DELINEATION OF FLOW PATHS, CAPTURE ZONES, AND SOURCE AREAS
ALLEQUASH BASIN, VILAS COUNTY, WISCONSIN

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PROJECT SUMMARY

Title: Delineation of Flow Paths, Capture Zones, and Source Areas, Allequash Basin, Vilas County, Wisconsin

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Background/Need: Lakes, streams, and wetlands in Wisconsin are well connected to the groundwater system. Consequently, the chemistry of groundwater may appreciably influence the chemistry of surface waters, and vice versa. The testing of tools to identify source areas of recharge and geologic controls on groundwater chemistry is therefore crucial to understanding and protecting both groundwater and surface water. One area where water resources protection is becoming increasingly important is the Northern Highlands Lake District (NHLD) located in northern Wisconsin, which is currently experiencing pressures from increasing development. As population increases within the NHLD, assessing groundwater flow and chemistry prior to further development will help efforts to mitigate effects of development and protect and maintain the ecology of these lakes. It is believed that the Allequash basin, a sub-basin of the Trout Lake watershed in Vilas County, Wisconsin, is representative of many other basins located within the NHLD.

Objectives: Four main objectives were addressed in this study, as follows: (1) to determine the spatial and temporal characteristics of source waters (terrestrial vs. lake/wetland) for groundwater along three transects within the Allequash basin using $\delta^{18}O$ data and to use this water isotopic signal to trace groundwater flow paths within the transects; (2) to characterize both the spatial and temporal variability of groundwater chemistry within the transects using $\delta^{87}Sr$ and major ion concentration data and to investigate controlling factors on groundwater chemistry; (3) to examine the effects of lake level fluctuations on groundwater flow direction within the Allequash basin and relate these changes in flow direction to temporal changes in groundwater chemistry; and (4) to delineate capture zones for selected lakes and streams.

Methods: Monthly groundwater samples were collected from 75 nested piezometers along three transects in the Allequash basin from June-November 2004. Samples were analyzed for the isotopes of $\delta^{18}O$ and $\delta^{87}Sr$, as well as major ion concentrations, iron, and inorganic and organic dissolved carbon species. The $\delta^{18}O$ data were used to identify the source areas of recharge and to delineate groundwater flow paths in the transects. Major ion chemistry, iron, and $\delta^{87}Sr$ data were used to investigate the chemical evolution of groundwater along each transect and to characterize mineral/water contact time and groundwater mobility. Transience in the groundwater flow field was investigated and the steady-state capture zones for surface waters within the Allequash basin were delineated using a three-dimensional groundwater flow model of the Trout Lake basin and particle tracking simulations.

Results and Discussion: Each transect contains multiple flow paths derived from different source areas causing surprisingly complex spatial variability of groundwater chemistry within the relatively homogeneous aquifer in Allequash basin. Significant temporal variability in groundwater chemistry was observed at two sites along one transect where fluctuation in lake level causes shifts in groundwater flow paths. Steady-state capture zone analysis indicates that capture zones delineated using particle tracking

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simulations are sensitive to the way in which particle capture by sinks, which are used to represent the lakes and stream, are specified in the groundwater flow model. The capture zone analysis showed underflow of groundwater beneath seepage lakes upgradient of Allequash Lake, signifying the importance of three-dimensional flow within the Trout Lake basin. Groundwater flow paths may originate upgradient of these seepage lakes, flow underneath the lakes to discharge to Allequash Lake. Travel times are as much as 160 years.

Conclusions and Recommendations: The methodology of using $\delta^{18}O$ to delineate source areas and flow paths was successfully applied in the Allequash basin and should be successful throughout the NHLD as aquifers in the NHLD consist of glacial sediments similar to that found within the Allequash basin and surface waters are well connected to the groundwater system throughout the NHLD. Delineation of groundwater flow paths provides insight into source areas and movement of contaminants due to human activity and development. Characterization of the current surface water/groundwater chemistry, using the methodologies presented in this study, will aid in identifying and quantifying future human impacts, which is the first step in developing a mitigation plan to protect and maintain the ecology of surface water and groundwater within the NHLD.

Related Publications:

Masbruch, M.D., Hunt, R.J., and Anderson, M. P. 2005. Investigation of Three Flowpaths of Different Lengths, Allequash Basin, Vilas County, Wisconsin (*abstract*). Wisconsin's Waters: A Confluence of Perspectives: Delavan, WI, *Wisconsin Section of the American Water Resources Association*, p. 44.

Masbruch, M.D., Hunt, R.J., and Anderson, M. P. 2005. Delineation of Flow Paths and Processes Affecting Chemical Variability, Allequash Basin, Wisconsin (*abstract*). *Geological Society of America Abstracts with Programs, Annual Meeting*, Salt Lake City, Utah, October 2005.

Masbruch, M.D., 2005, Delineation of Source Areas and Characterization of Chemical Variability using Isotopes and Major Ion Chemistry, Allequash Basin, Wisconsin, *MS Thesis*, Department of Geology and Geophysics: Madison, WI, University of Wisconsin - Madison, 131 pp.

Key Words: groundwater, groundwater chemistry, isotopes, flow paths, capture zones

INTRODUCTION

The Trout Lake watershed (Figure 1) is one of the National Science Foundation's Long-Term Ecological Research (NSF LTER) sites and the Allequash basin (Figure 1) is one of the U.S. Geological Survey's Water, Energy, and Biogeochemical Budgets (USGS WEBB) sites. Consequently, there is a wealth of information for this area from previous and ongoing work encompassing the fields of geology, biology, ecology and limnology. The Trout Lake watershed lies within two state forests with a mixture of deciduous and coniferous trees and within the Northern Highlands Lake District (NHLD), which contains thousands of kettle lakes formed during the last episode of continental glaciation (~10 Ka).
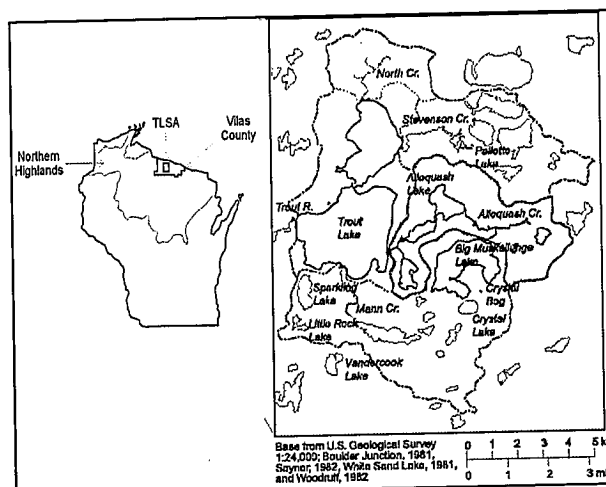

Figure 1. Location map of the Trout Lake watershed. Allequash basin is outlined in red. (Modified from Walker et al. 2003)

The geology of the Trout Lake watershed consists of Precambrian crystalline rock overlain by ~30-50 m thick unconsolidated glacial outwash sediments (Okwueze 1983; Attig 1985) of very well- to moderately well-sorted sand and gravelly sand (Attig 1985). These sediments, which make up the primary aquifer within the Allequash basin (Attig 1985; Kenoyer 1986), contain mainly silicate minerals homogeneously distributed throughout the aquifer with silicate hydrolysis the main control on groundwater chemistry (Kenoyer and Bowser 1992a; Bullen et al. 1996; Kim 1996; Keating and Bahr 1998; Walker and Krabbenhoft 1998; Bowser and Jones 2002).

The Allequash basin has a surface water drainage area of ~22 km^2 and ranges in elevation from ~490 m to 520 m above mean sea level (Walker et al. 2003). Lakes upgradient of the basin include Crystal Lake and Big Muskellunge Lake, which are seepage lakes with no surface water inlets or outlets. The main discharge areas for the basin are Allequash Lake and Allequash Creek (Figure 1). The lakes and other surface water features are well connected to the aquifer. For example, Crystal Lake and Big Muskellunge Lake are flow-through lakes, in which groundwater discharges to the lake on the upgradient side of the lake and lake water recharges the groundwater system on the downgradient side of the lake.

In conjunction with the NSF LTER and USGS WEBB research programs, numerous geochemical groundwater studies have been conducted in the area. The use of the stable water isotopes (δD and δ^{18}O) in groundwater studies in the Trout Lake watershed was pioneered by Krabbenhoft (1988) and has since been used by Krabbenhoft et al. (1992), Ackerman (1992), Kim (1996), Walker and Krabbenhoft (1998), Walker et al. (2003) and Hunt et al. (2005). Variability in ^{87}Sr/^{86}Sr ratios, observed by Walker et al. (2003) and Hunt et al. (2005) in studies in the basin, is caused by differences in groundwater mobility (Bullen et al. 1996).

In other geochemical research in the basin, Kim (1996) and Bullen et al. (1996) used δ^{18}O values and major ion concentrations to define groundwater flow paths across the isthmus between Crystal Lake and Big Muskellunge Lake. Bullen et al. (1996) used δ^{87}Sr values and major ion concentrations to describe the kinetic and mineralogic controls on chemical evolution of groundwater flowing beneath the isthmus between Crystal and Big Muskellunge Lakes. Keating and Bahr (1998), Walker and Krabbenhoft (1998) and Walker et al. (2003) collected groundwater samples in 1991-1994 at sites along Allequash Creek, within Allequash Lake, and at nested piezometers within three transects perpendicular to and across Allequash Creek. The transects were located at a headwaters site, an intermediate site known as the

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Middle Site, and a downstream site at Allequash Lake. Walker and Krabbenhoft (1998) and Walker et al. (2003) used δD and $\delta^{18}O$ values to determine the source of recharging waters, which led to the discovery of a plume of oxygen-18 enriched water in the subsurface derived from Big Muskellunge Lake and extending towards Allequash Creek. Keating and Bahr (1998), Walker and Krabbenhoft (1998), and Walker et al. (2003) used calcium concentrations to quantify flow path lengths, and Walker and Krabbenhoft (1998) and Walker et al. (2003) used $\delta^{87}Sr$ values to characterize the mobility of groundwater at these sites. Hunt et al. (2005) used $\delta^{18}O$ to delineate source waters for groundwater samples collected along the hill slopes and beneath Allequash Creek at the Middle Site. They used $\delta^{87}Sr$ data to identify a stagnation zone beneath Allequash Creek at the Middle Site.

The ongoing development of a groundwater-based watershed model for the Trout Lake watershed is represented in studies by Cheng (1994), Hunt et al. (1998), Champion and Anderson (2000), Pint (2002), and Hunt et al. (2005). The version of the model used in the current study is based on Pint (2002) as re-calibrated by Hunt (personal communication, April 2005). Pint (2002), Anderson and Pint (2002) and Pint et al. (2003) used a three-dimensional groundwater flow model to delineate groundwater capture zones in two-dimensions for selected lakes and streams in the Trout Lake basin, including Allequash Lake and Allequash Creek. Groundwater flow paths, delineated using backward particle tracking simulations, showed travel times as much as 200 years.

The NHLD is currently experiencing pressures from increasing development. Assessing groundwater flow and chemistry prior to further development will help efforts to mitigate effects of development and protect and maintain the ecology of these lakes, as many lakes within the NHLD are well connected to the groundwater system. The testing of tools to identify source areas of recharge and geologic controls on groundwater chemistry is therefore crucial to understanding and protecting both groundwater and surface water in this area.

Piezometers were installed and groundwater samples were collected along three transects within the Allequash basin to delineate flow paths and to assess spatial and temporal variability in groundwater chemistry. Samples were collected monthly from June to November 2004, and analyzed for the isotopes $\delta^{18}O$ and $\delta^{87}Sr$ as well as major ion concentrations, iron, and organic and inorganic dissolved carbon species. Measurements of temperature, pH, specific conductance, and dissolved oxygen were taken in the field. Four objectives were addressed, as follows: (1) to determine the spatial and temporal characteristics of source waters (terrestrial vs. lake/wetland) for groundwater within the three transects using $\delta^{18}O$ and to use this water isotopic signal to trace groundwater flow paths within the transects; (2) to characterize the spatial and temporal variability of groundwater chemistry within the transects using $\delta^{87}Sr$ and major ion concentration data and to investigate the controlling factors on groundwater chemistry; (3) to examine the effects of fluctuating lake levels on groundwater flow direction and changes in groundwater chemistry; and (4) to delineate capture zones for Crystal Lake, Big Muskellunge Lake, Allequash Lake, and Allequash Creek.

PROCEDURES AND METHODS
The three transects investigated in this study (transect 1, transect 2, and transect 5, Figure 2) include a total of 75 piezometers distributed among twelve sites. Sites along transects 1 and 2 contain piezometer nests and water table wells that were installed in the mid-1990's. Transects 1 and 2 were sampled in this research to compare with results from previous studies and to determine if there are temporal shifts in flow paths along these transects. Sites T5-10 and T5-20 (transect 5, Figure 2) had one piezometer each installed during a previous investigation in September 2001. In May 2004, additional piezometer nests and water table wells were installed in this transect. Sites in transect 5 were chosen to try to capture the long flow path predicted by Pint (2002) and Pint et al. (2003), which originates upgradient of Crystal

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Lake and is believed to discharge in Allequash Lake downgradient of site T5-95 (Figure 2). Sites T5-10, T5-20, and T5-30 were located to capture transience in this long flow path.

Analyses for $\delta^{18}O$, $\delta^{87}Sr$, and major cations were performed by the USGS National Research Program Laboratory in Menlo Park, CA. Oxygen-18 values were measured using CO_2-H_2O equilibration on a Finnigan-Mat 251 mass spectrometer (Walker et al. 2003). Strontium isotopes were measured on a Finnigan MAT 261 mass spectrometer (Bullen et al. 1996). Cations were measured on a Jarrel Ash inductively-coupled plasma atomic emission spectrophotometer (Bullen et al. 1996). All values of $\delta^{18}O$ are reported relative to the standard V-SMOW ($\delta^{18}O$ = 0.0‰) and all values of $\delta^{87}Sr$ are reported relative to the standard NIST-987 ($^{87}Sr/^{86}Sr$ = 0.71024).

Major anions were analyzed at the River Ecology Laboratory, Center for Limnology, University of Wisconsin-Madison, using a Dionex DX-500 Ion Chromatograph with an AS40 autosampler. Alkalinity samples were analyzed by Melissa Masbruch at the USGS field office in Middleton, WI using an automated titrator and 0.05 N HCl. The Gran plot method was used to calculate the alkalinity of the samples. Dissolved inorganic and organic carbon (DIC and DOC) were analyzed by the Water Chemistry Laboratory, University of Wisconsin-Madison, using a Shimadzu TOC-V$_{CPH}$ carbon and nitrogen analyzer.

Figure 2. Map showing locations of nested piezometer sites/transects investigated in the study. (Base from USGS 1:24,000 North Temperate Lakes Research Area map.)

The $\delta^{18}O$ data were used to delineate source waters of recharge to groundwater within the transects and to trace groundwater flow paths from point of origin to discharge. There are three main sources of recharge to the groundwater system within the Allequash basin, as follows: (1) terrestrial-derived recharge from meteoric water that recharges groundwater through the land surface, (2) wetland-derived recharge from meteoric water that recharges groundwater through wetland surfaces, and (3) lake-derived recharge from lake water that enters the groundwater system through the lakebed. Previous studies (Ackerman 1992; Krabbenhoft et al. 1994; Bullen et al. 1996; Walker and Krabbenhoft 1998; Walker et al. 2003) show that the average $\delta^{18}O$ value for lakes within the Allequash basin ranges from around -3.2‰ (Crystal Lake) to -4.5‰ (Big Muskellunge Lake) while the average $\delta^{18}O$ value for terrestrial-derived recharge is about -11.3‰. Groundwater recharged through wetlands has a $\delta^{18}O$ signature intermediate between these two end members. Because of the conservative nature of the water isotopes, groundwater retains a distinct $\delta^{18}O$ signature as it moves through the subsurface and thus the isotope is an excellent tracer.

Major ion chemistry, along with iron and $\delta^{87}Sr$ data, were used to investigate the chemical evolution of groundwater in each transect and to characterize mineral/water contact time and groundwater mobility.
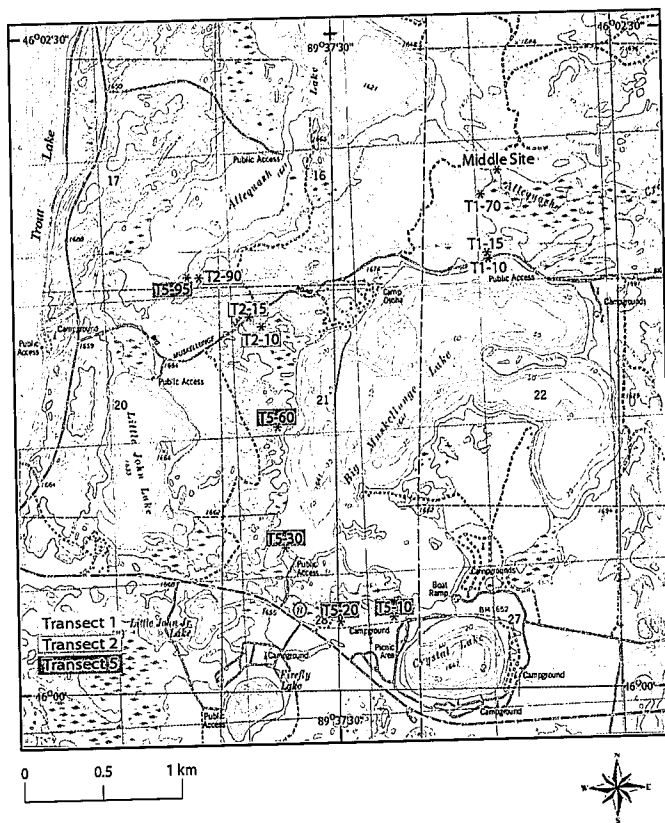
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Previous studies (Kenoyer and Bowser 1992a; Keating and Bahr 1998; Walker et al. 2003) show that calcium is a useful indicator of mineral/water contact time and flow path length at a given velocity owing to the absence of carbonate minerals and the near-neutral pH of groundwater in the aquifer. As mineral/water contact time increases, calcium concentration increases. However, because slow groundwater velocities also increase mineral/water contact time, calcium concentrations alone cannot be used to distinguish between short, slow velocity groundwater flow paths and long, fast velocity groundwater flow paths; $\delta^{87}Sr$ is useful in making this distinction.

The $\delta^{87}Sr$ values were used to identify dissolution of specific minerals and to characterize the relative mobility of groundwater. Where subsurface velocities are relatively slow, such as in the unsaturated zone or in poorly transmissive, fine-grained portions of the aquifer, $\delta^{87}Sr$ tends to become more positive relative to the $\delta^{87}Sr$ of the source water (Bullen et al. 1996). Low groundwater mobility tends to suppress the dissolution of plagioclase and calcium-magnesium silicates due to the precipitation of clay minerals under stagnant conditions, which are more likely to form on the surfaces of plagioclase and hornblende (Bullen et al. 1996). Therefore, under low mobility conditions, there is preferential dissolution of the more radiogenic strontium mineral phases such as K-feldspar and biotite. In contrast, where subsurface velocities are relatively fast, such as in highly transmissive portions of the aquifer, $\delta^{87}Sr$ becomes more negative relative to the source water. Under higher groundwater mobility, clay minerals, which form due to the dissolution of aluminosilicate minerals, are thought to be carried in suspension and the amount of relatively unradiogenic strontium released from the dissolution of plagioclase and calcium-magnesium silicates tends to be much greater than the amount of strontium released from the dissolution of the more radiogenic strontium phases (Bullen et al. 1996). By interpreting calcium concentration data in conjunction with $\delta^{87}Sr$ data, groundwater flow path lengths and relative magnitudes of mobility are inferred.

An existing three-dimensional groundwater flow model of the Trout Lake basin (Masbruch 2005) was used with particle tracking simulations to determine the effects of fluctuations in lake level on groundwater flow direction and to delineate capture zones of surface water features within the basin. The model was run using the finite difference code MODFLOW-2000 (Harbaugh et al. 2000). Particle tracking simulations used MODPATH (Pollock 1994) (version 4.3). Both codes were run using the graphical user interface Groundwater Vistas (Environmental Simulation International, Inc.), version 4.18 build 19.

Figure 3. Transect 1. (A) Contours of $\delta^{18}O$ in cross section, June 2004. (B) Contours of $\delta^{87}Sr$ in cross section, July 2004.

RESULTS AND DISCUSSION

Transect 1: Two distinct groundwater flow paths are evident in this transect. Contours of $\delta^{18}O$ data in cross section (Figure 3A) indicate a large, lake-derived groundwater plume at depth extending the entire length of the transect with a smaller
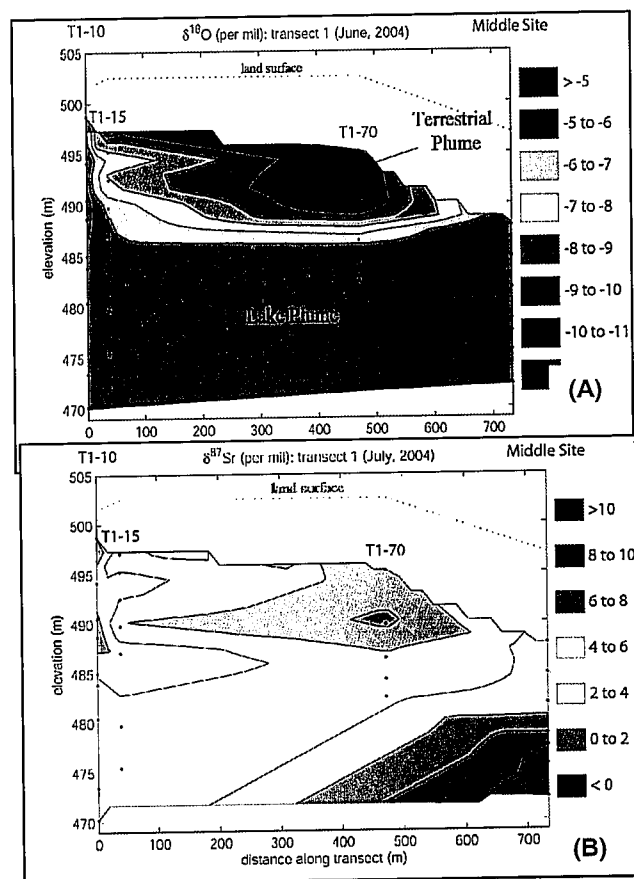
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terrestrial-derived plume at shallower depths. There is little mixing between the two plumes as implied by the closely spaced contours at the interface between the plumes. The contoured data also imply upward flow and discharge at the Middle Site where the thickness of terrestrial-derived water diminishes. These δ^{18}O data are consistent with results by Walker et al. (2003) and Hunt et al. (2005).

The δ^{87}Sr values (Figure 3B) decrease between sites T1-10 and T1-70 along both the terrestrial-derived groundwater plume and shallower sections of the lake-derived groundwater plume, indicating preferential dissolution of plagioclase and calcium-magnesium silicates and relatively mobile groundwater. However, δ^{87}Sr increases between site T1-70 and the Middle Site (Figure 3B), indicating preferential dissolution of K-feldspar and biotite and decreasing groundwater mobility towards the discharge point at the Middle Site. Lower groundwater velocity near the Middle Site is most likely due to the existence of a stagnation point/zone beneath Allequash Creek (Hunt et al. 2005).

Calcium concentrations of ~16 to 18 mg/L at the Middle Site are consistent with Walker et al. (2003) who reported a concentration of ~18 mg/L there. Furthermore, according to Walker et al. (2003) concentrations between 10 and 20 mg/L indicate an intermediate-length flow path on the order of a kilometer; the length of transect 1 is ~733 m. Calcium concentrations near the Middle Site are likely enhanced by low groundwater mobility, which increases mineral/water contact time.

Transect 2: There are four distinct groundwater flow paths in this transect. Contours of δ^{18}O in cross section (Figure 4A) indicate a plume of lake water between sites T2-10 and T2-15 at depth, transitioning upward into plumes of wetland-derived water and terrestrial-derived water, which extend the length of the transect. A terrestrial-derived source for groundwater in the deepest piezometer at site T2-10 is also indicated. The configuration of contours in the shallower terrestrial-derived and wetland-derived plumes implies downward flow along the entire length of the transect. Unlike transect 1, there does not appear to be any upward flow at the downgradient end of the transect (site T2-90), indicating that the discharge point for this transect likely occurs further downgradient closer to or in Allequash Lake. These data are consistent with Walker et al. (2003), who in 1994 measured δ^{18}O values of approximately -5.5‰ to -11.5‰ downgradient of site T2-90 indicating lake-derived, terrestrial-derived, and mixed (wetland-derived) source waters discharging into the lake.

The δ^{87}Sr values in the shallow terrestrial-derived plume and the lake-derived plume decrease downgradient (Figure 4B) indicating preferential dissolution of plagioclase and calcium-magnesium silicates and relatively more mobile
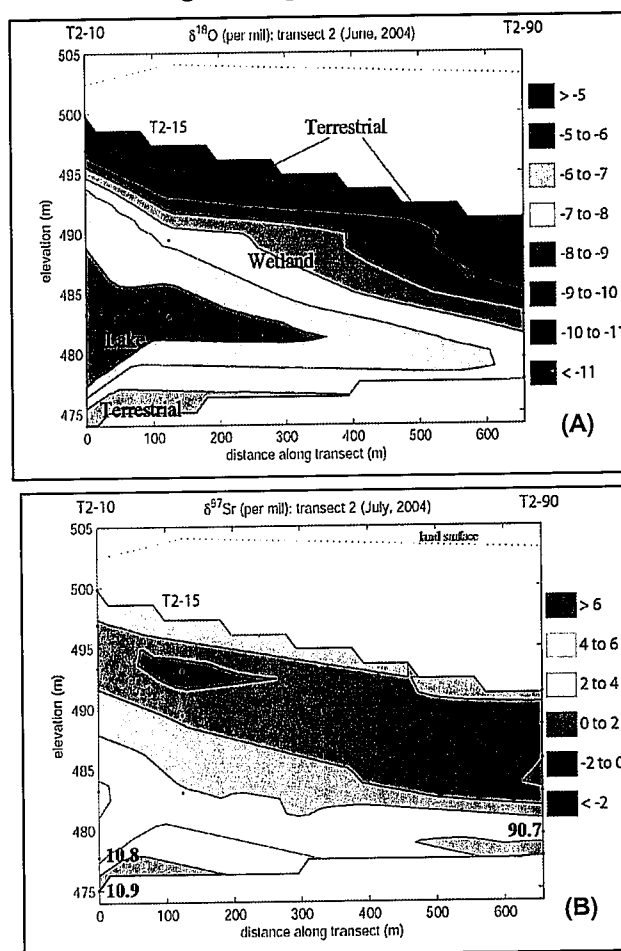

Figure 4. Transect 2. **(A)** Contours of δ^{18}O in cross section, June 2004. **(B)** Contours of δ^{87}Sr in cross section, July 2004. Numbers (10.8, 10.9 and 90.7) indicate sampling locations.

water. In the wetland-derived plume, however, $\delta^{87}Sr$ increases downgradient towards piezometer T2-90.7 indicating preferential dissolution of K-feldspar and biotite and decreasing groundwater mobility. Low groundwater velocities would also explain the high calcium concentrations (~18-20 mg/L) measured at piezometers T2-90.7, T2-10.8 and T2-10.9. This area of low groundwater velocity may indicate the presence of less permeable material such as a buried till layer. The calcium concentrations observed in this study are consistent with Walker et al. (2003), who measured calcium concentrations of ~10-25 mg/L beneath Allequash Lake downgradient of site T2-90. Calcium concentrations between 10 and 20 mg/L indicate an intermediate-length flow path on the order of a km; the length of transect 2 is ~655 m.

Transect 5: Chemical trends along transect 5 are hard to characterize because not all of the sites along this transect lie along the same flow path. The locations of the nested piezometer sites were chosen to capture transience in a long flow path predicted to originate upgradient of Crystal Lake (Pint et al. 2003). Sites T5-10, T5-20, and T5-30 were purposely located west of the predicted flow path to capture directional shifts in response to changes in level in Big Muskellunge Lake. Sites T5-60 and T5-95 are located on the horizontal coordinates of the predicted flow path; however, $\delta^{18}O$ data (Figure 5A) indicate that groundwater at these sites is from a lake-derived source, either Crystal Lake or Big Muskellunge Lake, while Pint et al.'s (2003) model suggests that a terrestrial-derived plume from a source upgradient of Big Muskellunge Lake exists at depth. However, since piezometers in the transect penetrate only to ~3.7 m, they likely are not deep enough to capture the terrestrial-derived source suggested by Pint et al. (2003).

Contours of $\delta^{18}O$ (Figure 5A) indicate a plume of lake water extending from sites T5-30 to T5-60. There is a small shallow plume of terrestrial-derived water upgradient of site T5-30. Flowing wells, indicative of a strong upward gradient, were observed at site T5-95, which is the discharge zone for this transect. The mixed-source $\delta^{18}O$ signal at site T5-95 indicates that terrestrial-derived water mixes with lake-derived water downgradient of site T5-60. The mixed $\delta^{18}O$ signal at site T5-95 is consistent with Walker et al. (2003), who also observed a mixed $\delta^{18}O$ signature from samples collected beneath Allequash Lake just downgradient of site T5-95 in 1994.

Figure 5. Transect 5. (A) Contours of $\delta^{18}O$ in cross section, June 2004. (B) Contours of $\delta^{87}Sr$ in cross section, July 2004.

The $\delta^{87}Sr$ values (Figure 5B) increase downgradient towards site T5-30 indicating preferential dissolution of the more radiogenic mineral phases of K-feldspar and biotite and decreasing groundwater mobility. As T5-30 is in an area of divergent groundwater flow, there may be a stagnation point in the vicinity or a lens of fine-grained, less permeable material from slumping of deposits along depressions/lakes formed from buried chunks of ice, which is commonly observed along the southern margins of these depressions
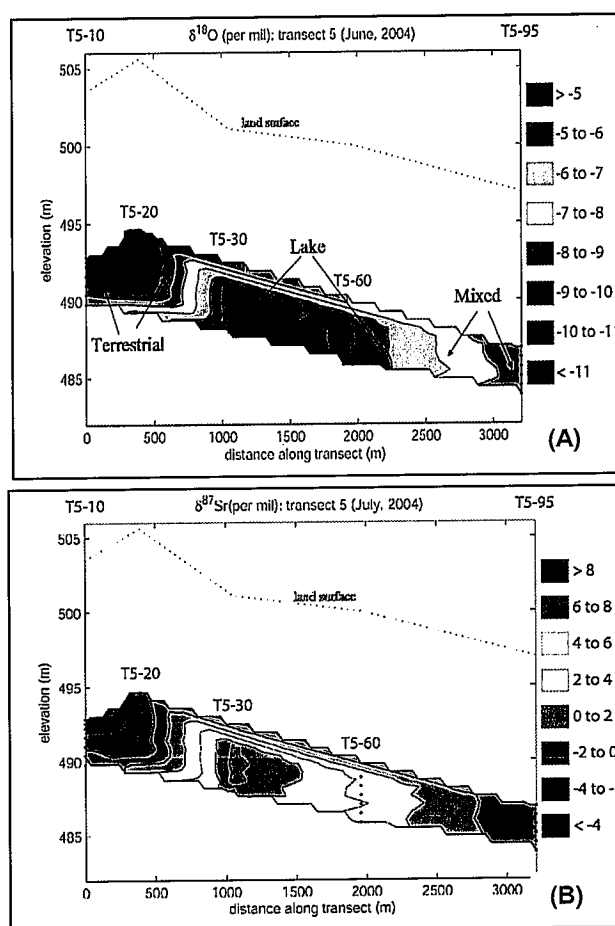
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(Attig 1985). Downgradient of site T5-30 groundwater becomes less radiogenic indicating preferential dissolution of plagioclase and calcium-magnesium silicates and increasing groundwater mobility.

Calcium concentrations along transect 5 are relatively low with highest concentrations of ~13 mg/L at site T5-60, which is ~2000 m along the transect. Furthermore, calcium concentrations at site T5-95, which is located over 1 km farther downgradient of site T5-60, are only ~7 to 8 mg/L. Walker et al. (2003) predicted calcium concentrations in excess of 20 mg/L for flow paths of several kilometers in length; they measured calcium concentrations up to 45 mg/L in groundwater samples collected (in 1994) beneath Allequash Lake just downgradient of site T5-95, suggesting discharge of water from a very long flow path as predicted by Pint et al. (2003). It is likely the piezometers sampled in the present study were not deep enough to capture groundwater from this long flow path but instead captured shorter and shallower flow paths with lower calcium concentrations.

Flow Paths: The flow paths estimated from the oxygen isotope analyses are shown schematically in Figure 6.
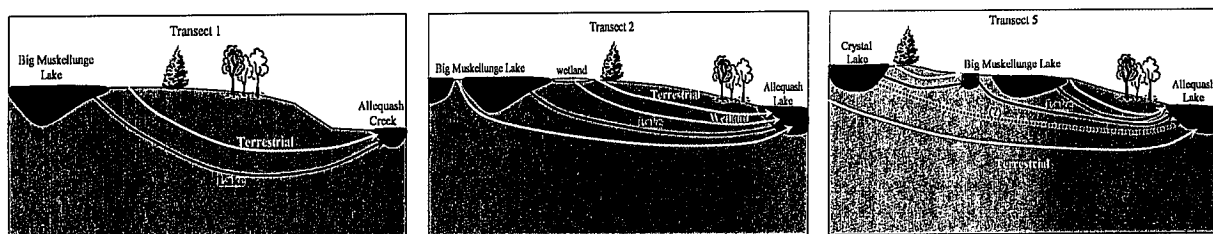

Figure 6. Schematic diagrams showing inferred flow paths in transects 1, 2 and 5.

Temporal variability: Alkalinity data illustrate the temporal variability in major ion chemistry as these data reflect temporal trends observed in other major ions. While there was little to no monthly variability at most of the sites, sites T5-30 and T5-60 showed significant variability (Figure 7). Both of these sites are near or downgradient of a divergent area in the flow field west of Big Muskellunge Lake (Figure 8). Depending on the level of Big Muskellunge Lake, groundwater flows towards Allequash Lake (flow paths 4, 5 in Figure 8) or directly towards Trout Lake (flow paths 1, 2, 3). Fluctuations in lake level cause the flow paths to shift. Therefore, as lake levels in Big Muskellunge Lake fluctuated during the summer of 2004 different parcels of groundwater moving along different flow paths flowed through sites T5-30 and T5-60 causing transience in the groundwater chemistry measured at the sites. Our simulations did not consider fluctuations in recharge rate, which may also cause flow paths to change direction. Kim et al. (2000) found that flow paths in the isthmus between Crystal and Big Muskellunge Lakes were affected more by fluctuations in recharge rate than lake level.
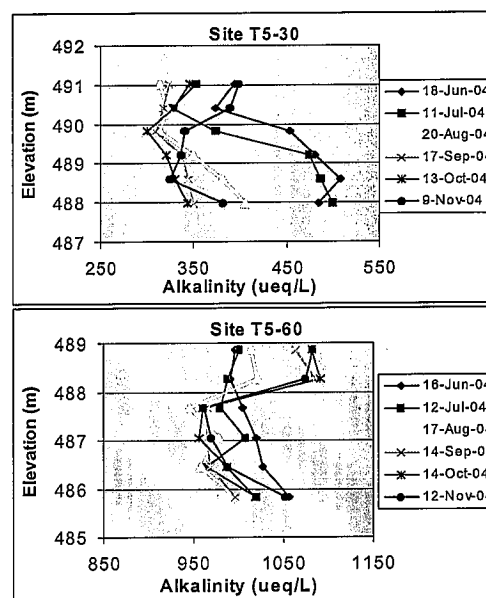

Figure 7. Alkalinity data at sites T5-30 and T5-60, located along transect 5 in an area of divergent flow.

Capture zone analysis: Capture zone results (Figure 9) are generally consistent with Anderson and Pint (2002) showing significant underflow of groundwater beneath Crystal Lake and Big Muskellunge Lake. Flow paths may originate upgradient of Crystal and Big Muskellunge Lakes (Figure 9) flowing underneath the lakes to discharge to Allequash Lake with travel times as much as 160 years. Results were sensitive to the way in which particle discharge to weak-sink cells was specified; groundwater inflow to the lakes taken from Ackerman (1992) were used to estimate appropriate values for the strength of the sink nodes used to represent the lakes (Masbruch 2005).
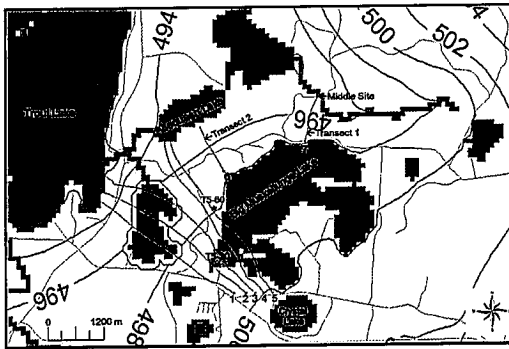

Figure 8. Particle tracking simulations showing area of divergent flow west of Big Muskellunge Lake. Particle paths, numbered 1 –7, are shown in red with starting positions indicated by red dots. Big Muskellunge Lake level is 499.25 m above m.s.l. in this simulation.
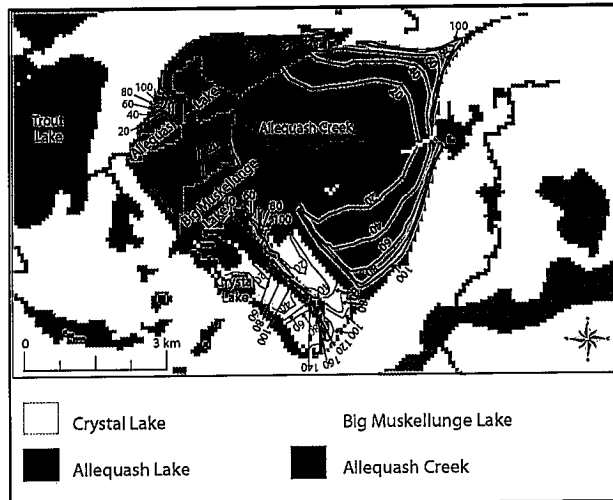

Figure 9. Capture zones for Crystal Lake, Big Muskellunge Lake, Allequash Lake, and Allequash Creek. Travel time contours (in years) for Big Muskellunge Lake are shown in red and in black for Allequash Lake and Allequash Creek.

CONCLUSIONS AND RECOMMENDATIONS

The use of $\delta^{18}O$ as a tracer to delineate groundwater flow paths and source areas was successfully applied in three transects in the Allequash basin. Each transect studied in this research contains multiple flow paths derived from different source areas (Figure 6). Differences in source area, flow path length and magnitude of groundwater velocity cause considerable spatial variability in groundwater chemistry within the Allequash basin (Figures 3B, 4B, 5B) even though the glacial outwash aquifer is relatively homogeneous.

Groundwater chemistry in a natural setting is usually assumed to be constant with time. However, we found that fluctuation in the level of Big Muskellunge Lake caused groundwater flow paths to shift in an area of divergent flow west of the lake (Figure 8), producing significant temporal variability in groundwater chemistry (Figure 7) at two sites.

Groundwater flows under both Crystal Lake and Big Muskellunge Lake, so that flow paths that eventually discharge farther downgradient into Allequash Lake may originate upgradient of Crystal and Big Muskellunge Lakes (Figure 9). Hence, it is important to consider groundwater flow in three-dimensions when performing capture zone analyses for lakes and streams. Moreover, particle tracking simulations used in the capture zone analysis were quite sensitive to the way in which particle capture by sinks, representing the lakes and stream, were specified in the simulation.

The methodology of using $\delta^{18}O$ to delineate source areas and flow paths should be successful throughout the NHLD as aquifers in the NHLD consist of glacial sediments similar to that found within the

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Allequash basin and surface waters are well connected to the groundwater system throughout the NHLD. Delineation of groundwater flow paths provides insight into source areas and movement of contaminants due to human activity and development. Characterization of groundwater flow paths and the current surface water/groundwater chemistry, using the methodologies presented in this study, will aid in identifying and quantifying future human impacts, which is the first step in developing a mitigation plan to protect and maintain the ecology of surface water and groundwater within the NHLD.

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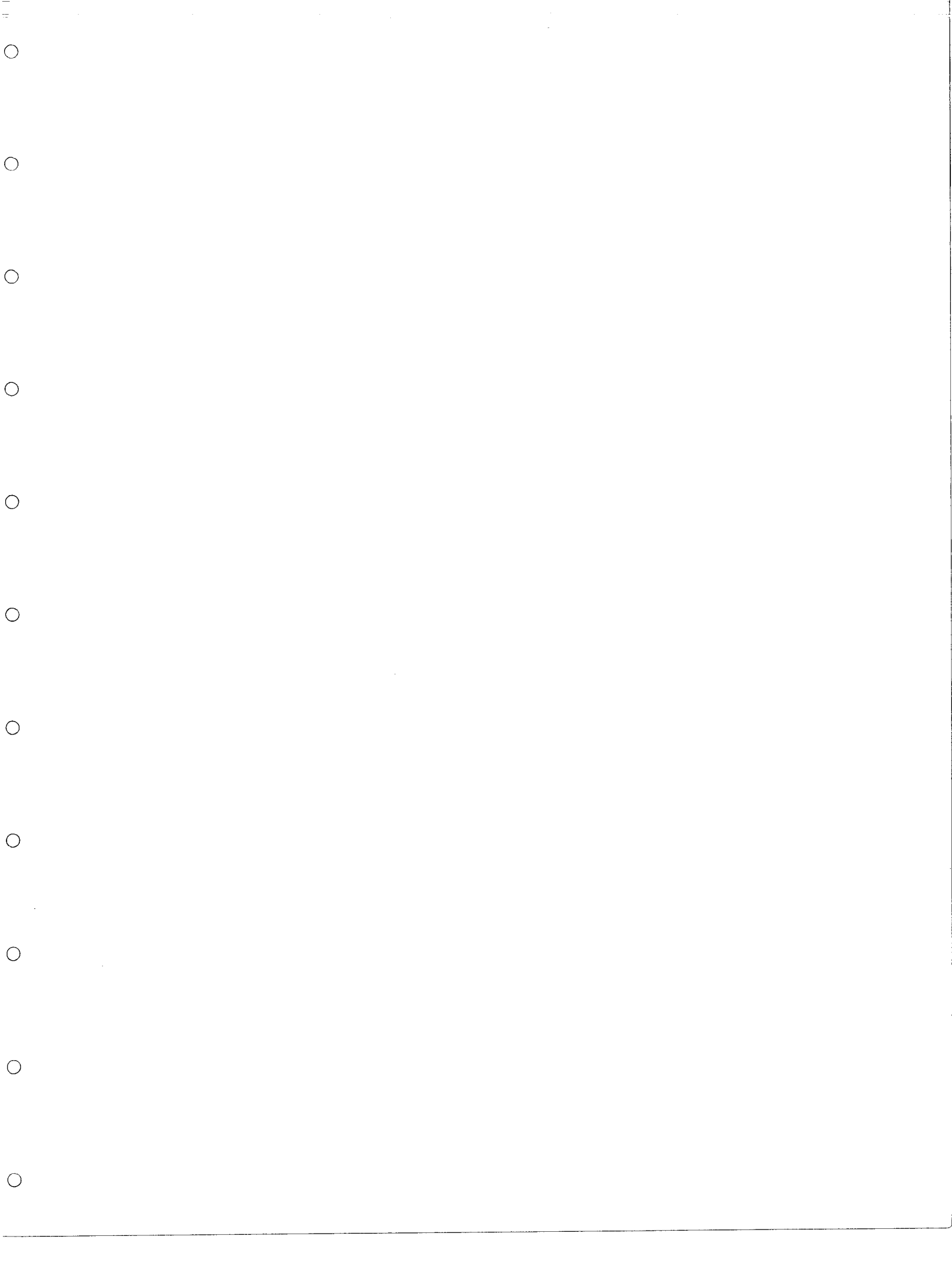
APPENDIX A. Publications.

Abstracts:
(1) Masbruch, M.D., Hunt, R.J., and Anderson, M. P. 2005. Investigation of Three Flowpaths of
 Different Lengths, Allequash Basin, Vilas County, Wisconsin *(abstract)*. Wisconsin's Waters: A
 Confluence of Perspectives: Delavan, WI, *Wisconsin Section of the American Water Resources
 Association*, p. 44.

There are numerous lakes, streams, and wetlands in Wisconsin that are well connected to the groundwater system. Consequently, the chemistry of groundwater may appreciably influence the chemistry of surface waters. Tools that identify the source areas of recharge and the geologic controls on groundwater chemistry are therefore crucial to understanding and protecting both groundwater and surface water. In this study, monthly (June-November, 2004) groundwater samples were taken along three transects located within the Allequash basin, a sub-basin within the Trout Lake watershed, Vilas County, Wisconsin. These samples were analyzed for the isotope $\delta^{87}Sr$, as well as major ion concentrations, iron, and dissolved carbon species. Using these data, the effects of transience and the geologic factors controlling the chemistry of groundwater along these paths from point of origin to discharge point were investigated. Initial results indicate that well nests adjacent to lakes show more ion variability than well nests located farther away from the lakes. Well nests located closer to the lakes show that alkalinity concentrations within the nest can differ by as much as a factor of seven, while within the well nests located farther away from the lakes alkalinity concentrations only differ by a factor of two. Cation data also show a similar trend. An existing three-dimensional groundwater flow model of the Trout Lake watershed was modified and refined to delineate lake capture zones and characterize seasonal chemical variability within the Allequash basin.

(2) Masbruch, M.D., Hunt, R.J., and Anderson, M. P. 2005. Delineation of Flow Paths and Processes
 Affecting Chemical Variability, Allequash Basin, Wisconsin *(abstract)*. *Geological Society of
 America Abstracts with Programs, Annual Meeting*, Salt Lake City, Utah, October 2005.

Most lakes, streams, and wetlands in Wisconsin are well connected to the groundwater system. Many lakes are flow-through lakes, in which groundwater discharges to the lake and is also recharged by water from the lake. In the Allequash Basin in northern Wisconsin, the exchange between surface water and groundwater affects the entire catchment ecosystem. Geochemical sampling and particle tracking simulations were used to identify the source areas of recharge, and trace groundwater flow paths from point of origin to discharge. Monthly (June-November, 2004) groundwater samples collected from 75 nested piezometers along three transects were analyzed for the isotopes of $\delta^{18}O$ and $\delta^{87}Sr$, as well as major ion concentrations, iron, and inorganic and organic dissolved carbon species. An existing three-dimensional groundwater flow model was used for particle tracking.

Flow paths delineated on the basis of the chemistry data showed groundwater derived from terrestrial, wetland, and lake source areas, which exhibited differing degrees of transient effects. Monthly/seasonal chemical variability observed along two transects with aquatic sources was caused by fluctuations in lake levels, which significantly affect the short-term orientation of the flow paths. These effects were also demonstrated in the particle tracking simulation where path lines pass both through and under a lake before finally discharging into strong sinks at the downgradient end of the basin. Thus, groundwater at the upgradient end of a flow path may discharge in different areas of the basin under different lake stage conditions. Transient effects in a discharge area near a 2-m wide stream was larger than transience near a relatively wide (> 400 m) lake. The study demonstrates that both aquatic and terrestrial components of flow are important in this watershed.

Thesis:
Masbruch, M.D. 2005. Delineation of Source Areas and Characterization of Chemical Variability using
 Isotopes and Major Ion Chemistry, Allequash Basin, Wisconsin. MS Thesis, Department of
 Geology and Geophysics, Madison, WI, University of Wisconsin – Madison: 131 pp.

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APPENDIX B. Acknowledgements.