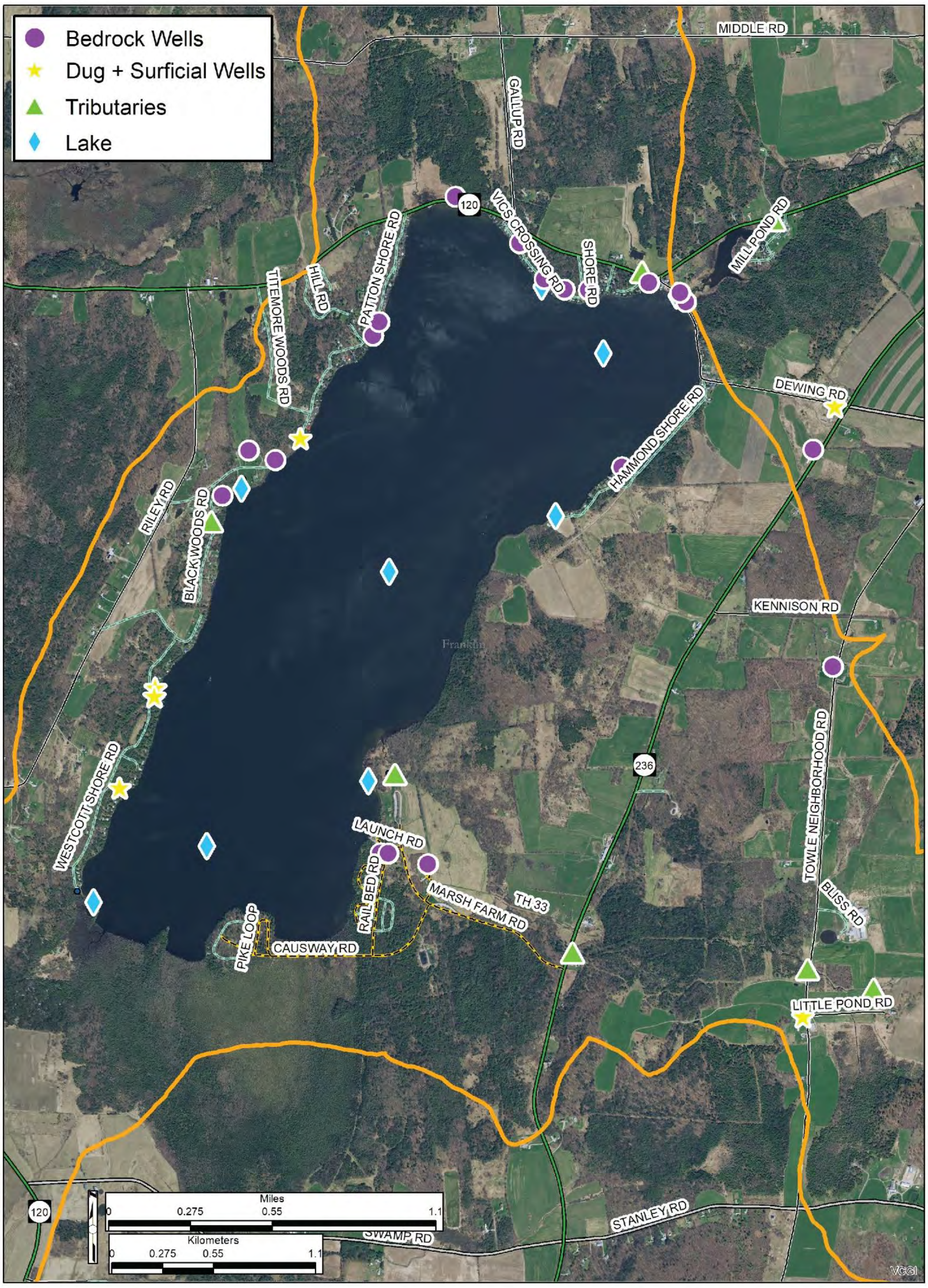
3.2.1.8 Silica (SiO_2)

Figure 19 presents the concentrations of SiO_2 from water sampling. Groundwater from bedrock wells average SiO_2 concentrations of 10.7 ppm (median = 10.5 ppm) and that from dug and surficial wells averages 13.9 ppm (median = 12.6 ppm). Surface water samples from tributaries average SiO_2 concentrations of 5.1 ppm (median = 3.6 ppm) and Lake Carmi samples average SiO_2 concentrations of 1.8 ppm (median = 1.4 ppm). Groundwater from the surficial aquifer followed by the bedrock aquifer is highest in SiO_2, with a large decrease in SiO_2 for surface water from tributaries and the lake. The SiO_2 in Lake Carmi has a more variable spatial distribution than Ba, Sr, and TCH.

3.2.1.9 Sulfate (SO_4)

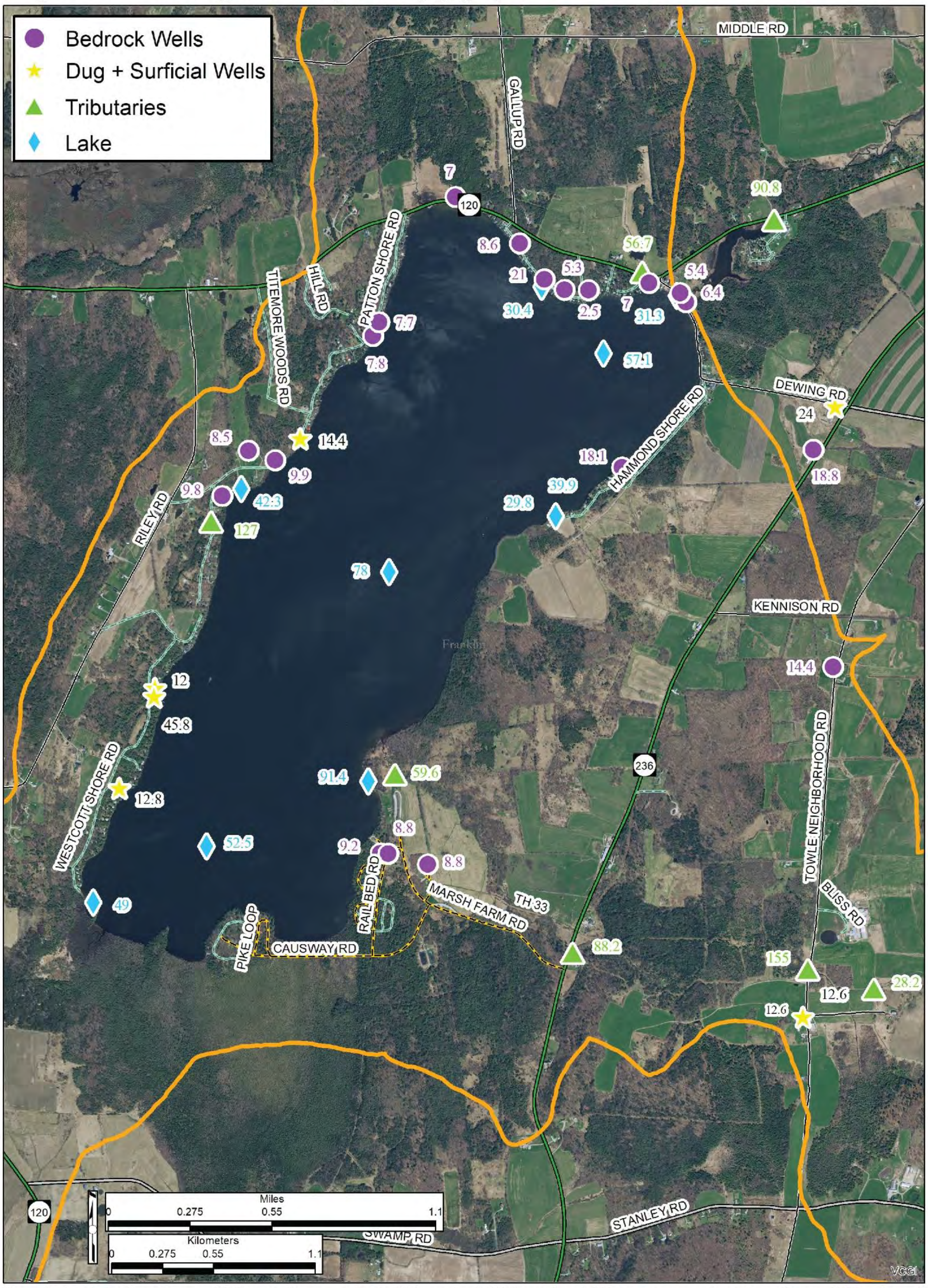
Figure 20 presents the concentrations of SO_4 from water sampling. Groundwater from bedrock wells averages SO_4 concentrations of 19.5 ppm (median = 17.3 ppm) and that from dug and surficial wells averages 12.7 ppm (median = 7.9 ppm). Surface water samples from tributaries average SO_4 concentrations of 3.8 ppm (median = 3.1 ppm) and Lake Carmi samples average SO_4 concentrations of 3.1 ppm (median = 3.0 ppm). Groundwater from the bedrock and surficial aquifers are highest in SO_4, with a large decrease in SO_4 for surface water from tributaries and the lake. The SO_4 in Lake Carmi has a uniform spatial distribution.

Figure 11- Water Sample Base Map



Water sample type basemap showing locations of groundwater samples from "Bedrock Wells" (n=19) and "Dug + Surficial Wells" (n=6), and surface water from "Tributaries" (n=7) and the "Lake" (n=10). The total number of unique sample locations is 42.

Figure 12- Phosphorus (Ptotal)(ppb)



Spatial distribution of Phosphorus (total)(parts/billion (ppb)) in groundwater from “Bedrock” and “Dug + Surficial ”wells and surface water from “Tributaries” and the “Lake”. Concentration values are color-coded to match the water sample type.

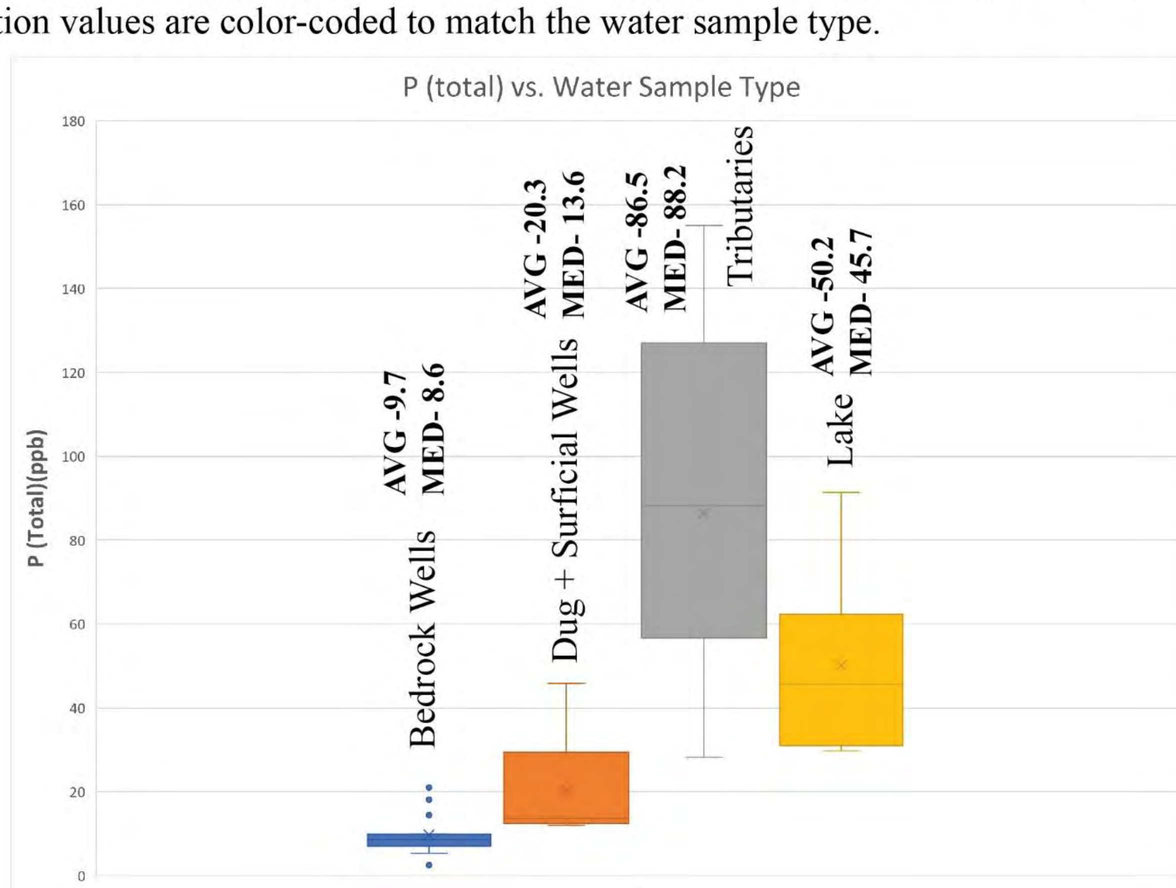
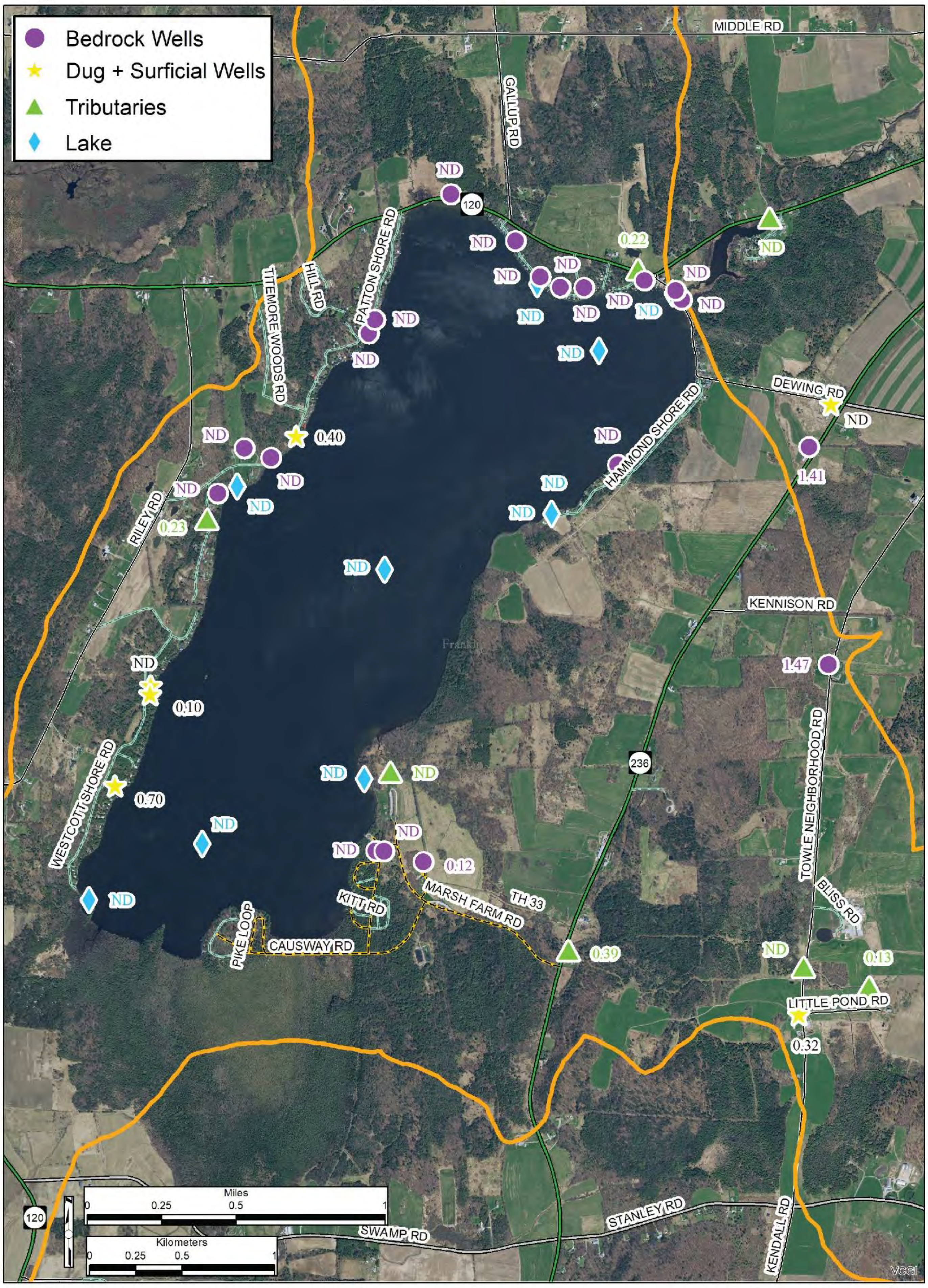


Figure 13- Nitrate (NOx)(ppm)



Spatial distribution of Nitrate (NOx)(parts/million (ppm)) in groundwater from “Bedrock” and “Dug + Surficial ”wells and surface water from “Tributaries” and the “Lake”. Concentration values are color-coded to match the water sample type.

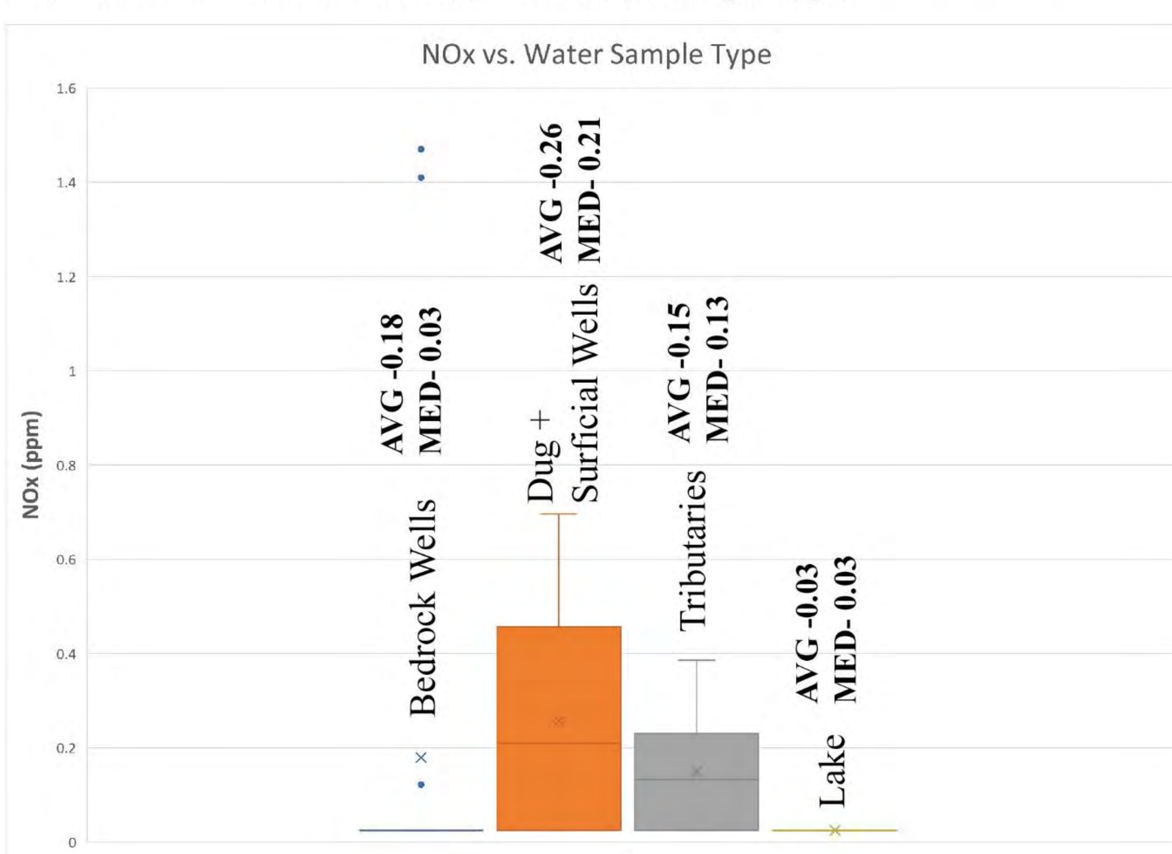
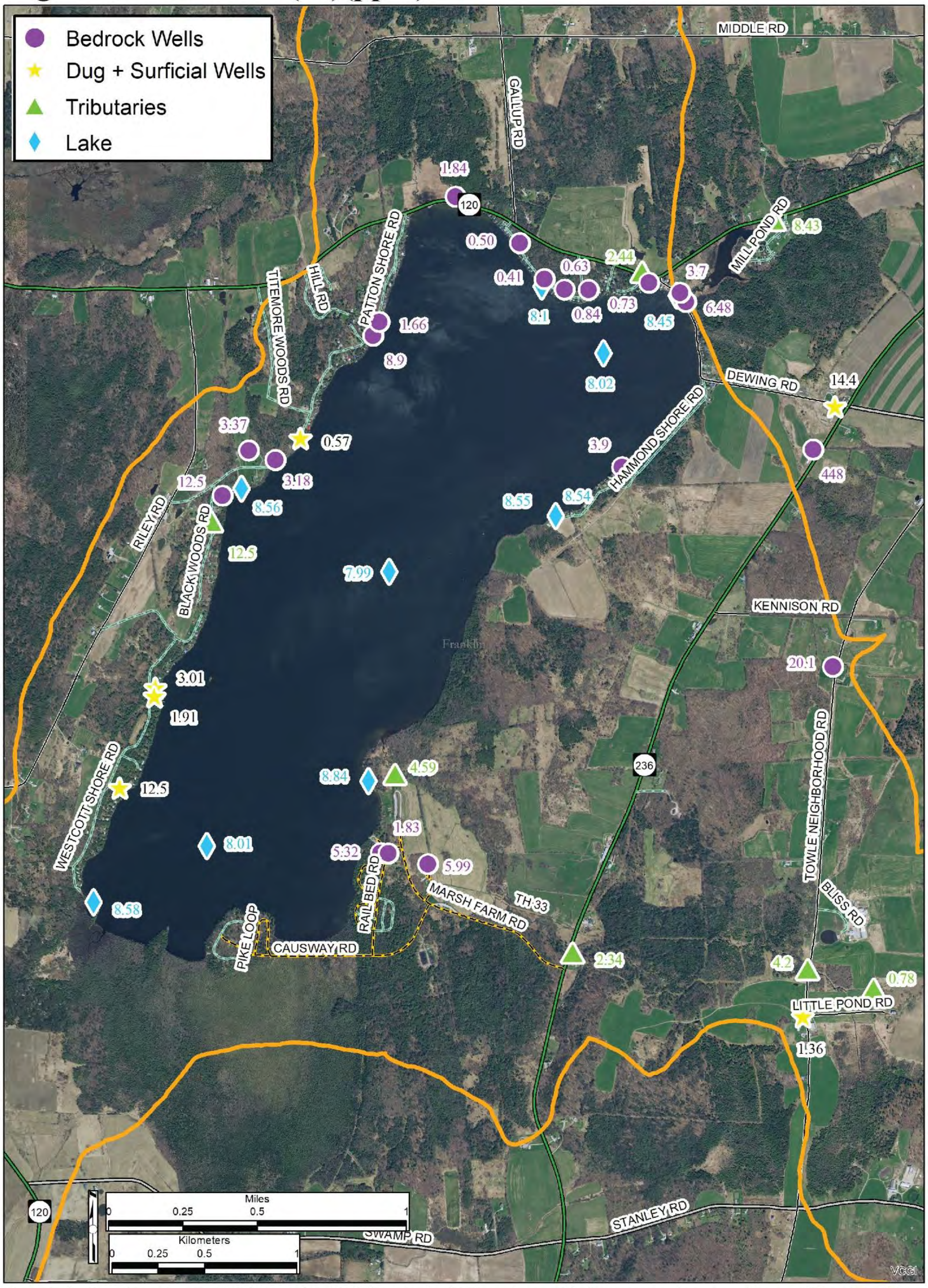


Figure 14- Chloride (Cl)(ppm)



Spatial distribution of Chloride (Cl)(parts/million (ppm)) in groundwater from “Bedrock” and “Dug + Surficial ”wells and surface water from “Tributaries” and the “Lake”. Concentration values are color-coded to match the water sample type.

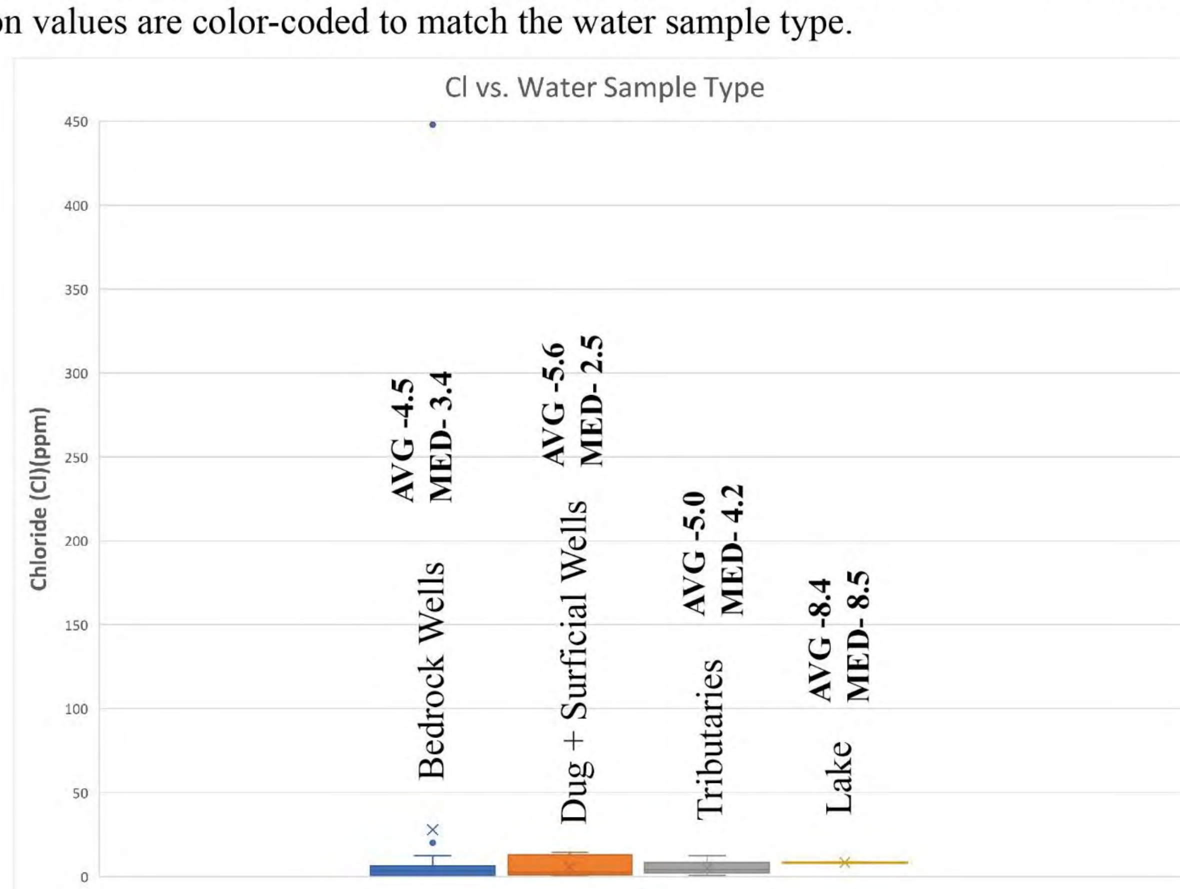
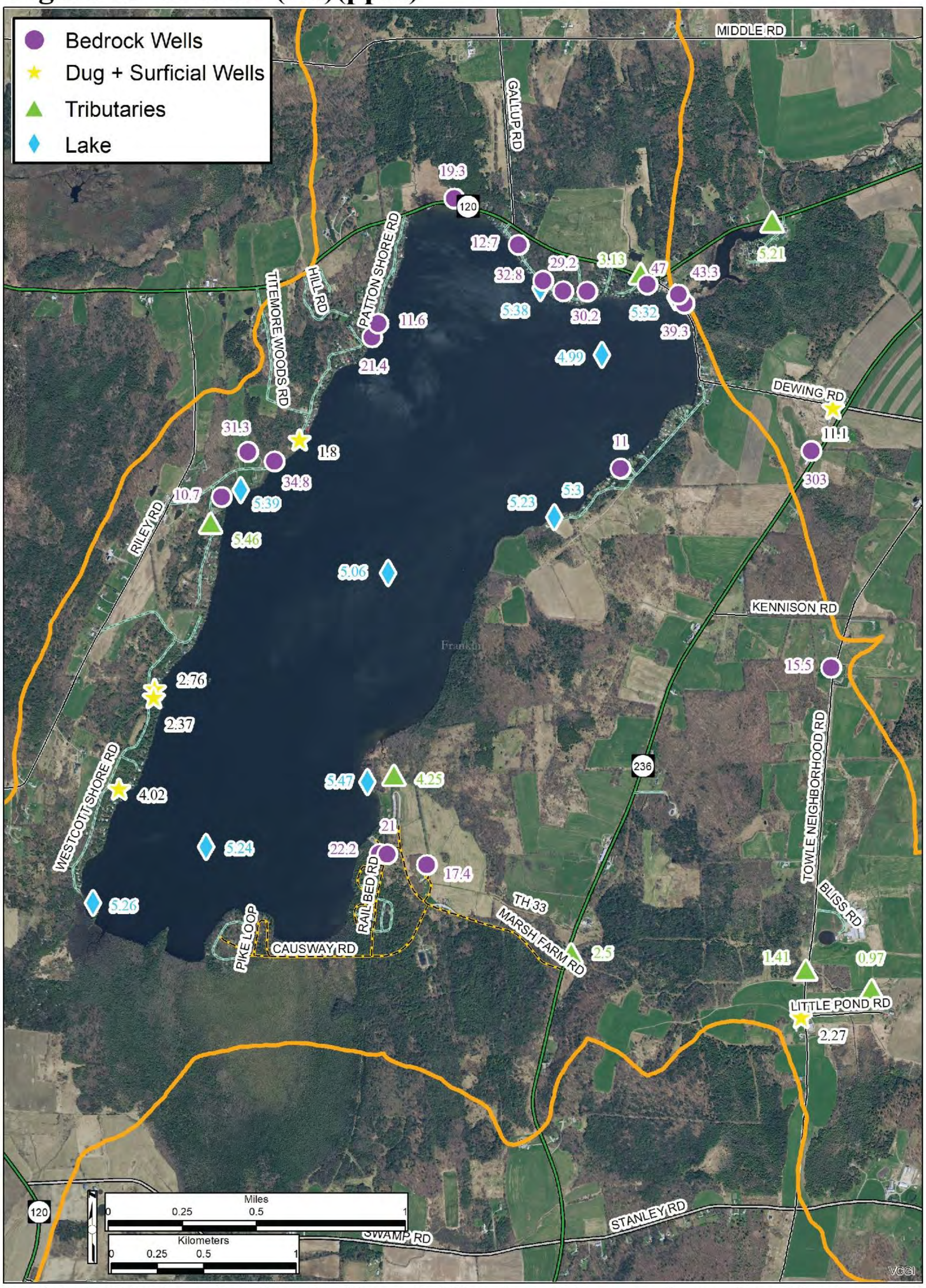


Figure 15- Sodium (Na)(ppm)



Spatial distribution of Sodium (Na)(parts/million (ppm)) in groundwater from "Bedrock" and "Dug + Surficial "wells and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.

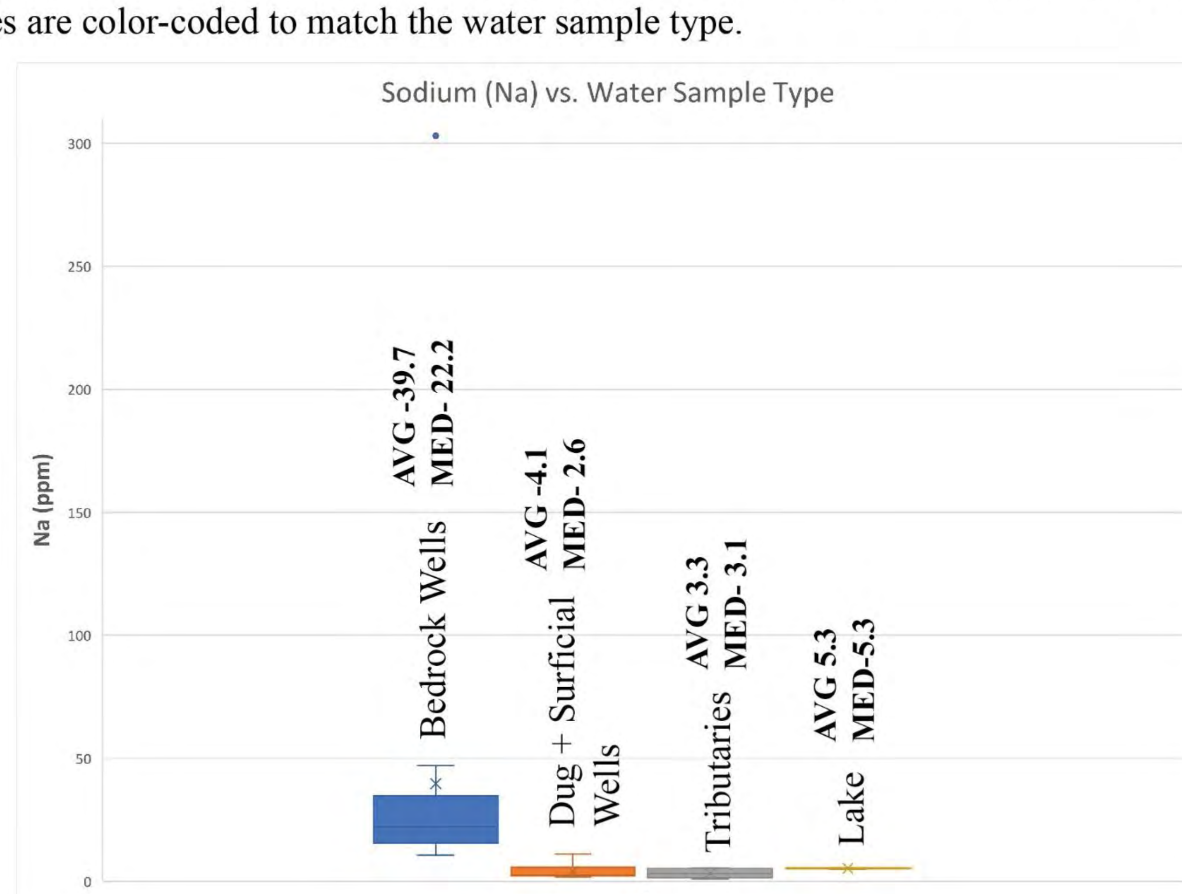
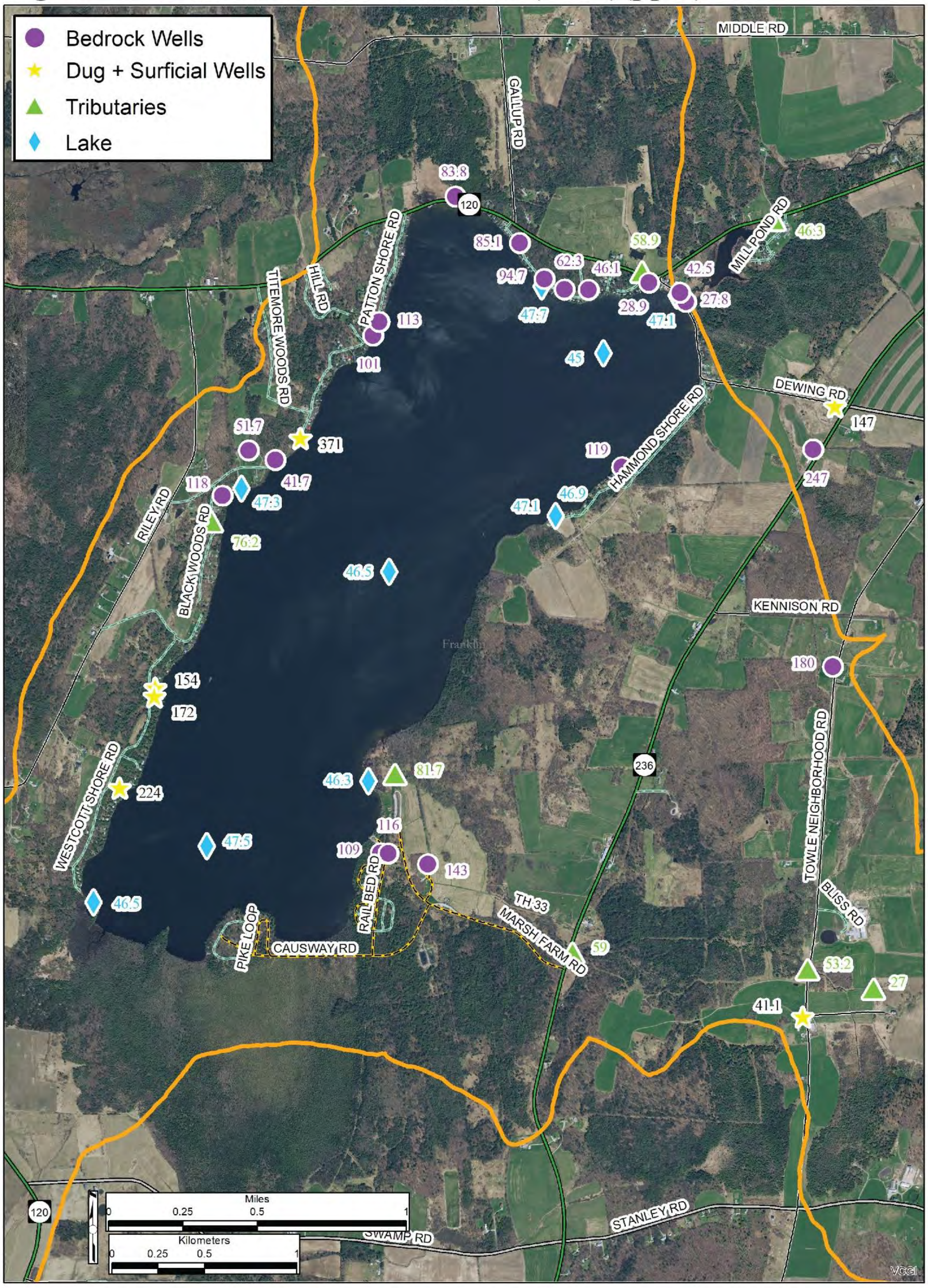


Figure 16- Total Carbonate Hardness (TCH)(ppm)



Spatial distribution of Total Carbonate Hardness (TCH)(parts/million (ppm)) in groundwater from "Bedrock" and "Dug + Surficial "wells and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.

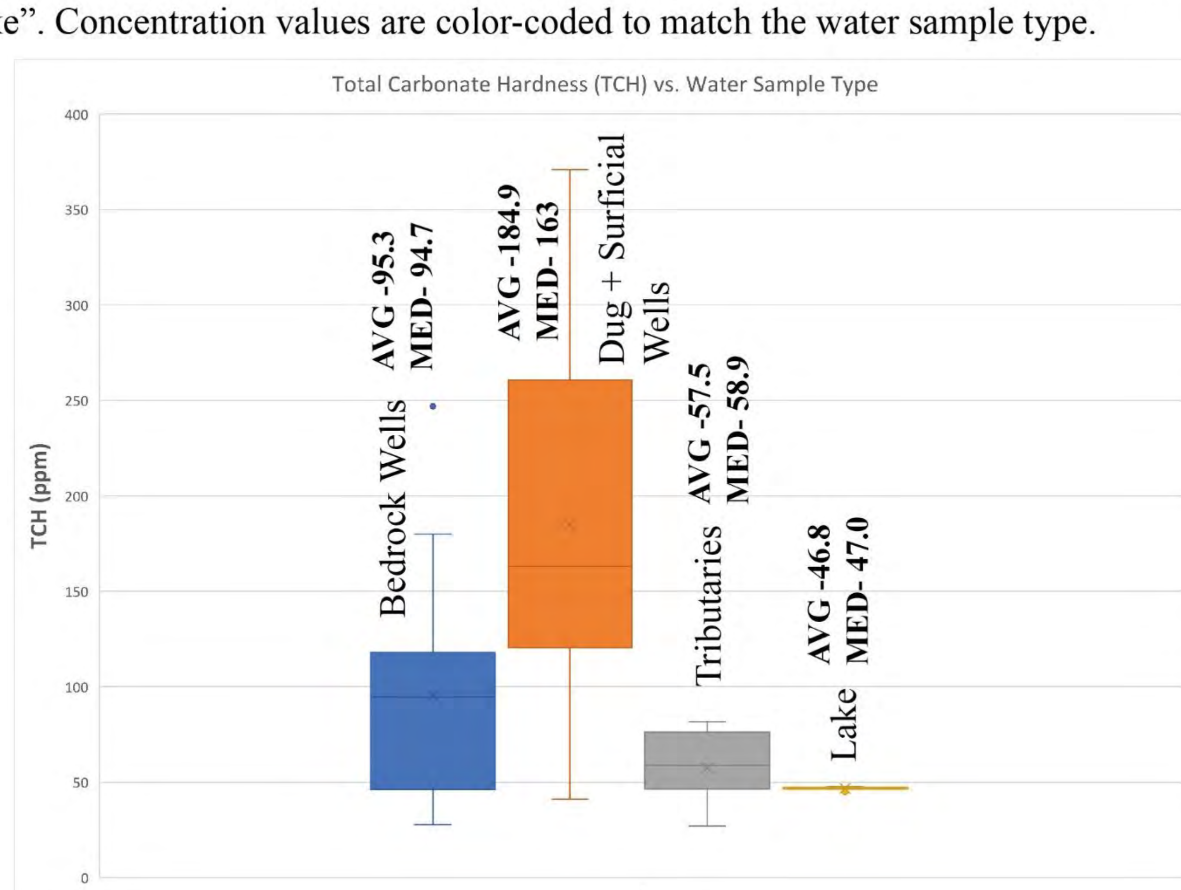
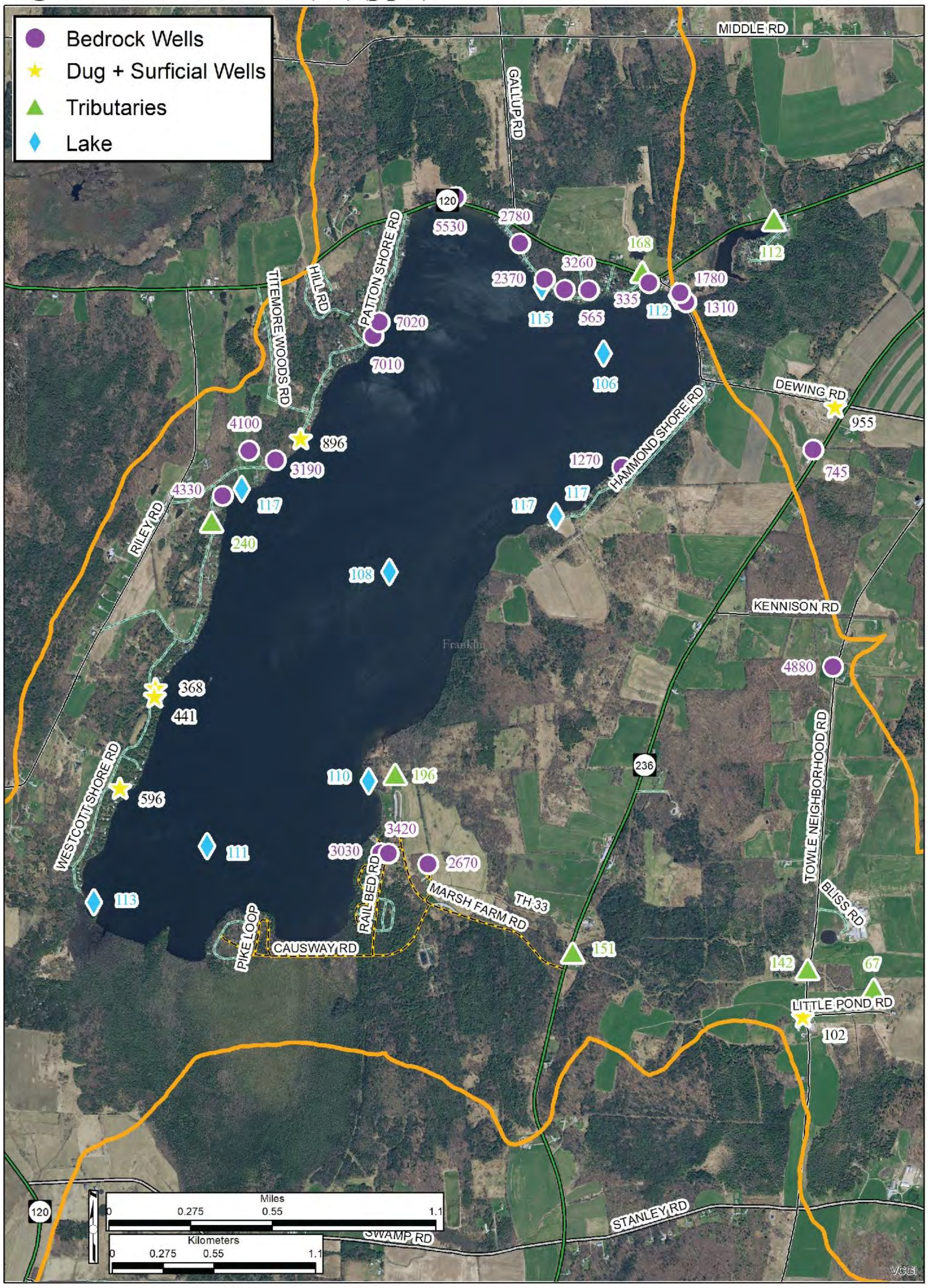


Figure 17- Strontium (Sr)(ppb)



Spatial distribution of Strontium (Sr)(parts/billion (ppb)) in groundwater from "Bedrock" and "Dug + Surficial "wells and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.

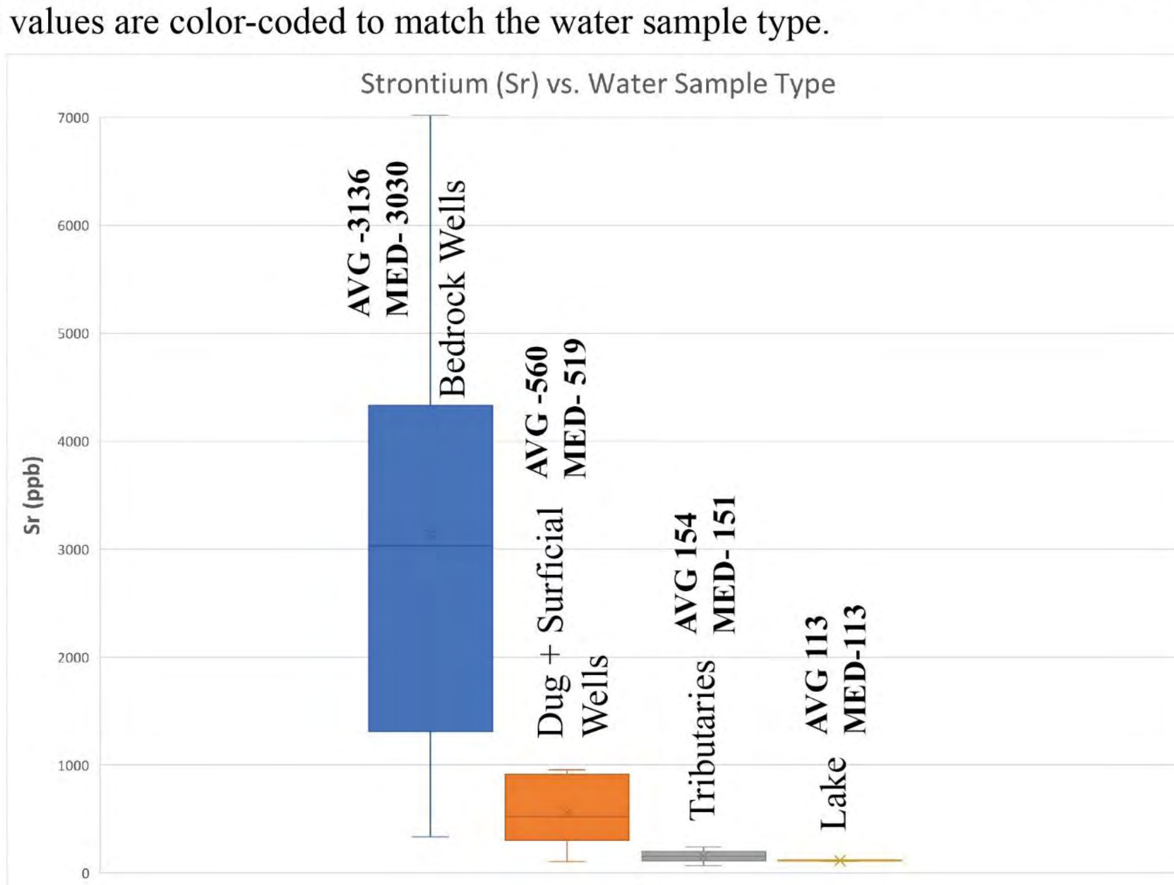
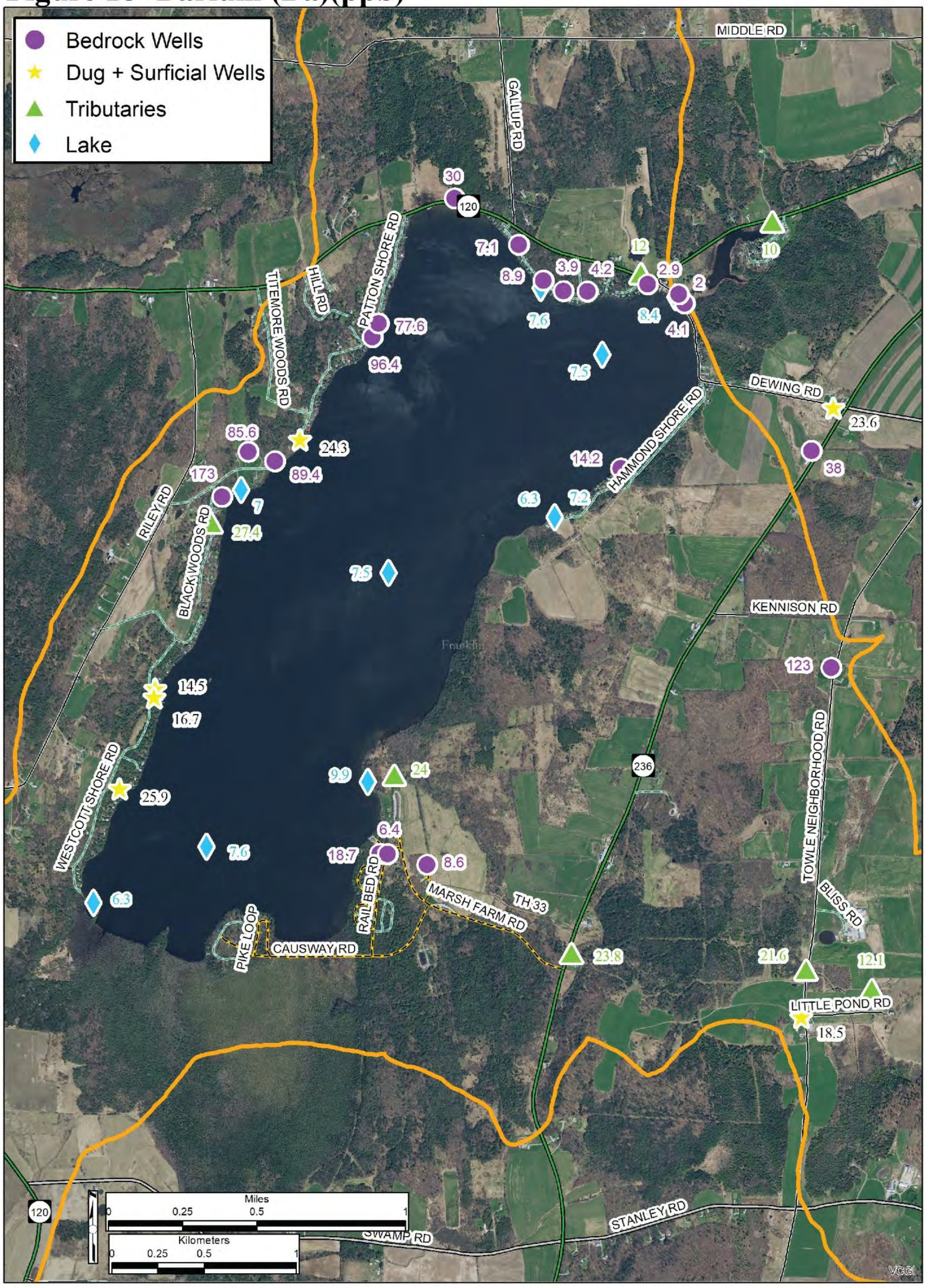


Figure 18- Barium (Ba)(ppb)



Spatial distribution of Barium (Ba)(parts/billion (ppb)) in groundwater from "Bedrock" and "Dug + Surficial "wells, and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.

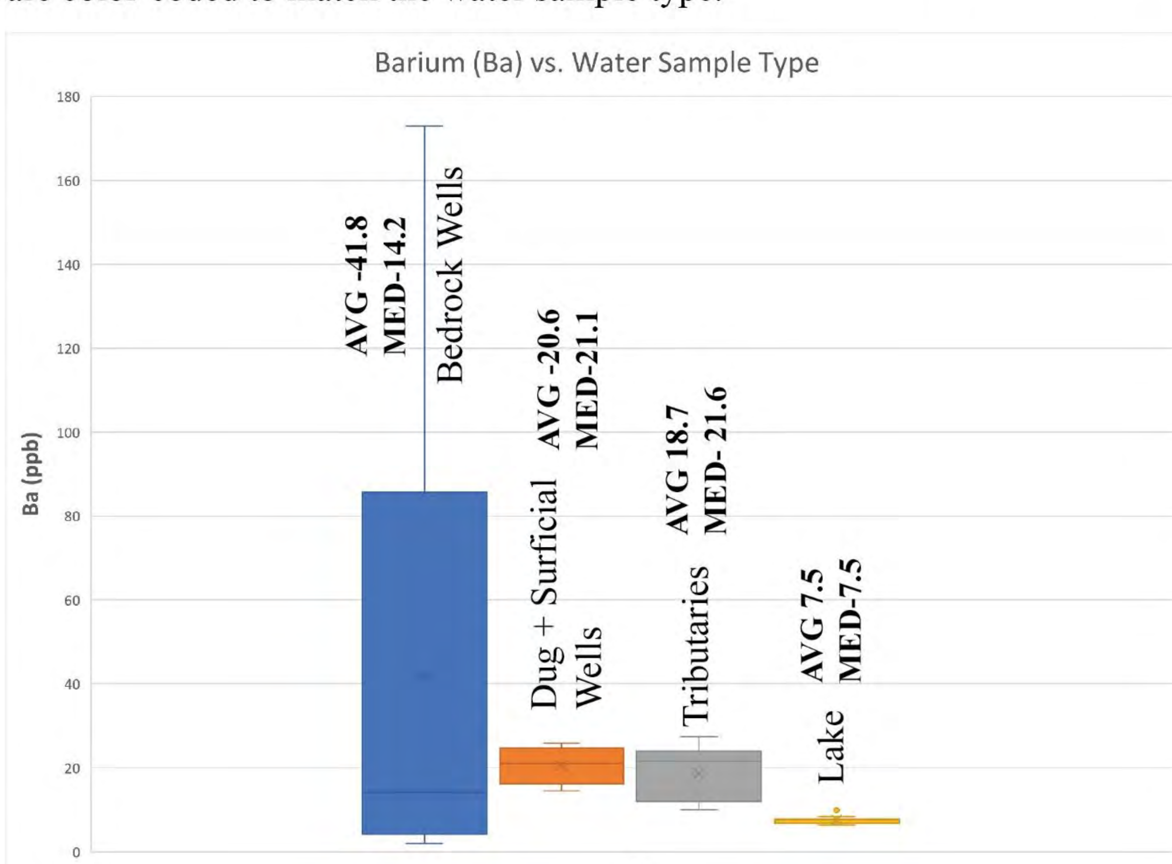
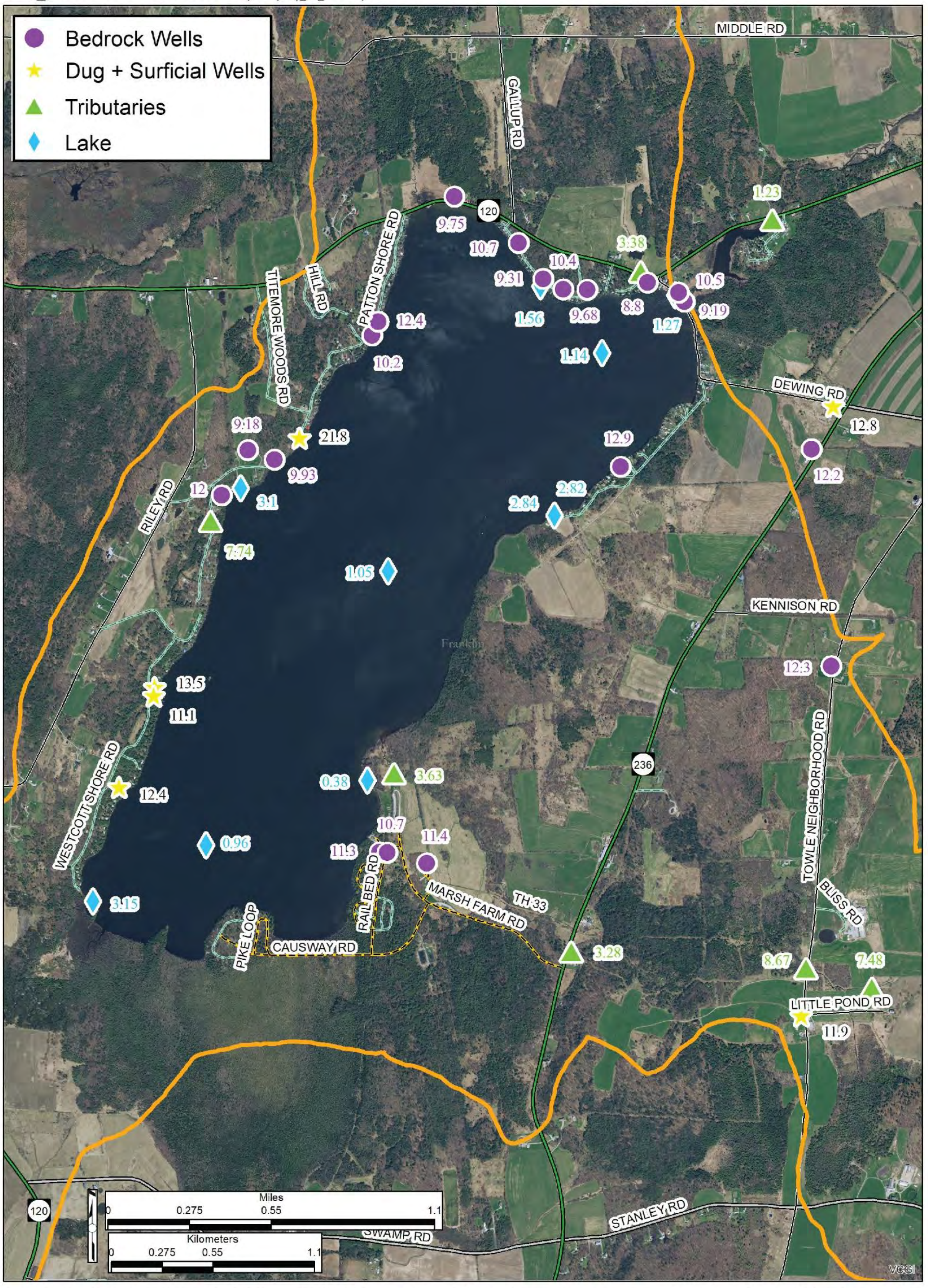


Figure 19- Silica (Si)(ppm)



Spatial distribution of Silica (SiO2)(parts/million (ppm)) in groundwater from "Bedrock" and "Dug + Surficial "wells, and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.

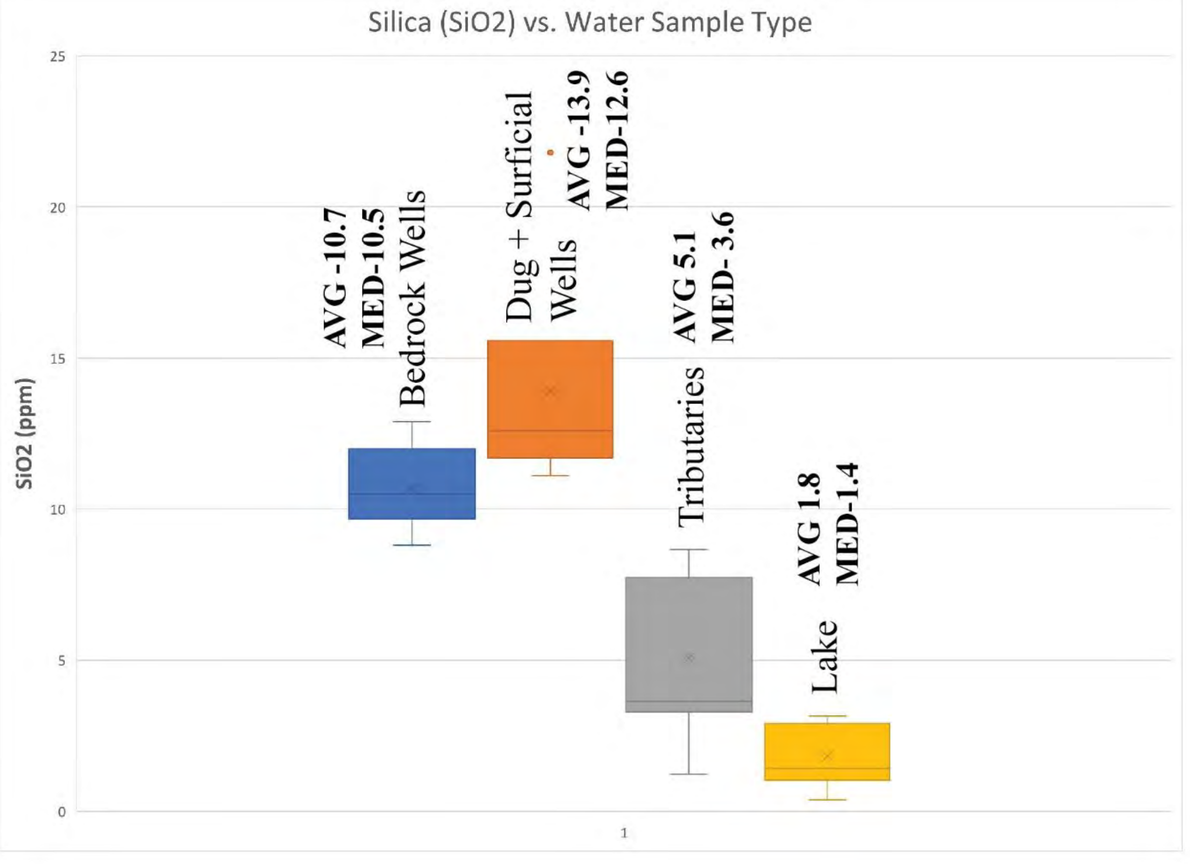
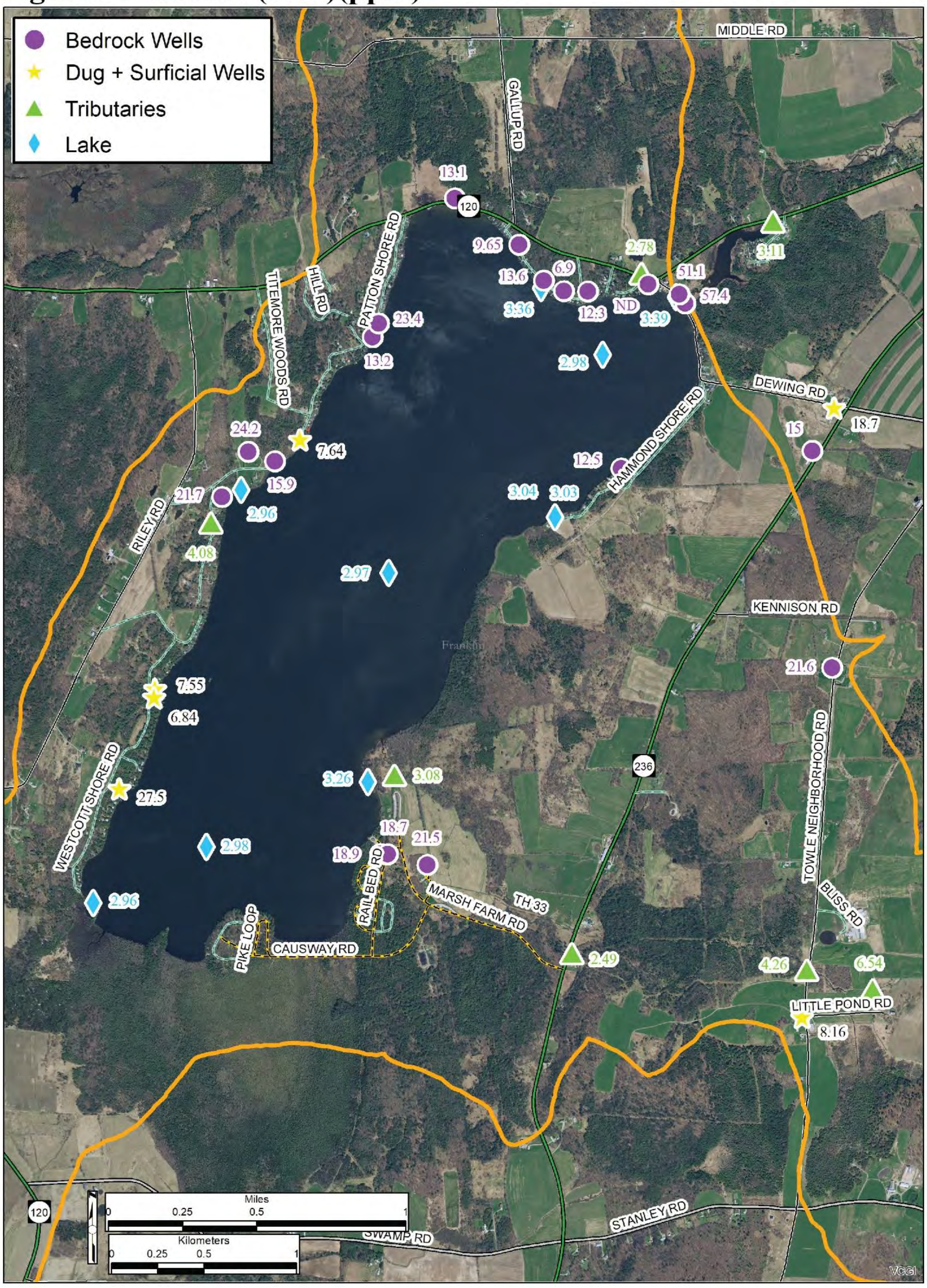
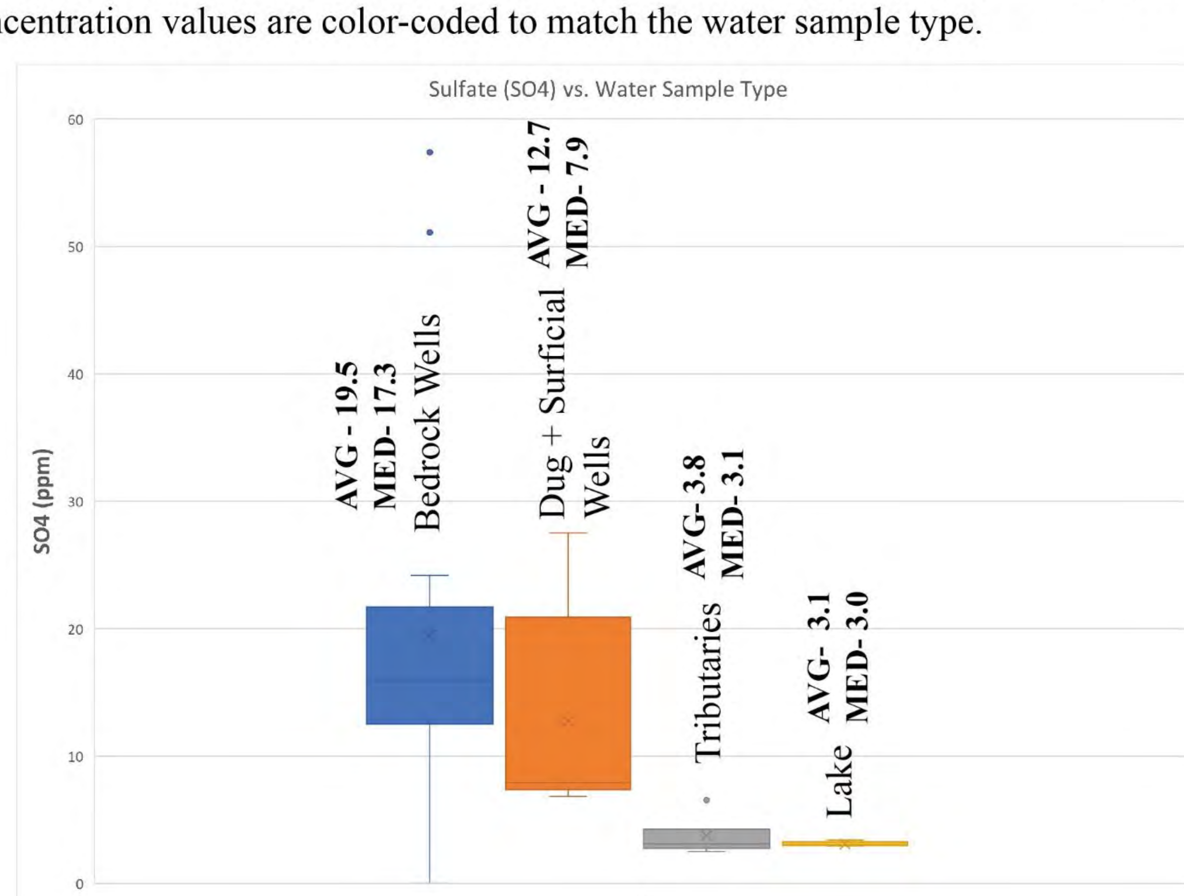


Figure 20- Sulfate (SO4)(ppm)



Spatial distribution of Sulfate (SO4)(parts/million (ppm)) in groundwater from "Bedrock" and "Dug + Surficial "wells, and surface water from "Tributaries" and the "Lake". Concentration values are color-coded to match the water sample type.



3.2.2 Groundwater and Surface Water Chemistry - Stable Isotope Chemistry

Isotopes of an element have the same number of protons, but a different number of neutrons. Oxygen and hydrogen each have two main isotopes ^{16}O and ^{18}O and ^{2}H ^{1}H, respectively. Hydrologic atmospheric processes, such as precipitation and evaporation, selectively partition the heavier and lighter isotopes of these elements, which gives information about the history of groundwater and surface water samples. Oxygen and hydrogen isotope compositions of water samples from the four main components of the hydrologic system in the Lake Carmi watershed reveal two end members as well as evidence for mixing (**Figure 21**). (Note: rain and snow compositions are outside the focus of this study). Water from bedrock wells is the isotopically lightest (most negative) component, while lake water is the isotopically heaviest (least negative) (**Figure 21**). The trajectory with lower slope is caused by evaporation of lake water that results in progressively heavier (less negative) values in the water that remains in the lake. Tributaries (streams) and dug/surficial wells have signatures that overlap the ranges of these two end members. The origin of the evaporation trend coincides with overlapping tributary and dug/surficial well compositions, consistent with evidence that the lake water is derived from a mix of tributary streams and groundwater influx.

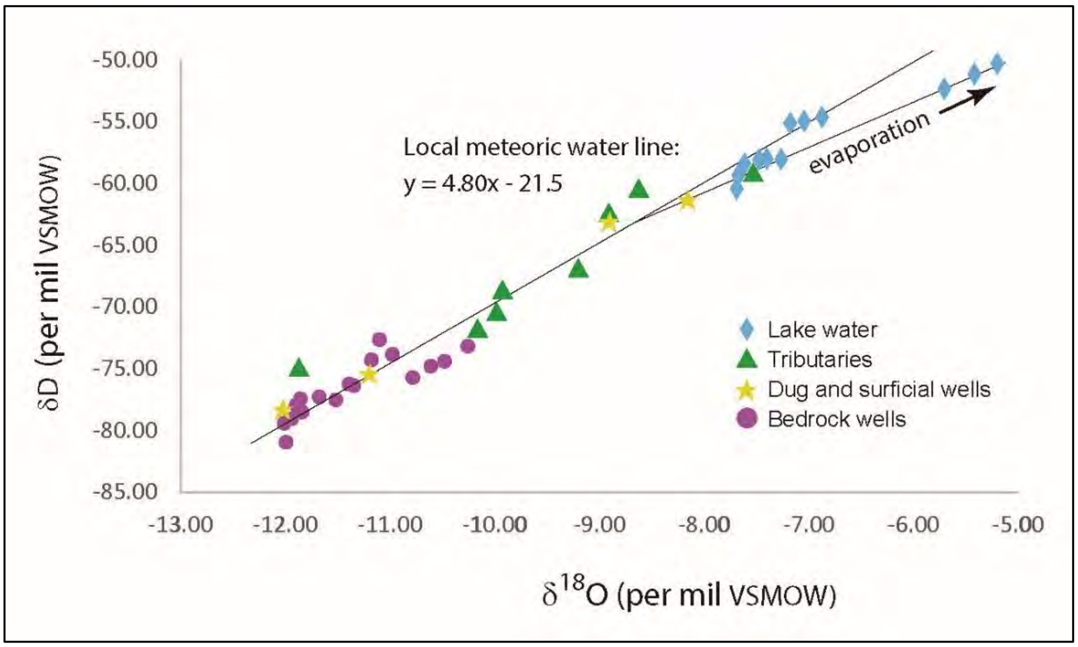


Figure 21- Stable isotope plot.

3.2.3 Groundwater Recharge Ages (Task F)

Precipitation falls on the ground surface, infiltrates below the ground surface where it becomes isolated from the atmosphere and becomes groundwater that flows in the surficial and bedrock aquifers. Industrial compounds such as Chlorinated Fluorocarbons (CFCs) and Sulfur Hexafluoride (SF_6) were introduced into the atmosphere by industrial processes that generated compounds for air conditioning and refrigeration, as well as electronics manufacturing. Tritium was first introduced in significant quantities to the atmosphere by atomic bomb testing in the early 1950s, with the first major atmospheric spike of tritium in rainfall occurring in 1953 (Solomon and Cook, 2000). The concentrations of these compounds can be used to date the time that precipitation became isolated from the atmosphere and became groundwater, by comparing with global atmospheric curves of the compounds over decades, hence the recharge age /date. The locations of the bedrock wells (n=7) and a surface water supply (n=1) that were sampled for recharge ages is shown in **Figure 22**. Average recharge ages were calculated from the CFC concentrations using appropriate recharge temperatures and elevations and converted to year of recharge by the Tritium Laboratory (e.g., Plummer and Busenberg, 2000). **Figure 23A** shows the average recharge age (years before 2021) and the recharge date, whereas **Figure 23B** shows the amount of tritium (Tritium Units (TU)) in each sample. Water of one or multiple recharge ages/dates may exist in a single water sample.

Groundwater from bedrock well samples 1, 2, 4, and 5 have the oldest average recharge dates, ranging from ~1956-1963, and the lowest amounts of tritium ("tritium-dead"). The tritium levels plot below the approximate current tritium threshold for "modern" water (~0.2-0.4 TU, e.g., Solomon and Cook, 2000), indicating recharge that predates the presence of tritium in rainfall from atmospheric atomic bomb testing in rainfall in ~1953. Samples 6, 7, and 8 have younger average CFC recharge dates of 1970-1981 and tritium levels of 1.0-9.2 TU, likely indicating a mix of younger water with older water at varying proportions. Sample 3, which has an average CFC recharge age of 1976 and the highest tritium level of 10.8 TU, was sampled from a house faucet that drew water from the lake shoreline near the lake bottom. The high tritium level can be attributed to the fact that lake water is in contact with the atmosphere and is mixed by wind and currents. However, the 1976 average CFC recharge age is enigmatic, because one would expect that lake water would only have average recharge ages approximating the date of sampling. The persistence of these old average ages could be explained by a significant component of groundwater that discharges at/near the lake shoreline, that is not diluted by younger surface water.

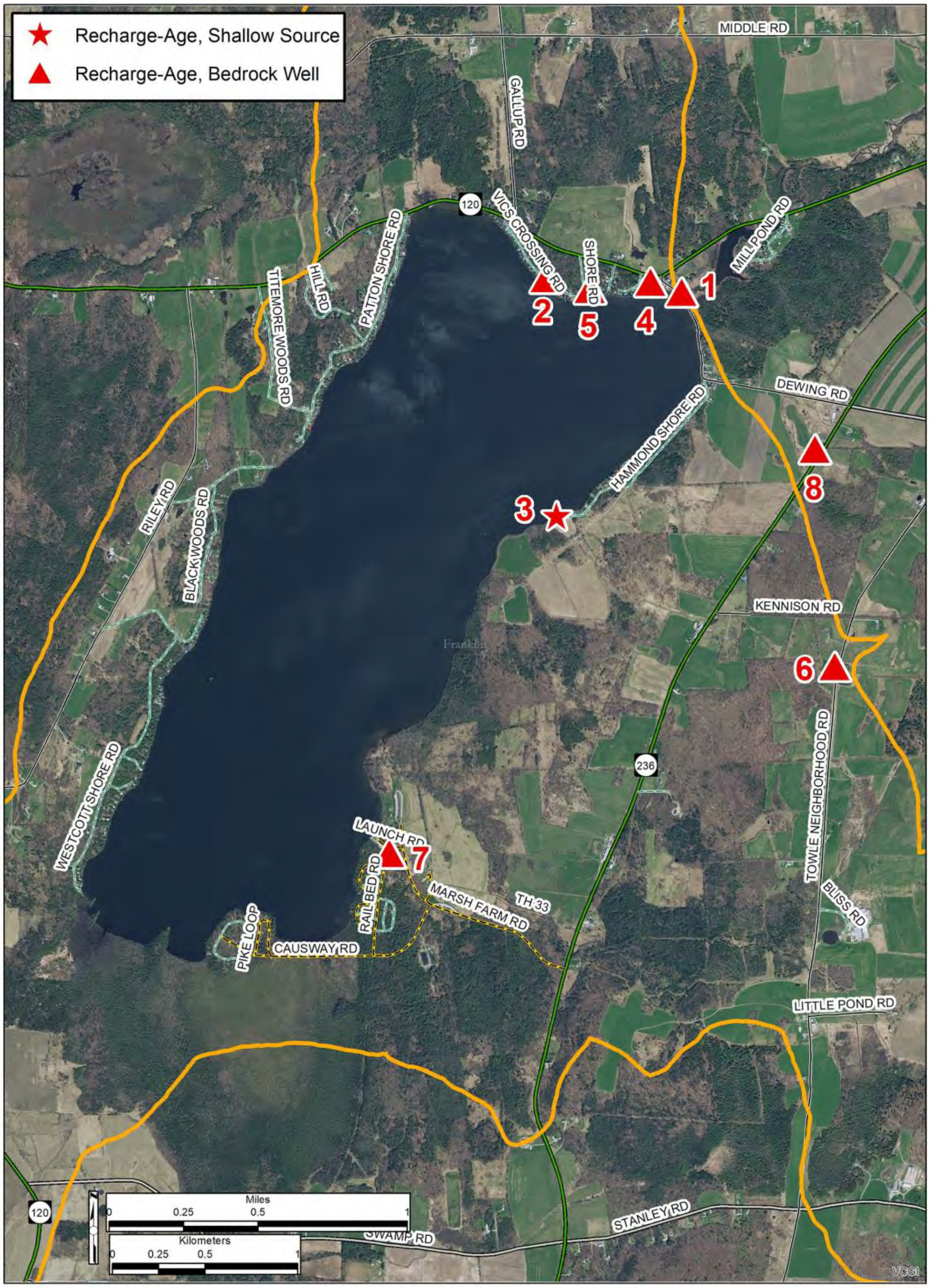


Figure 22- Recharge- age location map.

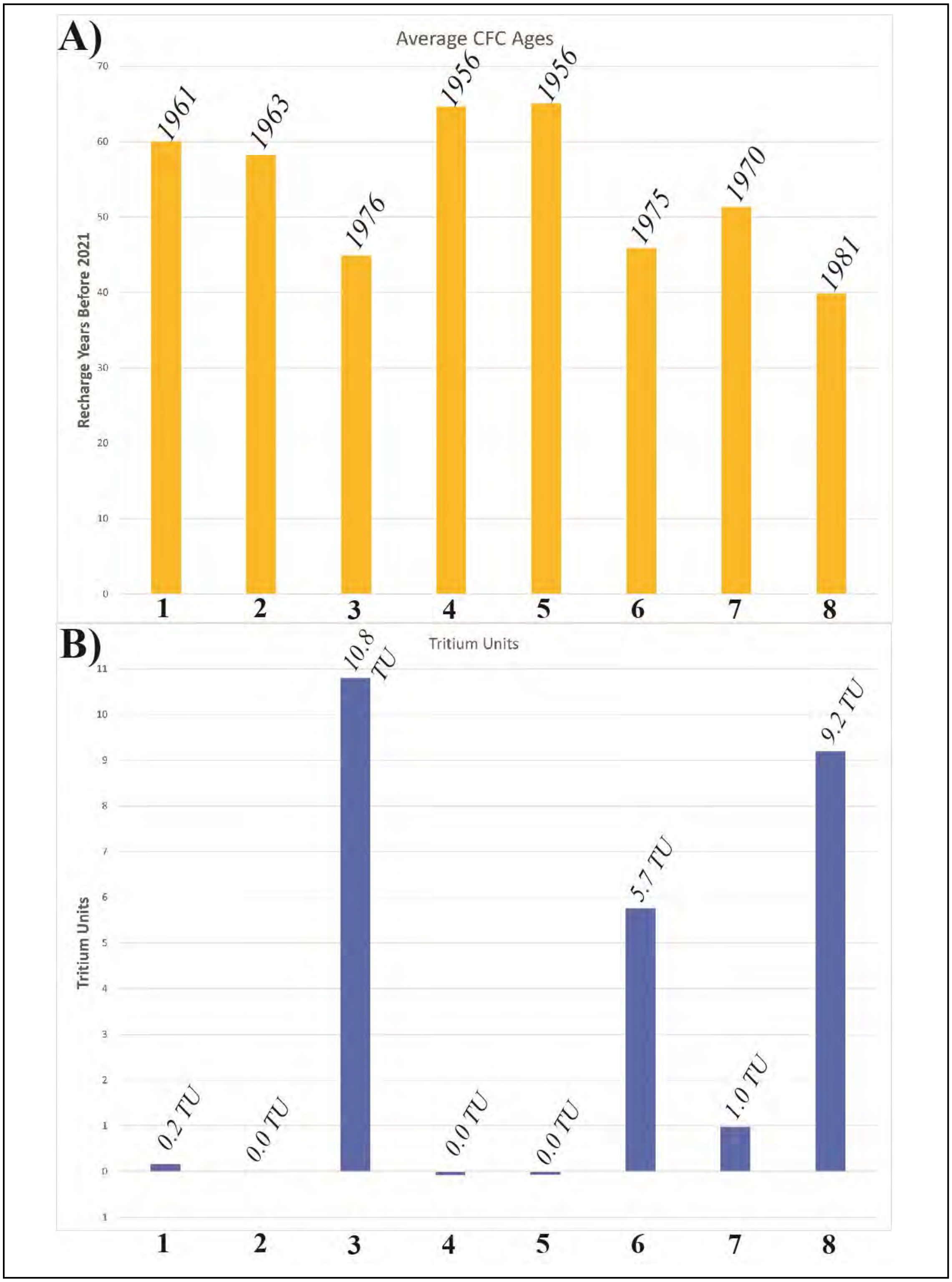


Figure 23- A) Average CFC recharge years (Y axis) and dates above, and B) Tritium concentrations (Tritium Units).

4.0 Discussion and Conceptual Site Model

Our methodology was to 1) build a 3D physical hydrogeological framework for the Lake Carmi Watershed through bedrock and surficial geologic mapping, and the spatial analysis of well driller reports (isopach, bedrock surface contour, and static water level maps), 2) perform a chemical hydrogeologic analysis of groundwater and surface, and 3) integrate the physical and chemical hydrogeologic parameters together to generate a Conceptual Site Model (CSM) for phosphorus and nitrate fate and transport.

4.1 Physical Hydrogeology Synthesis

The bedrock geology map and cross sections (**Figures 2 and 3**) show that the Lake Carmi Watershed is underlain by metamorphic rocks (phyllitic quartzites) of the Fairfield Pond, Pinnacle, and Cheshire formations. Extensive chemistry of the groundwater in these same formations (and the bedrock itself) was completed in west-central Vermont (Kim et al., 2014) and can be used as a reference for this study. The shape of Lake Carmi is strongly controlled by this underlying bedrock 1) in the NE-SW dimension (lake length) by the moderately to steeply dipping dominant foliation ("layering"), and 2) in the NW-SE dimension (lake ends) by the most pervasive fracture set (**Figure 4**). Bedrock islands are present in the SW part of Lake Carmi and have the same structures as in the surrounding bedrock outcrops, indicating they are connected at depth.

Building on the bedrock geology, the surficial geologic map and cross sections (**Figures 5 and 6**), and isopach map (**Figure 8**) show that the surficial deposits in the Lake Carmi Watershed are thickest at the NE end of the lake and very thin in most other areas, particularly on the west and NW sides where the surficial deposits are so thin that the "grain" of the bedrock foliation ("layering") parallel to the lake can be seen in LiDAR imagery. The bedrock surface contour map (**Figure 9**) adds an important 3rd dimension showing that the thickest surficial deposits filled in a channel/depression in the bedrock surface. The static water level (SWL) map for the bedrock aquifer basically shows that groundwater flows from the surrounding highlands toward Lake Carmi (**Figure 10**). By combining all the physical hydrogeology map information together, Lake Carmi can be viewed as a depression in the bedrock surface that extends both to the NNE and SW beneath thick surficial deposits. The areas of thick surficial deposits may host persistent surficial aquifers that may in turn be connected to the underlying bedrock aquifer.

Because there are so few surficial wells in the watershed, it was not possible to make a SWL map for the surficial aquifer at this scale. However, it is reasonable to assume that groundwater in the surficial aquifer also flows towards Lake Carmi. Monitoring wells installed along the lakeshore in a different study (Lakes in Crisis funding) dominantly show flow towards the Lake, with two wells having flow away from the Lake (Kim et al., 2022; Memeger, 2022) (**Figure 24**). The topography of the Lake Carmi Watershed causes streams to flow toward the lake, except at the NE lake outlet.

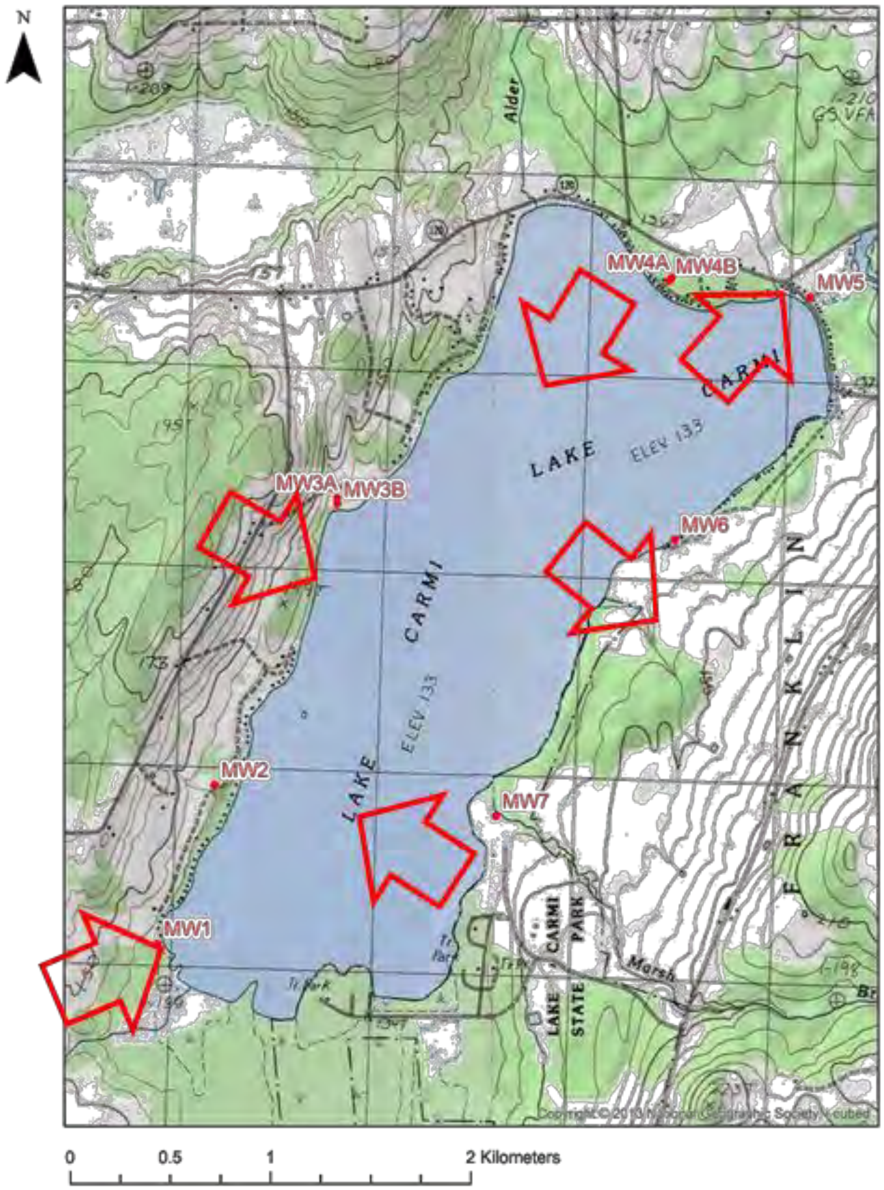


Figure 24- Groundwater flow directions in the surficial aquifer at 7 monitoring well locations around Lake Carmi (modified from Kim et al., 2022). Four locations show groundwater flow toward the lake, whereas two locations show flow from the lake toward the monitoring well. Data is from the separate "Lakes in Crisis"-funded study.

4.2 Chemical Hydrogeology Synthesis

Phosphorus that reaches lakes and causes cyanobacteria blooms can have external sources, including: 1) natural sources derived from the weathering of bedrock, surficial deposits, and soils, 2) agricultural sources related to farm nutrient management, and 3) shoreline development (septic systems, roads, etc.) (e.g., Kim et al., 2022). A fourth source of P, which is internal to a lake, is exchange from lake sediments, but is outside the scope of this investigation.

Groundwater from deep (bedrock) and shallow (surficial) wells indicates P (total) concentrations averaging 9.7 ppb and 20.3 ppb, respectively. Surface water from tributaries average 86.5 ppb and from Lake Carmi average 50.2 ppb. The higher average P (total) concentrations in the tributaries sampled in this study is consistent with the previous studies of VTANR (2008), Gearhardt (2018), and the State of Vermont (2020). A separate contemporary study (Lakes in Crisis funding) of groundwater from surficial (shallow) monitoring wells around Lake Carmi gave average P (total) values of ~54 ppb (Kim et al., 2022). Loewald (2021) determined that a significant amount of P is available in the vadose and saturated zone sediments from monitoring well cores and could be mobilized by groundwater.

The EPA and Vermont Department of Health (VDH) Maximum Contaminant Level (MCL) for nitrate in drinking water is 10 ppm. The potential anthropogenic sources of nitrate include septic systems, fertilized agricultural fields, and compost or manure piles (https://www.healthvermont.gov/health-environment/drinking-water/nitrates-and-nitrites); (http://www.usgs .gov/mission-areas/water-resources/science/chloride-salinity-and-dissolved-solids). The Minnesota Department of Health suggests that natural levels of nitrate can occur up to levels of 3 ppm (https://www.health.state.mn.us/communities/environment/water/contaminants/nitrate.html#Background).

The EPA secondary maximum contaminant level (SMCL) for chloride in drinking water is 250 ppm, which addresses odor, taste, or color issues, but is not a primary health standard. There is no drinking water standard for sodium, but EPA suggests that individuals on low salt diets not ingest water with sodium concentrations >20 ppm. The Center for Agriculture, Food, and the Environment at the University of Massachusetts Amherst summarizes that, although sodium and chloride can occur naturally, most sources in the environment are anthropogenic and include sewage, road salt, fertilizers, industrial waste, water softeners, and sea water proximity (https://ag.umass.edu/cafe/fact-sheets/sodium-chloride-in-private-drinking-water-wells). If a sodium chloride source for water contamination is present, the ratio of chloride to sodium in lab results should be approximately 1.5:1, due to atomic mass differences.

Since one of the goals of this study is to determine if anthropogenic sources of P are present in groundwater and/or surface water, we will first look to see if the concentrations of nitrate, chloride, and sodium occur at levels that would suggest derivation from agricultural or shoreline development. The nitrate levels analyzed in groundwater are very low (less than the maximum of 1.5 ppm), significantly less that the EPA drinking water standard of 10 ppm. The surface water samples from tributaries and the lake are also very low; there are no EPA standards for surface water that are not used for drinking water purposes. The nitrate levels could be natural and/or represent low levels of anthropogenic source input from agriculture or shoreline development.

The SMCL for Cl is 250 ppm and, with the exception of one bedrock well in the NE part of the Lake Carmi Watershed with respective Cl and Na levels of 448 ppm and 303 ppm, Cl and Na levels are low in all groundwater and surface water samples. This well has low NO_x (1.41 ppm), which is within natural (<3 ppm) limits, so the Na and Cl source is probably road salt. The average Cl/Na ratios and percentage of 1.5 Cl/Na for NaCl for each of the water sample groups are bedrock wells = 0.33 (21.7 %), dug and surficial wells = 1.2 (80.2 %), tributaries = 1.50 (99.9 %), and lake = 1.59 (106 %). On average, bedrock wells have the least NaCl followed by intermediate Na levels for surficial wells, and the most for tributaries, and lake samples having more equal proportions of Cl and Na, possibly reflecting low levels of Cl and Na coming from anthropogenic sources.

The next section will discuss the chemical parameters of Total Carbonate Hardness (TCH), Strontium (Sr), Barium (Ba), Silica (SiO_2), and Sulfate (SO_4), which have natural sources in the bedrock and surficial aquifers (Kim et al., 2014; Loewald, 2021; Memeger, 2022). TCH is much higher in the shallow dug and surficial Wells (**Figure 16**) compared to the bedrock wells. Glacial deposits, such as till, usually have similar mineralogy and chemistry as the bedrock formation(s) that it was derived from. The higher levels of TCH in dug and surficial wells could be explained by the fact that the advancing Pleistocene glaciers, which moved from NNW-SSE, carried sediments derived from more calcareous rock formations (i.e., Dunham and Cheshire formations) to the NNW of Lake Carmi to the SSE and deposited this sediment as till (Wright, 2015; 2021). The Fairfield Pond Formation is only locally calcareous. TCH can be a factor in a eutrophic lake, as it may cause P to precipitate (Gonsiorczyk et al., 1997) from the water column.

Kim et al. (2014) used higher Na, Ba, and Sr concentrations and lower Alkalinity (roughly equivalent to TCH) concentrations to "fingerprint" the groundwater chemistry from the Fairfield Pond, Pinnacle, and Cheshire formations in west-central Vermont. This groundwater chemical signature reflects the natural mineralogical and chemical composition of these formations, which is imparted to the groundwater through contact with the rocks and sediment derived from these rocks. In west-central Vermont, these formations comprise the hanging wall of the Hinesburg Thrust Fault. A correlative fault runs through the town center of Franklin. The bedrock wells in the Lake Carmi Watershed also demonstrate the enrichment in Na (**Figure 15**), Sr (**Figure 17**), and Ba (**Figure 18**), and relative depletion in hardness (Figure 16) as their west-central Vermont equivalents. Surficial wells have higher TCH levels and lower Sr and Ba than the bedrock wells. Sr and Ba are also present in tributary and lake samples, but at much lower concentrations. SiO_2 and SO_4, which are also considered to be natural (geogenic) and result from the weathering of silicate and sulfide minerals, respectively (e.g., Reinmann and deCaritat, 1998; Kim et al, 2014). SiO_2 and SO_4 are found in much higher concentrations in bedrock and surficial groundwater well samples than in tributary and lake samples.

For reference, P levels in groundwater for the Fairfield Pond, Pinnacle, and Cheshire formations in west-central Vermont (Kim et al., 2014) averaged 8.7 ppb, as opposed to 9.7 ppb in this study. Another set of wells completed in limestones in the footwall of the Hinesburg Thrust had average groundwater P levels of 25.8 ppb. Shallow surficial wells, tributaries, and lakes were not sampled in the Kim et al. (2014) study. Piper diagrams from Kim et al. (2022) showed that bedrock well samples from the Fairfield Pond, Pinnacle, and Cheshire formations plotted in the same general fields as those from Kim et al. (2014) for the same bedrock formations.

On the stable isotope plot of ð^{2}H (deuterium) vs. ð ^{18}O (**Figure 21**) the different water sample types generally plot in different sections along the local meteoric water line, with bedrock wells in the lower left, tributaries in the middle, and lake samples in the upper right; surficial wells ("dug + surficial") plot among the bedrock well and tributary samples. The fact that there is significant overlap between the surficial wells and both bedrock wells and tributaries is suggestive of mixing between these groups as deep and shallow groundwater interaction and/or as groundwater-surface water interaction. For regional comparison, the compositions of groundwater samples overlap those from the lower elevations on the west flank of Mount Mansfield (Abbott et al., 2000). Boutt (2021) and Boutt et al. (2019) also used stable isotopes in Massachusetts to trace the groundwater and surface water through the hydrologic cycle.

The recharge-ages are from seven bedrock well samples and a single shoreline shallow water supply. The bedrock wells can be divided into 2 groups, 1) "Older" groundwater that recharged to the bedrock aquifer at/before 1953 (**Figure 23**) and followed long flow paths over decades from the surrounding highlands toward Lake Carmi (samples 1, 2, 4, 5) where it discharged and/or was extracted by wells, and 2) "Younger" groundwater that recharged to the bedrock aquifer post-1953, mixed with recharging water of other ages and was extracted by wells on its way toward Lake Carmi (samples 6, 7, 8). Although sample 3 was drawn from the lake near the shore, the persistence of an average CFC date of 1976, may indicate that relatively old groundwater discharges near the lakeshore at this location and mixes with other groundwater and lake water.

4.2.1 Effects of Drought

The U.S. Drought Monitor, which is run by the National Oceanic and Atmospheric Administration (NOAA) and National Integrated Drought Information System (NIDIS) shows that Franklin County, Vermont was in D1 "Moderate Drought" conditions for the entire period of this study (https://www.drought.gov/states/vermont/county/franklin). The drought was documented in the local Vermont media including VTDigger (https://vtdigger.org/2021/07/16/13-month-drought-with-no-end-in-sight-prompts-task-force-to-reassemble/) and Vermont Public Radio (https://www.vermontpublic.org/programs/2020-09-29/is-drought-affecting-vermonts-groundwater). Because of the drought conditions, it was not possible to sample the full complement of tributaries that were sampled in the past by the Franklin Watershed Committee (FWC) and associated local citizen water sampling groups because they were dry. In addition to the drought factor, many tributaries that feed Lake Carmi do not flow year-round in non-drought conditions. We were in regular contact with the former Coordinator of the FWC, Tucker Wehner, during our 2020-2021 study, to see which tributaries he was able to sample biweekly. We sampled as many tributaries as possible during these drought conditions and added Lake Carmi sampling sites as replacements.

Even during drought or low rainfall periods, when the flow in some streams may lessen, most streams do not dry up completely. The replenishment of the surface water in streams comes from groundwater and is called “base flow” (https://www.usgs.gov/special-topics/water-science-school/science/base-flow-rivers), which is a significant form of groundwater-surface water interaction. The water samples that we took from tributaries during the moderate drought of 2020-2021 likely represent base flow and thus consist of a large percentage of groundwater. In fact, many of the tributaries we sampled did not flow continuously between sampling stations, which supports the base flow and groundwater-surface water interaction concept.

4.3 Integrating Physical and Chemical Hydrogeology - The Conceptual Site Model (CSM)

The CSM in **Figure 25** can be used as a framework to summarize the following:

1) Groundwater from the surficial and bedrock aquifers and surface water from tributaries flows from the surrounding highlands toward the Lake Carmi basin.

2) Groundwater from the bedrock and surficial aquifers and surface water can interact and mix on the way to or at the lake.

3) Bedrock islands in Lake Carmi show the same structures as the surrounding rock formations and may connect the bedrock aquifer to the lake.

4) Groundwater from the bedrock and surficial aquifers average ~10 ppb and ~20 ppb P, respectively. A separate study of monitoring wells installed in the surficial aquifer around Lake Carmi yields average P levels of ~50 ppb.

5) The chemistry of groundwater from the surficial and bedrock aquifers is consistent with that of the surficial deposits and bedrock formations, suggesting a natural component of P.

6) Surface water from Lake Carmi tributaries indicates the highest average P (~85 ppb) of all water samples, but a significant component of this may be from groundwater from baseflow during the 2020-2021 drought.

7) With the exception of groundwater from one well, which had Cl concentrations that exceeded EPA’s secondary standard (odor, taste, and color) of 250 ppm, no other shallow or deep wells exceeded either chloride or nitrate (10 ppm) drinking water standards. In fact, all other groundwater and surface water samples had low nitrate (<1.5 ppm) and chloride (<20 ppm), suggesting that input from anthropogenic sources such as agriculture and shoreline development is currently low.

Conceptual Site Model for Lake Carmi

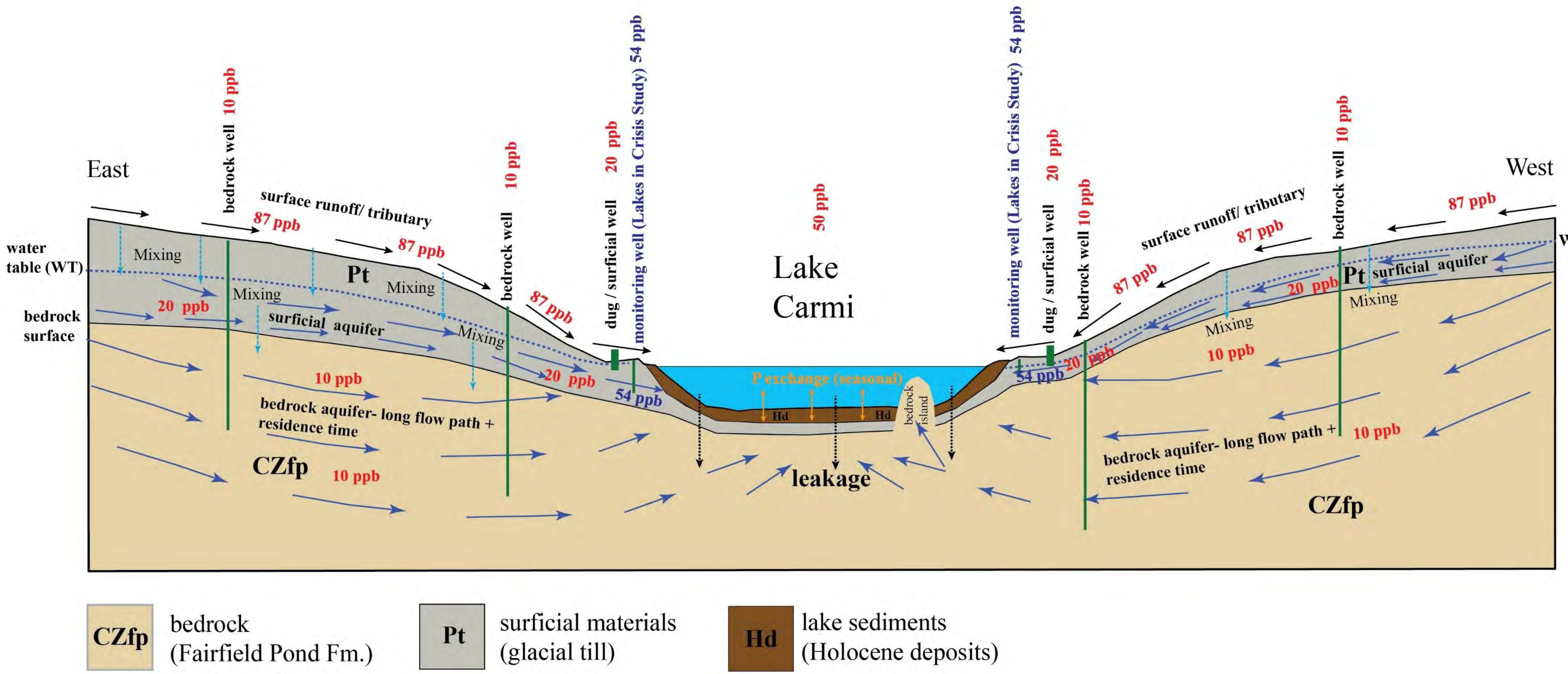


Figure 25

5.0 Outcomes

This study directly addressed the following outcomes in the original proposal:

1) Increased understanding of the role that groundwater plays in transporting nutrients from source(s) to surface water bodies will impact management of water quality in Lake Carmi and other surface waters in Vermont and the northeastern United States.

2) Developed preliminary visualization of groundwater and surface water interaction in the Lake Carmi watershed.

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