Exploring Hydraulic Residence in Minnesota’s Sentinel Lakes: Implications for Management

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Abstract

Lake systems present a challenge in determining how water associated solutes cycle with time. Lake hydraulic residence time is an important lake management variable dependent on several factors including: volume, watershed size, location within a watershed and climatic variability. The stable isotopes of hydrogen (Deuterium expressed as δD) and oxygen ($\delta^{18}O$) can provide some hydrologic insight to lake water quality management. Analyzing the stable isotopic composition of lake water δD and $\delta^{18}O$ over time can aid in identifying source water input mixing and evaporative processes. Lake water δD and $\delta^{18}O$ were compared to the isotopic composition of atmospheric water vapor which has a known isotopic concentration at specific latitudes and air temperatures (Burns and McDonnell, 1998; Dansgaard, 1964). Study lakes were sampled spring, summer, and fall over a three year period. Deviations in the amplitudes of fractionated lake water compared to water vapor was modeled to predict hydraulic residence time for twenty-four lakes throughout Minnesota. Results suggest hydraulic residence time was dynamic; variations occurred with annual source water contributions, watershed size and connectivity. Ranges of annual hydraulic residence time among individual lakes were as great as 18.8 years and as small as 0.4 years. δD and $\delta^{18}O$ values were plotted in relation to the Meteoric Water Line (MWL) for all study lakes. A gradient of δD and $\delta^{18}O$ values were found in relation to latitude. Lighter values of δD and $\delta^{18}O$ were found in northern Minnesota compared to southern Minnesota. Variations in seasonal δD and $\delta^{18}O$ created annual amplitudes that provide insight into lake water budgets and residence times. The use of δD and $\delta^{18}O$ offer water quality managers a tool to better understand, protect, and remediate lakes and their watersheds.

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Introduction

The landscape of the state of Minnesota is rich in water resources as a result of the last glaciation. The Minnesota lakes region is one of the largest concentrations of freshwater lakes in the United States. The state of Minnesota's history, culture, and economic vitality revolve around these unique water resources. Water-based tourism and outdoor recreation such as fishing, swimming, and boating along with lakeshore residential development are important activities that drive many local economies in Minnesota. Clean water lakes not only provide many recreational and economic opportunities to residents and tourists, but also provide excellent fish and wildlife habitat. Drinking water is also a limited, but important component derived from Minnesota surface waters.

In order to correctly assess the condition of water quality and properly manage each lake type in Minnesota, deep or shallow, by Major Land Use Region (MLUR), it is critical that managers have a wide range of tools and techniques at their disposal. The use of basic physical and chemical water quality parameters provide insight into lake conditions, but used alone limit knowledge and the ability to manage effectively. These physical and chemical parameters merely provide a snapshot of what lake water quality is like at the time of sampling, however when baseline water quality data are supplemented with varying modeling techniques (watershed, bathymetric, and lake cycling) the true condition of a lake can be better understood.

In the upper Midwest of the North American continent lakes are more or less resilient to water quality impairments based on size, watershed land use, morphology, and hydraulic residence time. Watershed size and the amount of runoff entering a lake influence water quality. Since lake basin morphology is relatively constant, we will explore lake hydraulic residence time in detail. Currently, lake hydraulic residence time is estimated based on apparent input and output; typically excluding groundwater exchange. This presents many challenges in understanding how hydraulic residence time varies depending on seen and unseen water source inputs/outputs. Determining how water cycles through lakes is challenging. The water budget of Midwestern wetlands, streams, and lakes is derived from various sources including precipitation, surface water and/or groundwater (Magner and Alexander, 2008). Depending on the location of the water body and season, evaporation can drastically influence water budgets. Analyzing the stable isotopic composition of lake water δD and $\delta^{18}O$ can provide insight into mixing and evaporative processes.

Background

Isotopes are atoms of a specific element with a different mass due to a different number of neutrons. Water is composed of oxygen and hydrogen isotopes which occur at different frequencies throughout the hydrologic cycle and are influenced by temperature and latitude (Dansgaard, 1964). Over time, water droplets move within the hydrologic cycle and slight changes in the molecular composition can be measured. This creates hydrologic fractionation end-member source waters unique isotopic signatures (International Atomic Energy Agency, 2009; Craig 1961b). The use of stable isotopes has emerged as a vital tool for defining source waters in lakes and predicting hydraulic residence time. The study of isotopes has allowed scientists to determine hydraulic residence time without extremely long data sets. Previously, this technique has been used to quantify the contribution of groundwater, precipitation, and runoff or snow melt to specific bodies of water (Burns and McDonnell, 1998; Magner and Alexander, 2008; Fritz and Fontes, 1980, 1986). The ratio of stable hydrogen (δD) and oxygen ($\delta^{18}O$) in a given lake is dependent on a variety of physical processes reflected in the evaporative signature of end-member sources and the final mixing zone. The decoupling of δD and $\delta^{18}O$ occurs due to fractionation; deuterium evaporates slightly faster than $\delta^{18}O$ (Craig, 1961a). The relationship between atmospheric δD and $\delta^{18}O$ shows a linear correlation which is known as the Meteoric Water Line (MWL). The isotopic enrichments, relative to ocean water, display a linear correlation over the entire range of waters which have not undergone excessive evaporation (Craig, 1961a). Some water bodies show deviations from the MWL, referred to as the "evaporative line," as a result of local climate and water budgets. For a given water sample, fractionation can produce a unique isotopic signature that can offer hydrologic insight. It is difficult, however to estimate the magnitude of end-member source water contributions to the overall water budget of a lake. Lake residence time will be driven by lake morphology, evaporation, and flow into and out of a lake. By identifying a lakes seasonal isotopic signature and its relation to annual oscillations, compared to that of latitudinal water vapor throughout the open water season, it is possible to predict hydraulic residence time (Burns and McDonnell, 1998). The difference in fractionation between the isotopic water vapor and that of a water body directly correlates to residence time. This difference can be quantified and modeled to give an estimated hydraulic residence time for a specific lake.

Freshwater lakes present the challenge of having many different water sources contributing to their annual water budget. Quantifying hydraulic residence time in lakes via stable isotopes will offer new insight that may explain many other lake water quality metrics. It may also be used to further explain which lakes are more or less susceptible to perturbations in the watershed that lead to lake impairment. Hydraulic residence time within lakes has a direct effect on the concentration of nutrients, contaminants, and other chemicals of concern. The only way to determine residence time through water chemistry is to look at the isotopic fractionation of a lake and determine the seasonal oscillation in $\delta^{18}O$ and δD (Maloszewski et al., 1983; Pearce et al., 1986; Stewart and McDonnell, 1991; Burns and McDonnell, 1998). Such data will provide residence time estimates for a small collection cost. It will allow for better lake models to be developed and aid in the understanding of how pollutants cycle. Hydraulic residence time can also be used as a tool to predict lakes that may be at risk of accelerated eutrophication.

Methods

Water samples were collected to measure δD and $\delta^{18}O$ from 24 lakes throughout the state of Minnesota (Figure 1). Currently, these 24 lakes are part of the “Sustaining Lakes in a Changing Environment” (SLICE) project, a joint study conducted by the Minnesota Department of Natural Resources and the Minnesota Pollution Control Agency to study how changes in climatic variables influence Minnesota’s lakes (Valley, 2009). The SLICE study provided physical and chemical lake water parameters that can be used in conjunction with stable isotopes δD and $\delta^{18}O$ to assess overall lake condition. These lakes represent typical lakes found within Minnesota's four MLURs; Canadian Shield, Transition Forest, Glacial Drift and Northern Forest, and Prairie and Cornbelt. Study lakes range from deep oligotrophic lakes with high groundwater contributions to shallow hypereutrophic, runoff driven lakes. Morphometric characteristics of the lakes studied are recorded in Appendix A. These lakes have very different water budgets and reflect the range of lakes systems found throughout the upper Midwest portion of North America. Valuable insight was gained into the contributions of source waters and the impacts of pollutants in MN Lakes.

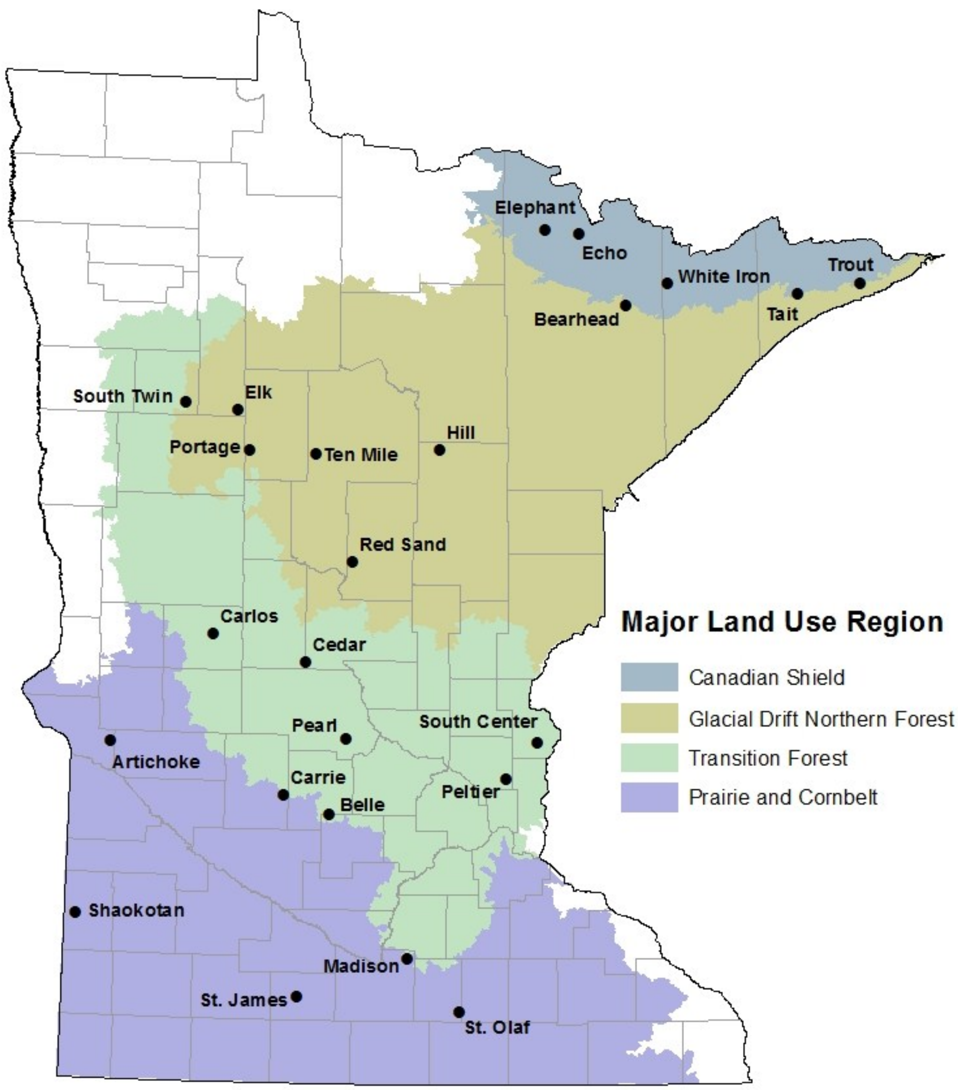

Figure 1. Map of study lakes and Major Land Use Regions.

From 2008 to 2010 each of the 24 lakes were visited during the months of May, July, and October to collect water samples for the analysis of stable isotopes δD and $\delta^{18}O$ (Appendix B). Sampling periods were timed to correspond closely with spring and fall turnover and during mid-summer when evaporation is highest. Sampling at these key time periods offers the best opportunity to capture oscillations in δD and $\delta^{18}O$ for each lake. To ensure that a consistent method of sampling for comparative purposes was used, a composite sample of the top two meters of lake water was taken over the deepest part of the lake basin. An integrated water quality sampler, which is a polyvinyl chloride tube 2 meters in length with an inside diameter of 3.2 centimeters, was used for sample collection. This ensures that the sample is well mixed and representative of the entire lake while eliminating variability from source waters and precipitation events. Surface water sampling protocols were followed from the Minnesota Pollution Control Agency's Standard Operating Procedure for Lake Water Quality Sampling (Anderson and Lindon, 2009). Samples collected were placed in 125ml plastic water bottles, sealed and sent to the University of Minnesota Biometeorology Lab in the Department of Soil, Water, and Climate under the direction of Dr. Timothy Griffis for analysis. All liquid water samples were analyzed for their isotopic composition using a laser spec-troscopy system (Liquid Water Analyzer, DLT-100, Los Gatos Research, Inc) coupled to an autosampler (HT-300A, HTA) for simultaneous measurements of δD and $\delta^{18}O$ (Appendix C).

Stable isotope compositions were compared to the isotopic composition of atmospheric water vapor which has a known isotopic concentration at specific latitudes and air temperatures (Burns and McDonnell, 1998; Dansgaard, 1964). The deviation in amplitudes of the fractionation of lake water to water vapor was modeled to predict hydraulic residence time for each lake.

Estimates for seasonal $\delta^{18}O$ water vapor values were determined based on seasonal mean minimum and maximum air temperatures using equation 1 (Yurtsever 1975).

$$(1) \qquad \delta^{18}O_{\text{water vapor}} = (0.521 +/- 0.014)\,T - (14.96 +/- 0.21)$$

Where T is the air temperature in degrees Celsius.

Air temperature data used in Equation 1 were derived from the Minnesota State Climatology Working Group web page (State Climatology Office, MDNR) (Appendix D). Minimum and maximum seasonal air temperatures were calculated to represent the expected range of stable isotope compositions of atmospheric water vapor for each sentinel lake. Air temperatures were calculated by sentinel lake location using ArcMap10.1 for each season; December-February, March-May, June-August, and September-November. The maximum seasonal range of calculated atmospheric stable isotope values was modeled with observed lake water isotopic values to estimate residence time.

Hydraulic residence time was estimated using Equation 2 (Maloszewski et al., 1983) by comparing the amplitude of a best-fit curve for precipitation to the amplitude of a similar curve for the water of interest. Seasonal changes in the $\delta^{18}O$ composition of precipitation at temperate latitudes tend to follow a sinusoidal pattern. This pattern occurs over one year, reflecting the seasonal changes in tropospheric temperature. Measured changes in $\delta^{18}O$ composition for a stream, lake, pond, soil water, or groundwater are obtained for a given location during different seasons. Mean hydraulic residence can then be calculated if the seasonal waters are considered in steady state and well mixed with an exponential distribution of residence time as:

$$(2) \qquad \tau = \omega^{-1} [(A/B)^{2} - 1]^{1/2}$$

Where τ is the estimated hydraulic residence time, in days, ω the angular frequency of variation (2π/365 days) or (0.07172), *A* the input amplitude (precipitation), and *B* the output amplitude (lake water).

Results

Regional Trends

Throughout the state of Minnesota trends in δD and $\delta^{18}O$ were similar in all four MLRUs studied (Figures 2 and 3). A general transition from light to heavy δD and $\delta^{18}O$ compositions was found from north to south in Minnesota lakes. The most pronounced difference occurs in the Canadian Shield lakes. This is a result of climatic conditions that are unique to the Canadian Shield MLUR. Weather systems in this region often originate in the Arctic, resulting in light isotopic sources of water vapor as compared to weather systems originating in the Gulf of Mexico. Lake water budgets may also receive higher volumes of light isotopic snow melt runoff than lakes south of the Canadian Shield. A transition from light to heavy δD and $\delta^{18}O$ values is evident along the Glacial Drift Northern Forest MLUR. Here δD and $\delta^{18}O$ values are slightly higher than Canadian Shield values. The highest values of δD and $\delta^{18}O$ were found in the Transition Forest and Prairie and Corn Belt MLURs. Heavier δD and $\delta^{18}O$ water compositions are a result of more gulf air precipitation, higher annual evaporation rates, and higher annual mean temperatures (Appendix D).

Study lakes show a strong correlation, $R^2 = 0.950$, to an evaporative line in Minnesota (Figure 4). Deviations from the MWL are evident at a range of scales. Results were interpreted by state, MLURs, and by individual lake. The further along the evaporative line a lake plots, the heavier the δD and $\delta^{18}O$ composition. Canadian Shield lakes plotted low and near the MWL representing waters with a lighter isotopic composition compared to the other three MLUR's studied.

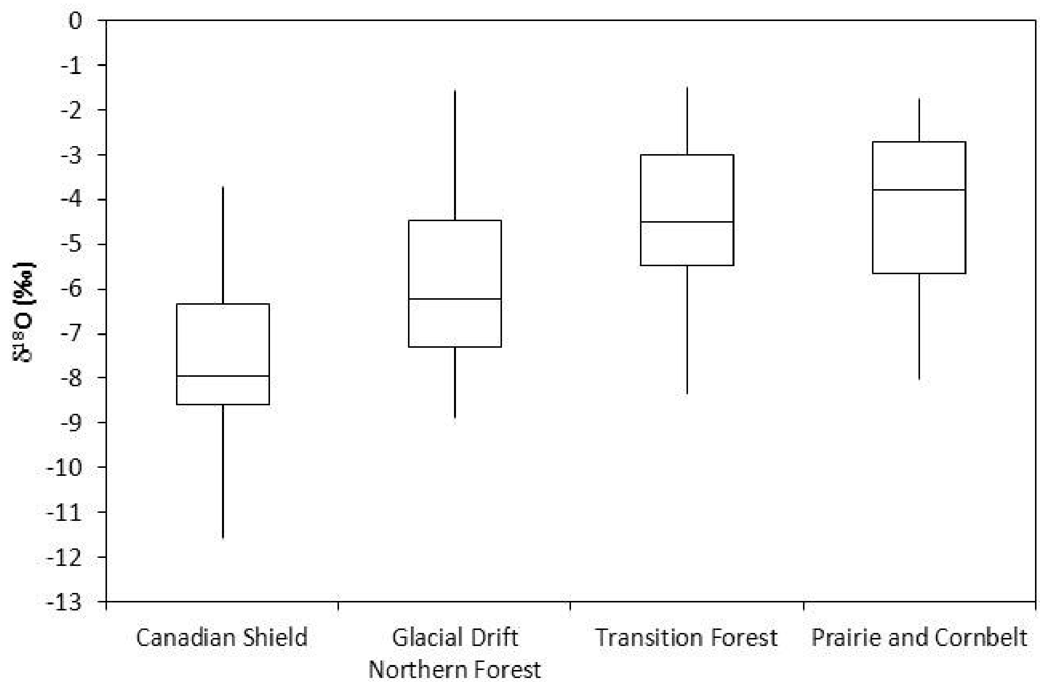

Figure 2. $\delta^{18}O$ values for study lakes within the MLUR's.

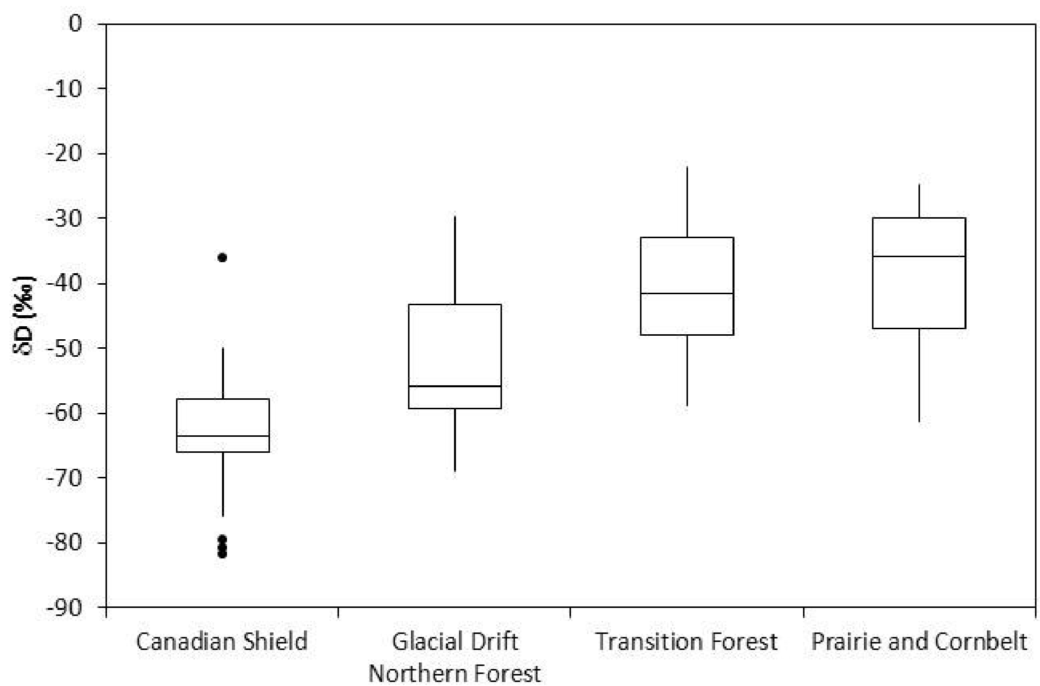

Figure 3. δD values for lakes within the MLUR's.

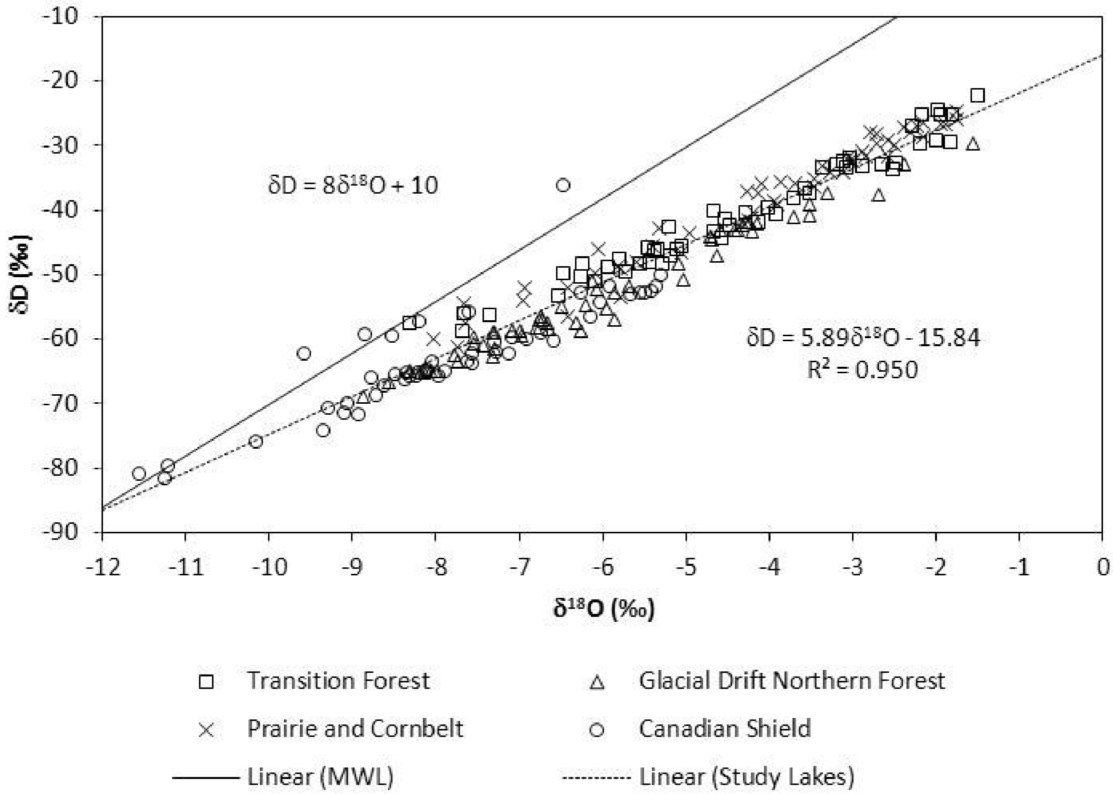

Figure 4. MLUR's $\delta^{18}O$ vs. δD compared to the MWL.

Canadian Shield

Stable isotope $\delta^{18}O$ values in the Canadian Shield are lower than in the other three MLURs (Figure 2). A wide range of lake types were sampled in the Canadian Shield MLUR. Measured $\delta^{18}O$ compositions for each lake in the region are shown in Figure 5. Canadian Shield lakes showed a correlation, $R^2 = 0.773$, to the evaporative line (Figure 6). This correlation may have been stronger in absence of White Iron Lake, since the lake is a reservoir with a very short residence time and plotted near the MWL. Deep oligotrophic lakes, Bearhead and Trout, had the smallest $\delta^{18}O$ amplitude in the Canadian Shield MLUR. As a result, these two lakes had the longest calculated hydraulic residence times (Table 1). Echo, Tait, and Elephant lakes are relatively shallow and well connected to their watersheds through many tributaries. Residence times in these lakes were shorter because open channel pathways move water into and out of these lakes (Table 1). White Iron Lake had the shortest residence time of all the Canadian Shield lakes because the lake has a large watershed and is an impoundment on the Kawishiwi River (Table 1). Large volumes of water move through White Iron resulting in a relatively short residence time.

Annual climatic variation also had an affect on $\delta^{18}O$ amplitudes and residence times in the Canadian Shield MLUR. In 2010, $\delta^{18}O$ amplitudes were reduced because of dryer climatic conditions as compared to 2008 and 2009. As a result, residence times increased in most Canadian Shield lakes.

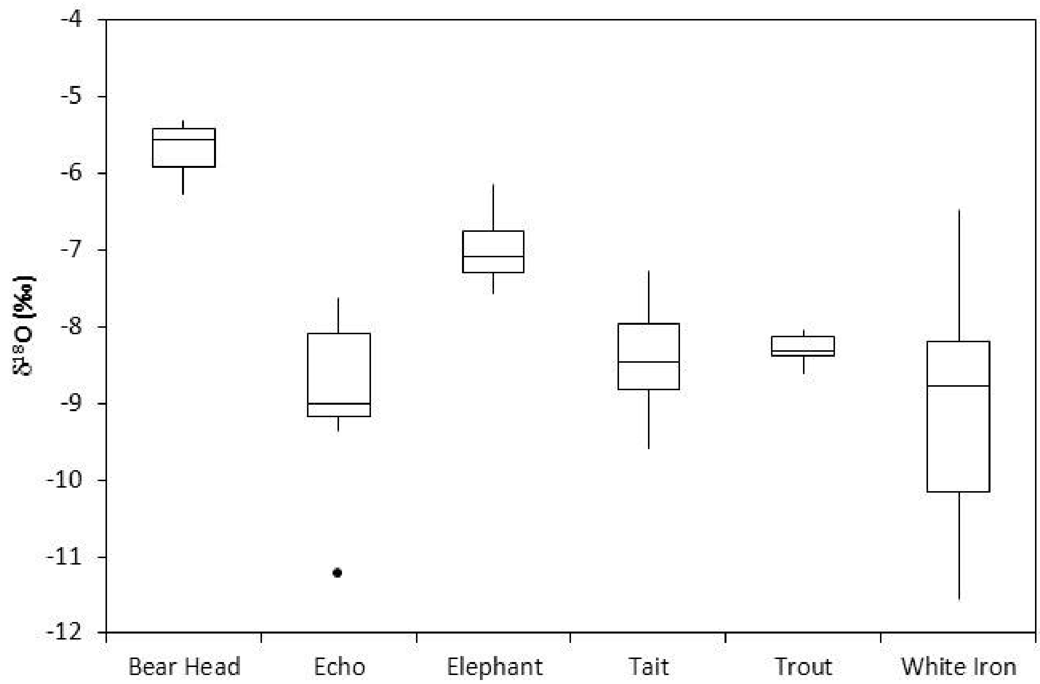

Figure 5. $\delta^{18}O$ values for study lakes within the Canadian Shield MLUR.

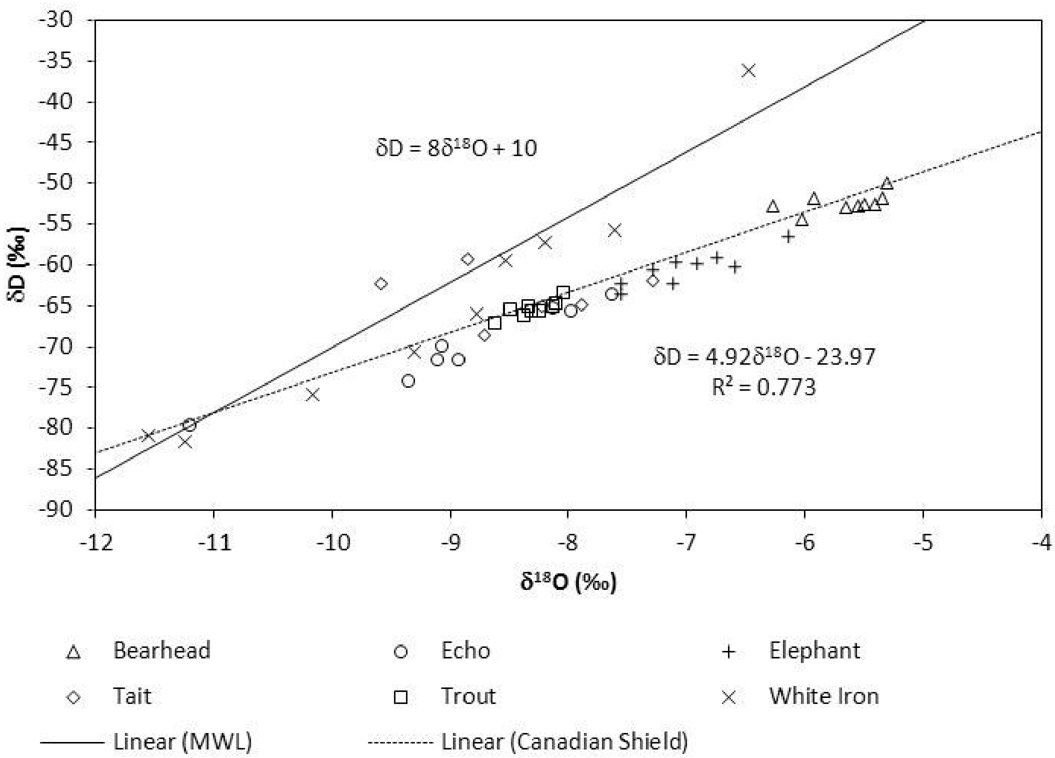

Figure 6. Canadian Shield $\delta^{18}O$ vs. δD compared to the MWL.

Table 1. Canadian Shield lakes modeled residence time range based on seasonal mean minimum and maximum air temperatures.

Lake Name	Min. 2008	Max. 2008	Min. 2009	Max. 2009	Min. 2010	Max. 2010	Range (Yr)	Residence Time (Yr)
Bearhead	2.5	2.6	3.9	3.8	17.7	17.3	15.2	2.5-17.7
Echo	0.7	0.7			2.2	2.1	1.5	0.7-2.2
Elephant	3.2	3.3	3.2	3.2	5.6	5.5	2.4	3.2-5.6
Tait			1.8	1.8	1.6	1.7	0.2	1.6-1.8
Trout	6.9	7.7	8.7	9.3	10.5	11.8	4.9	6.9-11.8
White Iron	1.0	1.0	0.8	0.8	1.3	1.3	0.5	0.8-1.3

Bearhead Lake

Bearhead Lake had the heaviest isotopic composition of the six Canadian Shield lakes sampled with $\delta^{18}O$ values ranging from -5.3 to -6.3 per mil. (Appendix E). Differences in residence time calculations are explained by the lake's morphology, climate, and lake levels. Bearhead Lake has a small watershed with no surface water inlets or outlets, limiting the annual water budget to direct precipitation and diffuse wetland and groundwater flow. Bearhead Lake appears to have a very low sill during wetter than normal climates, 2008-2009. Lake levels remained above the sill allowing water to diffuse out of the lake basin through surrounding wetlands adjacent to the lake's southern basin. This resulted in a calculated residence time of 2.5-3.9 years. In 2010, dry climatic conditions caused lake levels to decrease below the sill of the lake basin inhibiting outward flow. As a result, calculated lake residence time increased to 17.3-17.7 years (Table 1). This fluctuation in residence time is reflected in the observed amplitude of $\delta^{18}O$ values during wet and dry years (Appendix F). In wetter years, 2008 and 2009, $\delta^{18}O$ amplitudes were much greater than in 2010. Dry conditions and inhibited lake water movement greatly reduced $\delta^{18}O$ amplitudes in 2010.

Echo Lake

Echo Lake's isotopic composition shows high annual variability with $\delta^{18}O$ values ranging from -11.2 to -7.6 per mil. (Appendix E). This range can be explained by the connectivity of Echo Lake's watershed to the lake itself and its small lake volume. Echo Lake is large, but very shallow, with a surface area of 461 hectares and a maximum depth of 3 meters. Five inlets act as conduits directing precipitation that falls within the watershed to the lake in a relatively short period of time. The Echo River serves as the lake's outlet. Residence time calculations are relatively short, 0.7-2.2 years (Table 1). 2008 was wetter than 2010, resulting in more frequent flushing of the lake water. The 2009 spring sampling event was not collected, therefore the maximum $\delta^{18}O$ amplitude and residence time were not calculated. However, summer and fall 2009 $\delta^{18}O$ values were similar to 2008 $\delta^{18}O$ values, suggesting that residence time in 2009 was probably closer to 2008's calculation than 2010's (Table. 1).

Elephant Lake

Elephant Lake's $\delta^{18}O$ values range from -7.6 to -6.1 per mil. (Appendix E). Annual $\delta^{18}O$ amplitudes are similar in 2008 and 2009. In 2010, the $\delta^{18}O$ amplitude decreased slightly resulting in a higher residence time calculation. Residence time calculations ranged from 3.2-5.6 years (Table 1). Isotopic concentrations show strong correlation from year to year, plotting on the evaporative line. Strong correlation to the evaporative line is likely a result of the lake's small watershed and limited connectivity. These morphometric characteristics limit the probability of large $\delta^{18}O$ amplitude shifts caused by runoff or evaporation. Elephant Lake has four small inlets and one lake outlet via Elephant Creek.

Tait Lake

Tait Lake's $\delta^{18}O$ values range from -9.5 to -7.3 per mil. (Appendix E). Tait Lake was added to the Sentinel Lakes program in 2009, therefore isotope samples were not collected in 2008. Isotope values in 2009 poorly correlate and plot above the MWL. It is unclear what would cause this to happen, however 2010 shows good correlation to the evaporative line resulting in a residence time calculation of 1.6-1.7 years (Table 1).

Trout Lake

Trout Lake's $\delta^{18}O$ isotopic composition varied the least of the six Canadian Shield lakes. Conservative $\delta^{18}O$ values are strongly influenced by lake morphology, primarily depth and lake surface area to volume ratio. Trout Lake is the deepest of all the Canadian Shield lakes sampled with a maximum depth of 23.5 m and a mean depth of 10.7 m. A large volume to surface area ratio limits evaporative influences on annual $\delta^{18}O$ amplitudes. Trout Lake's $\delta^{18}O$ values ranged from -8.0 to -8.6 per mil. (Appendix E) and residence time calculations ranged from 6.9-11.8 years (Table 1). Trout Lake's $\delta^{18}O$ amplitudes decreased each year, 2008-2010, as climatic conditions in the area became progressively dryer and limited water entering from Marsh Lake and exiting through the Kadunce River. A reduction in source waters, snow melt, and precipitation likely decreased variation in $\delta^{18}O$ amplitudes and increased residence time in Trout Lake.

White Iron Lake

White Iron Lake's $\delta^{18}O$ isotopic composition varied the most of the six Canadian Shield lakes (Figure 5). The wide range of $\delta^{18}O$ values is not surprising since White Iron Lake is a reservoir with a very large watershed. The contributing watershed has a total area of over 239,573.9 ha. White Iron Lake's $\delta^{18}O$ values ranged from -6.5 to -11.6 per mil. (Appendix E) and residence time calculations ranged from 0.8-1.3 years (Table 1). Isotopic $\delta^{18}O$ values show good correlation to the MWL which suggests that White Iron's lake water consists of primarily unaltered precipitation. This means that there is little storage in the watershed and water flows quickly through White Iron Lake.

Glacial Drift Northern Forest

Measured $\delta^{18}O$ values for each lake in the Glacial Drift Northern Forest MLUR are shown in Figure 7. The isotopic compositions of all lakes sampled in the Glacial Drift Northern Forest MLUR show a strong correlation to the evaporative line, $R^2 = 0.974$ (Figure 8). In general, a shift towards lighter $\delta^{18}O$ values was observed from 2008 to 2010 (Appendix C). This correlates to precipitation patterns in the region which were dryer in 2008 and became progressively wetter by 2010 (Appendix F).

Deep lakes in this MLUR are suspected to have a significant groundwater component to their water budget because of underlying glacial depositional sediment. Conservative $\delta^{18}O$ amplitudes found in Elk and Ten Mile Lakes provide evidence for the presence of groundwater contributions. As a result, the longest calculated residence times within the Glacial Drift Northern Forest MLUR were in Elk and Ten Mile Lakes (Table 2).

Red Sand Lake was found to have the heaviest and widest range of $\delta^{18}O$ values of all Glacial Drift Northern Forest Lakes. This suggests that the origins of source waters for Red Sand Lake are different than other lakes in this MLUR. Red Sand Lake was the southernmost lake studied in the Glacial Drift Northern Forest MLUR and is likely near the transition between Arctic and Gulf of Mexico derived precipitation (Figure 1). Red Sand Lake's water budget consists of a higher proportion of heavier isotopic precipitation from storms originating in the Gulf of Mexico. In contrast the rest of the lakes in this MLUR, located further north, receive lighter isotopic precipitation from storms originating more in the Pacific West and the Arctic.

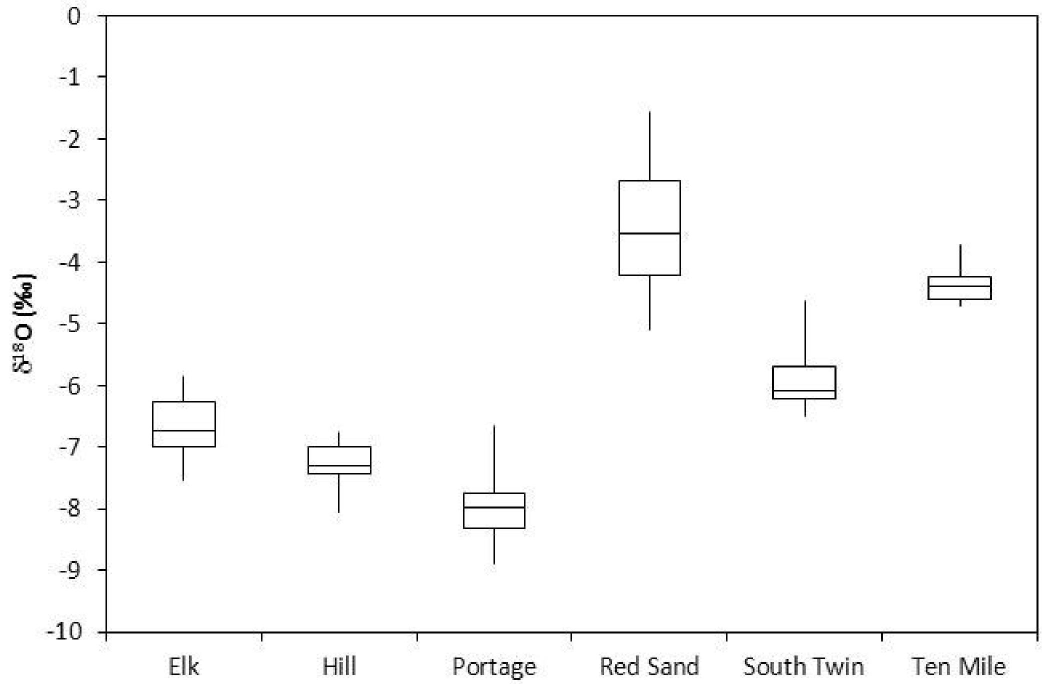

Figure 7. $\delta^{18}O$ values for study lakes within the Glacial Drift Northern Forest MLUR.

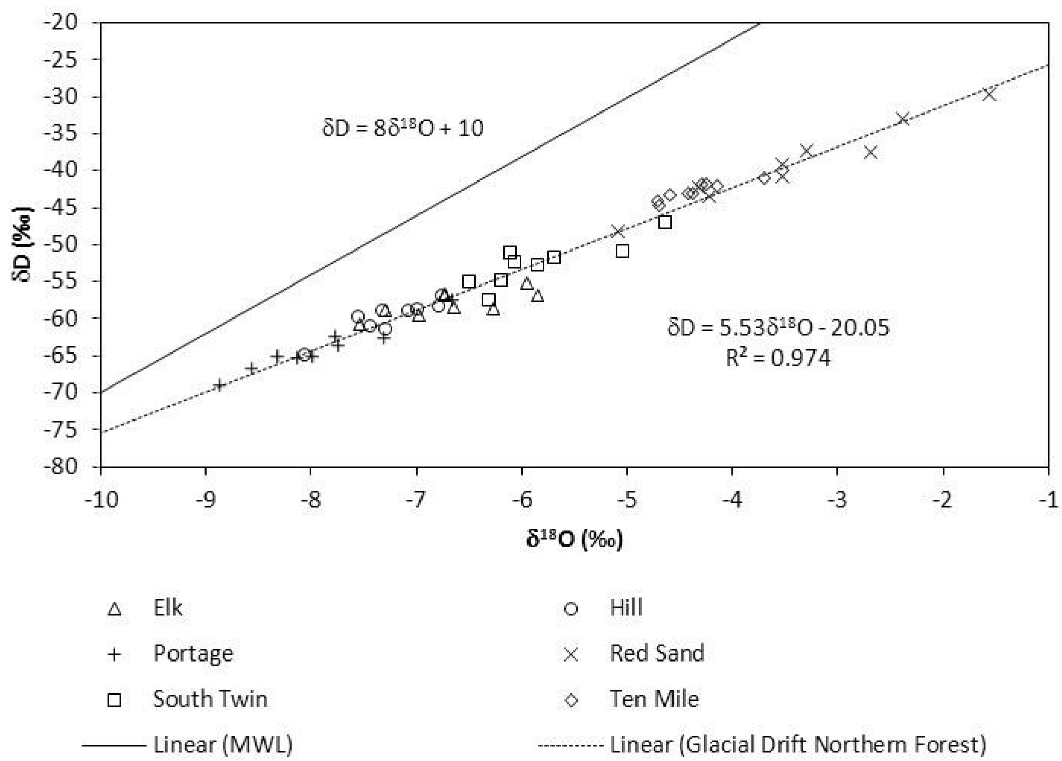

Figure 8. Glacial Drift Northern Forest $\delta^{18}O$ vs. δD compared to the MWL.

Table 2. Glacial Drift Northern Forest lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

Lake Name	Min. 2008	Max. 2008	Min. 2009	Max. 2009	Min. 2010	Max. 2010	Range (Yr)	Residence Time (Yr)
Elk	6.2	6.4	10.9	10.5	2.9	2.9	8.1	2.9-10.9
Hill	7.7	8.2	2.0	2.0	9.9	10.1	8.1	2.0-10.1
Portage	2.0	2.0	3.4	3.3	2.3	2.3	1.5	2.0-3.4
Red Sand	1.3	1.4	1.4	1.3	1.6	1.7	0.4	1.3-1.7
South Twin	2.5	2.6	6.4	6.2	5.6	5.7	4.0	2.5-6.4
Ten Mile	3.8	3.9	15.7	15.2	22.6	22.9	19.1	3.8-22.9

Elk Lake

Variable δD and $\delta^{18}O$ values are a result of Elk Lake's large watershed, depth, and variety of source water inputs. Large contributions of groundwater along with diffuse wetlands and tributaries contribute to Elk Lake's annual water budget. Elk Lake's $\delta^{18}O$ values ranged from -5.9 to -7.5 per mil. (Appendix E) and residence time calculations ranged from 2.9-10.9 years (Table 2). Residence time and $\delta^{18}O$ values are strongly influenced by the amount of precipitation in a given year. 2008 and 2010 were both wetter than normal years which increased lake flushing and reduced residence times. In 2009, precipitation values were normal and a residence time of 10.9 years was calculated. Increased residence time in 2009 was likely related to a reduction in outflow to Lake Itasca.

Hill Lake

Hill Lake has two distinct lake basins; the north basin is deep and stratifies during summer months, while the southern basin is relatively shallow and acts as the lakes outlet. Isotope samples were taken from the deep northern basin resulting in higher residence times as compared to what would likely be observed in the shallow southern basin. Hill Lake's $\delta^{18}O$ values range from -6.8 to -8.1 per mil. (Appendix E) and residence time calculations ranged from 2.0-10.1 years (Table 2). Annual $\delta^{18}O$ amplitudes were similar in 2008 and 2010. In 2009, the $\delta^{18}O$ amplitude was much greater resulting in a lower residence time calculation.

Portage Lake

Portage Lake had the lightest isotopic composition of the six Glacial Drift Northern Forest lakes sampled, with $\delta^{18}O$ values ranging from -6.7 to -8.9 per mil. (Appendix E). Residence time calculations ranged from 2.0-3.4 years (Table 2). Short residence times were expected in Portage Lakes because it is shallow with a 5.2 m maximum depth and mean depth of 2.3 m. Source water inputs from the watershed, which is primarily forested, are consistent and supported by similar annual $\delta^{18}O$ amplitudes. Slight shifts in $\delta^{18}O$ amplitudes occurred along the evaporative line which can be attributed to seasonal variability in precipitation and evaporation. Portage Lake's $\delta^{18}O$ values shifted from light values in the spring to heavier values though the summer and fall.

Red Sand Lake

Red Sand Lake had the heaviest isotopic composition of the six Glacial Drift Northern Forest lakes sampled with $\delta^{18}O$ values ranging from -1.6 to -5.1 per mil. (Appendix E). Annual $\delta^{18}O$ values show the strongest correlation with the evaporative line as well. Red Sand Lake is the southernmost lake in the Glacial Drift Northern Forest land type region. As a result, Red Sand Lake likely has higher evaporation rates and receives heavier isotopic precipitation, rain vs. snow, than other lakes in this region. Residence time calculations ranged from 1.3-1.7 years (Table 2). Short residence times are to be expected in a shallow lake with a water control structure. Residence times and $\delta^{18}O$ amplitudes vary slightly depending on annual source water contributions and lake volume changes.

South Twin Lake

South Twin Lake's $\delta^{18}O$ values ranged from -4.6 to -6.5 per mil. (Appendix E) and residence time calculations ranged from 2.5-6.4 years (Table 2). Annual precipitation and evaporation fluctuations affected $\delta^{18}O$ amplitudes and how they correlate to the evaporative line. Higher evaporation rates and limited source water contributions caused a shift toward heavier $\delta^{18}O$ values in 2008. Lighter $\delta^{18}O$ values were observed in 2009 and 2010 during wetter years. Lake water became progressively lighter as precipitation increased, suggesting that snow melt or Arctic derived water vapor are contributing to annual lake water budgets. This seems to be supported by South Twin Lake's geographic location which is the furthest northwestern lake in the Glacial Drift Northern Forest MLUR.

Ten Mile Lake

Ten Mile Lake's $\delta^{18}O$ values ranged from -3.7 to -4.7 per mil. (Appendix E) and residence time calculations ranged from 3.8-22.9 years (Table 2). Residence times in Ten Mile Lake shows the highest variability of all lakes in the Glacial Drift Northern Forest MLUR. The lake is very complex with a maximum depth of 63.4 m and a mean depth of 16.2 m. Groundwater is also known to make up a large portion of the lakes annual water budget (Magner, 1995). As precipitation values increased form 2008-2010, $\delta^{18}O$ amplitudes decreased and residence times increased. This suggests that wetter years are influenced by increased groundwater discharge.

Transition Forest

Measured $\delta^{18}O$ values for each lake in the Transition Forest MLUR are shown in Figure 9. The isotopic composition of lakes sampled in this MLUR show a strong correlation to the evaporative line, $R^2 = 0.961$ (Figure 10). In general, a shift towards lighter $\delta^{18}O$ values was observed from 2008 to 2010. Lakes in the western portion of the Transition Forest region received an annual surplus of 20.3-30.5 cm of precipitation in 2010 (Appendix E). Lakes without an outlet, such as Belle, showed a shift to a lighter isotopic composition that was pronounced. This may result in an over-estimate of residence time since lake levels did not stabilize due to excess precipitation.

Carlos, Cedar, and South Center are all deep lakes, however their annual water budgets are different. Carlos and South Center are both part of a chain of lakes. During dry years, 2008-2009, discharge from Lake Carlos decreased along with $\delta^{18}O$ amplitudes, causing residence time to increase (Table 3). South Center Lake has a relatively short residence time for a deep lake due to a complex lake bed and watershed hydrology. During drought years water levels can drop relatively fast due to evaporation and a groundwater sink in the lake bed which increases annual water loss (HDR Engineering Inc. 2008). Pearl and

Peltier Lakes receive large watershed contributions during wet periods so residence times remain relatively short. Shallow depth and limited lake volume allow for quick flushing of lake water.

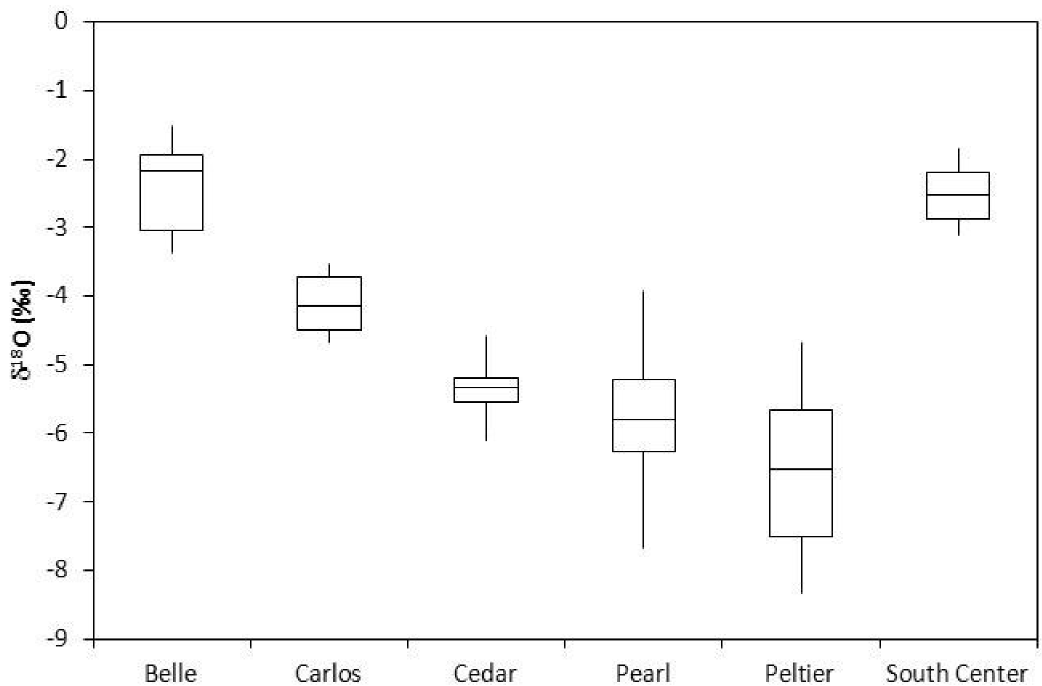

Figure 9. $\delta^{18}O$ values for study lakes within the Transition Forest MLUR.

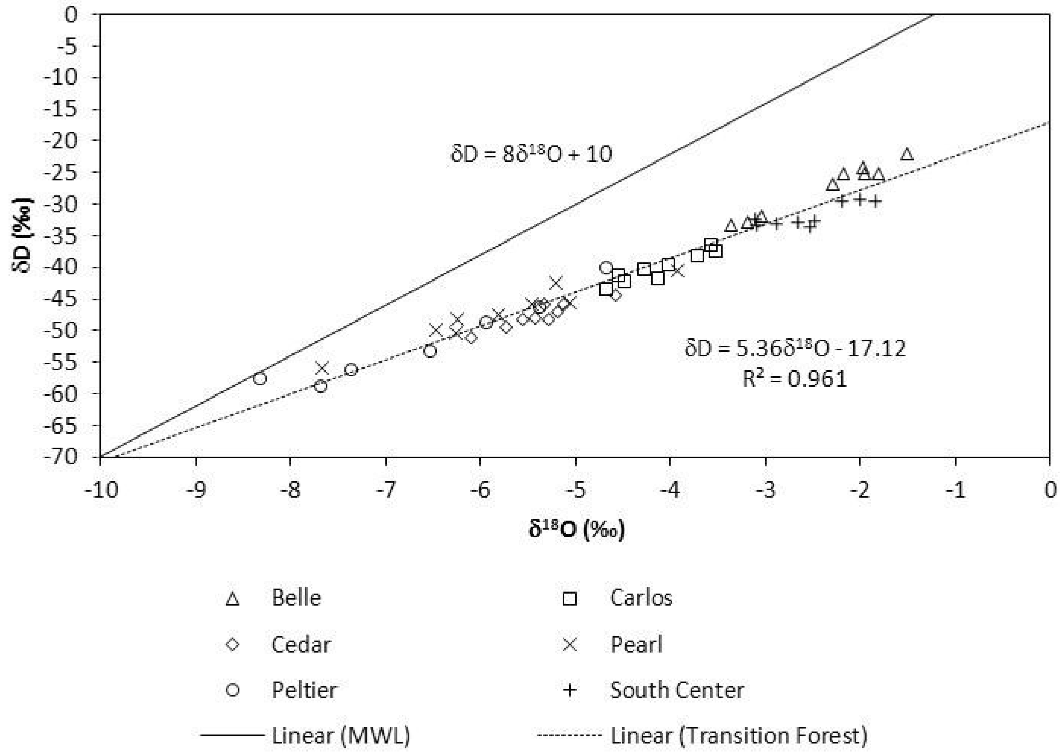

Figure 10. Transition Forest $\delta^{18}O$ vs. δD compared to the MWL.

Table 3. Transition Forest lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

Lake Name	Min. 2008	Max. 2008	Min. 2009	Max. 2009	Min. 2010	Max. 2010	Range (Yr)	Residence Time (Yr)
Belle	3.9	4.2	5.4	5.4	8.4	9.0	5.0	3.9-9.0
Carlos	13.6	14.2	5.1	5.0	4.8	5.1	9.3	4.8-14.2
Cedar	2.6	2.8	8.5	8.3	3.1	3.3	5.8	2.6-8.5
Pearl	1.3	1.4	2.4	2.4	1.8	1.9	1.1	1.3-2.4
Peltier			0.9	0.9	1.5	1.5	0.6	0.9-1.5
South Center	2.7	2.9	2.0	2.0	6.3	6.4	4.5	2.0-6.4

Belle Lake

Belle Lake's $\delta^{18}O$ values ranged from -3.4 to -1.5 per mil. (Appendix E) and residence time calculations ranged from 3.9-9.0 years (Table 3). Belle Lake's $\delta^{18}O$ values parallel the MWL which, suggest that the lakes water budget consists primarily of precipitation. A near parallel shift in the regression of $\delta^{18}O$ values, evaporative line from the MWL, suggests source waters represent a localized MWL influenced by local climate. In 2008 and 2009 residence time calculations ranged from 3.4-5.9 years as compared to 2010, 8.4-9.0 years. The increase in residence time is a result of 2010 being an extremely wet year causing the annual lake water budget to consist primarily of precipitation based source waters. This caused the $\delta^{18}O$ amplitude to decrease resulting in a higher residence time calculation in 2010. In addition, precipitation based source waters also caused a shift to a much lighter isotopic composition.

Lake Carlos

Lake Carlos $\delta^{18}O$ values ranged from -4.7 to -3.5 per mil. (Appendix E) and residence time calculations ranged from 4.8-14.2 years (Table 3). Lake Carlos is the last lake in the Alexandria, MN chain of lakes and its outlet forms the Long Prairie River. The lake is deep with a maximum depth of 48.8 m and a mean depth of 13.9 m. Residence time calculations were the greatest in 2008, 13.6-14.2 years, because of low lake levels and reduced discharge out of the lake. This reduced the $\delta^{18}O$ amplitude causing residence time to increase. In 2009 and 2010, $\delta^{18}O$ amplitudes were similar. Increased lake levels and flow rates reduced residence time ranges to 4.8-5.1 years.

Cedar Lake

Cedar Lake's $\delta^{18}O$ values ranged from -6.1 to -4.6 per mil. (Appendix E) and residence time calculations ranged from 2.6-8.5 years (Table 3). The lake is deep, with a maximum depth of 26.8 m and a mean depth of 10.7 m. Cedar Lake's watershed is relatively small and source waters likely consist of groundwater and direct precipitation. In 2008 and 2010, $\delta^{18}O$ amplitudes were fairly consistent, however a reduction in $\delta^{18}O$ amplitude was observed in 2009 which caused residence time to increase. The reduction in $\delta^{18}O$ amplitude for 2009 was caused by high fall precipitation rates which skewed Cedar Lake's isotopic composition towards the MWL.

Pearl Lake

Pearl Lake's $\delta^{18}O$ values ranged from -7.7 to -3.9 per mil. (Appendix E) and residence time calculations ranged from 1.3-2.4 years (Table 3). Pearl Lake is a simple circular basin of moderate depth and has an inlet and outlet via Mill Creek. 2010 precipitation values were approximately 30.5 cm higher than normal. This caused Pearl Lake to shift towards a lighter isotopic composition, however increased precipitation did not have a significant effect on residence time. Pearl Lake, lies on top of an outwash plain and is suspected to have significant groundwater contributions. Further investigation into surface and groundwater interactions may occur on Pearl Lake in a future follow up study.

Peltier Lake

Peltier Lake's $\delta^{18}O$ values ranged from -8.3 to -4.7 per mil. (Appendix E) and residence time calculations ranged from 0.9-1.5 years (Table 3). Peltier Lake is part of a large wetland complex that is relatively shallow. A dam is in place to maintain water levels. Only one isotope sample was collected in the spring of 2008, so residence times were not calculated. Residence times for 2009 and 2010 are both relatively short which is expected in a shallow reservoir.

South Center Lake

South Center Lake's $\delta^{18}O$ values ranged from -3.1 to -1.8 per mil. (Appendix E) and residence time calculations ranged from 2.0-6.4 years (Table 3). South Center Lake is part of the Chisago, MN chain of lakes. The complex hydrology of South Center Lake makes it difficult to interpret patterns in $\delta^{18}O$ amplitudes. The lake has a deep complex basin, is known to be a groundwater sink, and has had highly variable precipitation and water levels (HDR Engineering Inc. 2008). As a result, higher resolution and spatial isotope data is needed to interpret South Center Lake's hydrology.

Prairie and Cornbelt

Measured $\delta^{18}O$ values for each lake in the Prairie and Cornbelt MLUR are shown in Figure 11. The isotopic composition of lakes sampled in this MLUR show a strong correlation to the evaporative line R^2 = 0.969 (Figure 12). In general, a shift towards lighter $\delta^{18}O$ values was observed from 2008 to 2010. This shift was driven by precipitation patterns in the region. In 2008 and 2009 precipitation was below normal, however 2010 was a wet year and lakes in this MLUR received 33.0-50.8 cm of precipitation above normal (Appendix F).

$\delta^{18}O$ amplitudes responded differently among study lakes in this region. An increase in precipitation based source waters were routed through these lakes and their watersheds. The presence of lake outlets and the affect of evaporation in shallow lake basins were found to affect $\delta^{18}O$ amplitudes. This resulted in a shift to lighter $\delta^{18}O$ values and an increase in residence times in Shaokotan, Madison, and St. Olaf. This was not the case in Artichoke or St. James. Wet years did shift to lighter $\delta^{18}O$ values, but large evaporative losses to these shallow lakes increased annual $\delta^{18}O$ amplitudes and decreased residence times. Artichoke's isotopic composition parallels the MWL, suggesting that the lake is influenced by its own local climate and that source waters consist primarily of precipitation. Carrie Lake's $\delta^{18}O$ values showed the least variation as a result of above normal precipitation. This is likely because few inflow conduits limit runoff to the lake. This allows precipitation to infiltrate and enter Carrie Lake via groundwater. In contrast, lakes such as St. James have well connected watersheds that quickly transport water through the watershed and lake causing greater variation in $\delta^{18}O$ amplitudes.

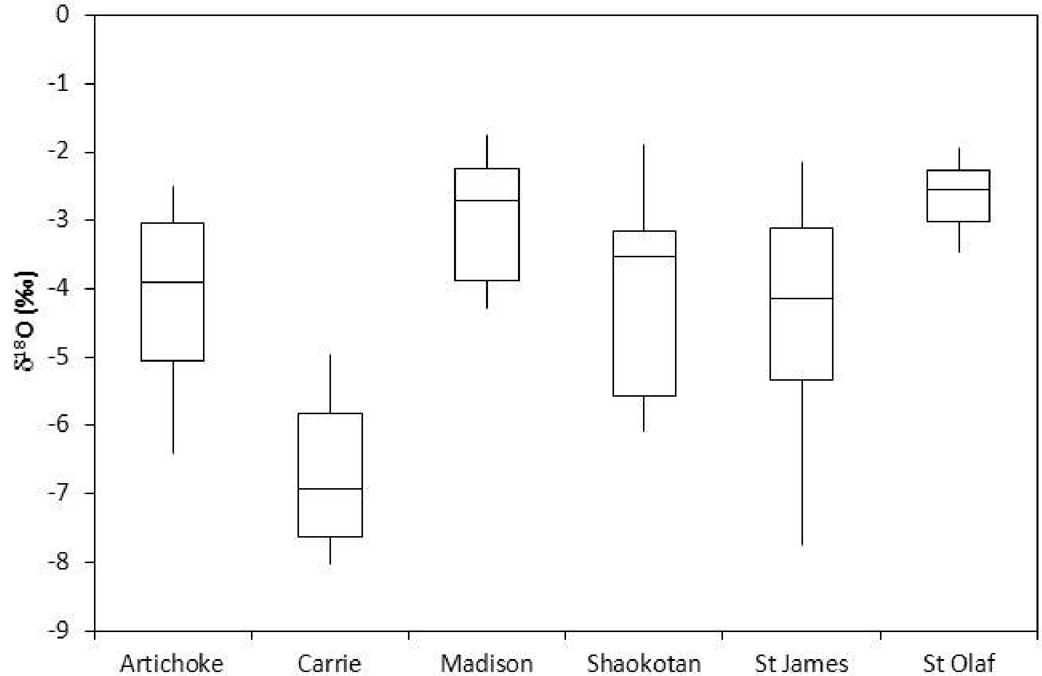

Figure 11. $\delta^{18}O$ values for study lakes within the Prairie and Cornbelt MLUR.

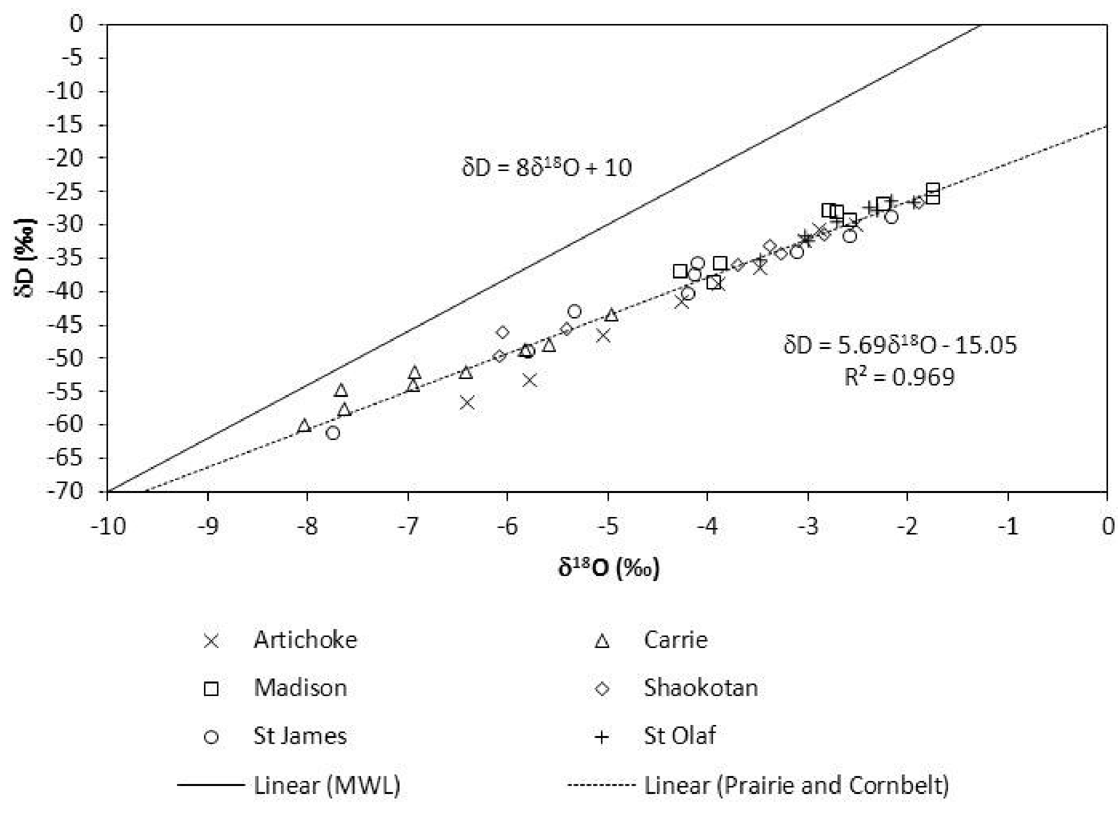

Figure 12. Prairie and Cornbelt $\delta^{18}O$ vs. δD compared to the MWL.

Table 4. Prairie and Cornbelt lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

Lake Name	Min. 2008	Max. 2008	Min. 2009	Max. 2009	Min. 2010	Max. 2010	Range (Yr)	Residence Time (Yr)
Artichoke	5.0	5.2	3.3	3.3	1.9	2.1	3.3	1.9-5.2
Carrie	1.3	1.4	1.4	1.4	2.4	2.6	1.3	1.3-2.6
Madison	2.4	2.6	2.9	3.0	6.7	7.1	4.7	2.4-7.1
Shaokotan	1.4	1.5			3.8	4.1	2.8	1.4-4.1
St James	1.3	1.4	1.5	1.5	1.1	1.2	0.4	1.1-1.5
St Olaf			3.2	3.2	5.7	5.9	2.7	3.2-5.9

Artichoke Lake

Artichoke Lake's $\delta^{18}O$ values ranged from -6.4 to -2.5 per mil. (Appendix E) and residence time calculations ranged from 1.9-5.2 years (Table 4). $\delta^{18}O$ values parallel the MWL which suggests that Artichoke Lake's water consists of primarily precipitation. Deviation from the MWL suggests source waters represent a localized MWL influenced by local climate. In general, 2008-2009 had slightly higher than normal precipitation levels and 2010 was a wet year. As a result 2010 had the lightest $\delta^{18}O$ values and the largest $\delta^{18}O$ amplitude.

Carrie Lake

Carrie Lake's $\delta^{18}O$ values ranged from -8.0 to -5.0 per mil. (Appendix E) and residence time calculations ranged from 1.3-2.6 years (Table 4). Carrie Lake is relatively deep compared to other lakes in this area and is suspected to have groundwater contributions. The lake has one outlet which drains through a diffuse wetland into Lake Elizabeth. Precipitation values for 2008 and 2009 were slightly below average and residence time ranged between 1.3-1.4 years. 2010 was a very wet year, receiving approximately 35.6 cm above normal precipitation. As a result, summer and fall $\delta^{18}O$ values deviated from the evaporative line and plotted closer to the MWL. This shift shows that 2010's annual water budget consisted of a different ratio of source waters, primarily rain water, as compared to the annual water budget of 2008 and 2009.

Madison Lake

Madison Lake's $\delta^{18}O$ values ranged from -1.8 to -4.3 per mil. (Appendix E) and residence time calculations ranged from 2.4 -7.1 years (Table 4). Madison Lake is deep with a maximum depth of 17.7 m and a mean depth of 3.0 m. The lake has an outlet through a culvert to Mud Lake. 2008 and 2009 had below normal precipitation values and residence times were between 2.4 - 3.0 years. 2010 was a wet year, receiving approximately 40.6 cm of precipitation above normal, and residence times increased to 6.7 - 7.1 years. The 2010 water budget consisted of a different ratio of source waters, primarily rain water, as compared to the annual water budget of 2008 and 2009. As a result Madison Lake shifted towards lighter $\delta^{18}O$ values in 2010.

Lake Shaokotan

Lake Shaokotan's $\delta^{18}O$ values ranged from -1.9 to -6.1 per mil. (Appendix E) and residence time calculations ranged from 1.4 -4.1 years (Table 4). One sample was not collected in spring of 2009, therefore, residence time was not calculated for that year. Annual precipitation values were highly variable for the years sampled. 2008 and 2009 were both below annual mean precipitation values. Precipitation values in 2010 were approximately 50.8 m above normal. Large volumes of rain event source waters entered Lake Shaokotan and shifted the lake towards lighter $\delta^{18}O$ values and increased residence time in 2010.

St. James Lake

St. James Lake's $\delta^{18}O$ values ranged from -2.2 to -7.7 per mil. (Appendix E) and residence time calculations ranged from 1.1 -1.5 years (Table 4). St. James Lake is a shallow impoundment on the St. James River. Since the lake is shallow and has an outlet, residence times are short. Annual precipitation values were highly variable for the years sampled. 2008 and 2009 were both below annual mean precipitation values and precipitation values in 2010 were approximately 45.7 cm above normal. As a result St. James had the largest range of $\delta^{18}O$ values in the Prairie and Cornbelt region. Drainage through the St. James River cause the watershed to be highly connected to the lake. As a result, lake waters are reflective of source water inputs which shifted to lighter $\delta^{18}O$ values in 2010.

St. Olaf Lake

St. Olaf Lake's $\delta^{18}O$ values ranged from -1.9 to -3.5 per mil. (Appendix E) and residence time calculations ranged from 3.2 -5.9 years (Table 4). One isotope sampling event was missed in the fall of 2008; therefore, residence times were not calculated for that year. St. Olaf Lake is relatively deep, 9.1 m, and has a watershed to surface area ratio of 3:1. These characteristics limit source water inputs from the lake's watershed. As a result, St. Olaf Lake has the smallest $\delta^{18}O$ amplitude and some of the heaviest $\delta^{18}O$ values in the Prairie and Cornbelt MLUR. Precipitation values in 2008 and 2009 were both below annual mean values. Precipitation values in 2010 were approximately 33.0 cm above normal, causing a shift toward lighter $\delta^{18}O$ values.

Discussion

Broad climatic patterns are responsible for regional differences in δD and $\delta^{18}O$ values. As a result, isotopic compositions were lighter in $\delta^{18}O$ at higher latitudes throughout Minnesota and in all four MLURs. Differences in weather pattern origin and air temperature are responsible for the transition. This transition was expected and serves as the local MWL for Minnesota, however in order to make lake management decisions δD and $\delta^{18}O$ data must be observed at a finer scale. By studying δD and $\delta^{18}O$ within a specific lake and its watershed, climatic differences from local weather and its impact on hydraulic residence time can be identified.

Three study lakes, White Iron, Artichoke, and Belle had isotopic compositions that parallel the MWL suggesting water budgets in these lakes consist primarily of precipitation. This is typical of watersheds with high connectivity such as reservoirs with short residence times. White Iron Lake's δD and $\delta^{18}O$ values overlie the MWL, as expected. Artichoke and Belle Lake's δD and $\delta^{18}O$ values plot parallel but to the right of the MWL. This shift suggests that precipitation in these watersheds was unique to localized climate and stresses the importance of lake specific δD and $\delta^{18}O$ measurements.

Annual variations in total precipitation among study years were found to have significant impacts on δD and $\delta^{18}O$ values. The most dramatic changes were observed in 2010 in portions of the Transition Forest and Prairie and Cornbelt MLURs, due to 33.0-50.8 cm above normal annual precipitation. This caused a strong shift to lighter δD and $\delta^{18}O$ values and increased variability amongst residence times. Belle Lake experienced the largest shift in isotopic composition caused by large volumes of water entering the lake without a significant outlet. As a result, the annual water budget was altered and was dominated by event based precipitation in 2010. This serves as an example of how extreme weather conditions can drastically alter hydraulic residence time.

Watershed size and connectivity had a large influence on the variability of hydraulic residence time among studied lakes. Two statistically significant outliers were identified and associated with White Iron and Echo Lakes. These lakes act as flow though systems and have short residence times. White Iron Lake is a reservoir and has the largest watershed of all the lakes in this study. Echo Lake is shallow with many tributaries and an outlet through the Echo River. As a result, precipitation events and runoff in these watersheds have a significant effect on δD and $\delta^{18}O$ amplitudes. Both lakes had large δD and $\delta^{18}O$ amplitudes resulting in short residence times. In contrast, lakes with small watersheds and limited connectivity, Trout and St. Olaf, had small δD and $\delta^{18}O$ amplitudes and the longest residence times.

Lakes receive various source water inputs, consisting of precipitation and groundwater. Of these, precipitation in the watershed and inflow through tributaries can be measured. Groundwater presents a challenge because diffuse seepages around the periphery of the lakes are difficult to quantify. This is problematic for calculating residence times, based on typical volume based lake models, in lakes such as Ten Mile, Elk, and Pearl where groundwater contributions may account for large portions of the annual water budget. By using δD and $\delta^{18}O$ amplitudes, a snapshot of all source water contributions, including groundwater, are accounted for. This approach provides insight into the dynamics of residence time and how these lake systems function over time and changing climatic conditions.

Geology within each watershed can also influence residence times. This was found to be important in annual hydraulic residence time variations in Bearhead and Carrie. Although both lakes likely have groundwater contributions both behave differently. Bearhead Lake's hydraulic residence time showed substantial variation between wet and dry years. This is likely a result of the underlying bed rock and the influence of wetlands in Bearhead Lake's watershed. Carrie Lake's watershed consists of glacial till and outwash which has the ability to infiltrate precipitation, buffering the effects of significantly higher than normal precipitation, opposed to other study lakes in 2010.

Conclusions

Hydraulic residence time in lakes is dynamic; changing as a result of variations in annual source water contributions and watershed characteristics. Source water contributions affect annual δD and $\delta^{18}O$ amplitudes and are determined by properties such as lake morphology, watershed size, connectivity, geology, and climate. Stable isotopes δD and $\delta^{18}O$ provide insight into annual fluctuations of lake water budgets and residence times. By documenting how individual lakes react over time to annual fluctuations, managers can better understand how to protect and remediate lakes and their watersheds.

Using stable isotopes δD and $\delta^{18}O$, it is possible to identify annual and seasonal variations in source waters and residence time while relating to a watershed's potential for contributing pollutants. Lakes with short residence times or large δD and $\delta^{18}O$ amplitudes tend to be highly connected to their watersheds. If best management practices (BMPs) are not used the potential for large pollutant loads to enter the lake is high. Some lakes have very conservative δD and $\delta^{18}O$ amplitudes. These lakes typically have a long residence time and are sensitive to even minimal pollutant loading because what enters the lake will reside for some time.

Watershed and lake models use hydraulic residence time to determine how long pollutants may reside in a lake. Typically, residence time is calculated by using lake volume and balancing inflows with outflows of a lake. This method does not represent the true range of residence times that exist. Groundwater is usually not considered and lakes are assumed to be in a steady state which is unlikely with current climatic variability. This is problematic since many protection and restoration plans are based on model results. δD and $\delta^{18}O$ offer a better understanding of hydraulic residence time and source water contributions then the current mass balance approach. Determining source water contributions and how seasonal variations affect δD and $\delta^{18}O$ compositions is key in determining loading to a lake. Residence time calculations via stable isotopes δD and $\delta^{18}O$ are made with all water sources to a lake including groundwater. This will in turn enhance lake water quality models and improve management of lakes and their watersheds.

More work is needed in order to better understand the dynamics of hydraulic residence time and lake water budgets. An increase in stable isotope data will allow for a more precise calculation of residence time ranges and provide insight into how lakes function under varying climate. When looking at stable isotopes δD and $\delta^{18}O$ in a lake it is critical to capture the entire seasonal amplitude. Additional stable isotope work in groundwater is needed in order to fully understand residence time and lake water budgets.

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Appendix A

Sentinel MLUR and morphometric data.

Lake ID #	Lake Name	MLUR	Watershed Area (Ac)	Lake Area (Ac)	Watershed to Lake Ratio	Max. Depth (ft)	Mean Depth (ft)	Mixing Class
69-0254	Bearhead	Canadian Shield	2,723	663	4:1	46	12	Stratified
69-0615	Echo	Canadian Shield	4,420	725	6:1	30	15	Stratified
69-0810	Elephant	Canadian Shield	32,069	1,140	28:1	11	6	Mixed
16-0384	Tait	Canadian Shield	2,708	357	8:1	15	7.8	Mixed
16-0049	Trout	Canadian Shield	1,148	259	4:1	77	35	Stratified
69-0004	White Iron	Canadian Shield	595,864	3,241	184:1	43	16	Mixed
15-0010	Elk	Glacial Drift Northern Forest	8,759	300	29:1	97	21.8	Stratified
10-1420	Hill	Glacial Drift Northern Forest	25,736	795	32:1	48	24.3	Stratified
29-0250	Portage	Glacial Drift Northern Forest	2,996	429	7:1	15	6.8	Mixed
18-0386	Red Sand	Glacial Drift Northern Forest	4,555	510	9:1	15	3.7	Mixed
44-0014	South Twin	Glacial Drift Northern Forest	6,745	1,128	6:1	29	12	Mixed
11-0413	Ten Mile	Glacial Drift Northern Forest	25,510	5,069	5:1	208	53	Stratified
47-0049	Belle	Transition Forest	5,207	927	6:1	22	14	Mixed
21-0057	Carlos	Transition Forest	156,569	2,606	60:1	160	45.7	Stratified
49-0140	Cedar	Transition Forest	1,603	236	7:1	88	37	Stratified
73-0037	Pearl	Transition Forest	16,311	753	22:1	18	9.8	Mixed
02-0004	Peltier	Transition Forest	69,034	550	126:1	16	7	Mixed
13-0027	South Center	Transition Forest	10,789	831	13:1	100	16	Stratified
60-0020	Artichoke	Prairie and Cornbelt	21,193	1,969	11:1	13	5.9	Mixed
34-0032	Carrie	Prairie and Cornbelt	4,044	90	45:1	26	10.4	Stratified
70-0440	Madison	Prairie and Cornbelt	11,167	1,442	8:1	58	11	Stratified
41-0089	Shaokotan	Prairie and Cornbelt	8,817	995	9:1	11	7.9	Mixed
83-0043	St James	Prairie and Cornbelt	2,340	203	12:1	14	4	Mixed
81-0003	St Olaf	Prairie and Cornbelt	278	91	3:1	30	14.5	Stratified

Appendix B

Isotope δD and δ18O sample dates.

		2008			2009			2010		
Lake ID #	Lake Name	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
69-0254	Bearhead	5/13/2008	8/11/2008	10/13/2008	5/20/2009	7/15/2009	10/13/2009	5/25/2010	7/20/2010	10/12/2010
69-0615	Echo	5/13/2008	8/11/2008	10/13/2008		7/20/2009	10/13/2009	5/25/2010	7/20/2010	10/12/2010
69-0810	Elephant	5/13/2008	8/11/2008	10/13/2008	5/21/2009	7/20/2009	10/13/2009	5/25/2010	7/20/2010	10/12/2010
16-0384	Tait				5/19/2009	7/14/2009	10/12/2009	5/24/2010	7/19/2010	10/11/2010
16-0049	Trout	5/14/2008	8/14/2008	10/15/2008	5/19/2009	7/14/2009	10/12/2009	5/24/2010	7/19/2010	10/11/2010
69-0004	White Iron	5/12/2008	8/12/2008	10/14/2008	5/19/2009	7/14/2009	10/13/2009	5/24/2010	7/19/2010	10/12/2010
15-0010	Elk	5/22/2008	7/16/2008	10/8/2008	5/20/2009	7/15/2009	10/20/2009	5/27/2010	7/22/2010	10/12/2010
10-1420	Hill	5/8/2008	7/7/2008	10/8/2008	5/27/2009	7/21/2009	10/19/2009	5/13/2010	7/22/2010	10/12/2010
29-0250	Portage	5/20/2008	7/15/2008	10/8/2008	6/1/2009	7/6/2009	10/20/2009	5/13/2010	7/22/2010	10/12/2010
18-0386	Red Sand	5/8/2008	7/16/2008	10/7/2008	5/21/2009	7/28/2009	10/1/2009	5/13/2010	7/22/2010	10/11/2010
44-0014	South Twin	5/21/2008	7/16/2008	10/8/2008	5/20/2009	7/15/2009	10/19/2009	5/27/2010	7/29/2010	10/11/2010
11-0413	Ten Mile	5/21/2008	7/15/2008	10/7/2008	5/19/2009	7/14/2009	10/20/2009	5/19/2010	7/28/2010	10/11/2010
47-0049	Belle	5/21/2008	7/23/2008	10/7/2008	5/5/2009	7/8/2009	10/12/2010	4/29/2010	7/26/2010	10/4/2010
21-0057	Carlos	5/20/2008	7/24/2008	10/6/2008	5/20/2009	7/9/2009	10/5/2009	5/25/2010	7/20/2010	10/20/2010
49-0140	Cedar	5/6/2008	7/15/2008	10/7/2008	5/28/2009	7/29/2009	10/5/2009	5/20/2010	7/27/2010	10/20/2010
73-0037	Pearl	5/6/2008	7/15/2008	10/7/2008	5/22/2009	7/29/2009	10/5/2009	4/29/2010	7/27/2010	10/20/2010
02-0004	Peltier	4/23/2008			5/6/2009	7/23/2009	10/7/2009	5/28/2010	7/19/2010	10/14/2010
13-0027	South Center	5/14/2008	7/14/2008	10/10/2008	5/6/2009	7/23/2009	10/7/2009	5/24/2010	7/19/2010	10/14/2010
60-0020	Artichoke	5/7/2008	7/30/2008	10/6/2008	5/27/2009	7/21/2009	10/12/2009	4/29/2010	7/2/2010	10/4/2010
34-0032	Carrie	5/22/2008	7/23/2008	10/7/2008	5/5/2009	7/8/2009	10/12/2009	4/29/2010	7/20/2010	10/4/2010
70-0440	Madison	4/22/2008	7/9/2008	9/9/2008	5/28/2009	7/14/2009	10/15/2009	4/29/2010	7/21/2010	10/6/2010
41-0089	Shaokotan	5/6/2008	7/31/2008	10/7/2008		7/21/2009	10/13/2009	4/29/2010	7/21/2010	10/4/2010
83-0043	St James	4/22/2008	7/10/2008	9/11/2008	4/28/2009	7/14/2009	10/15/2009	4/29/2010	7/21/2010	10/6/2010
81-0003	St Olaf	4/22/2008	7/15/2008		4/29/2009	7/15/2009	10/15/2009	4/29/2010	7/21/2010	10/6/2010

Appendix C

Study lakes $\delta^{18}O$ and δD values (‰).

Lake Name	Sample Date	δD (‰)	δD sdev. (‰)	$\delta^{18}O$ (‰)	$\delta^{18}O$ sdev. (‰)	Analysis Date
Shaokotan	5/6/2008	-35.937387	1.026887	-3.694738	0.296802	12/21/2010
Shaokotan	7/31/2008	-33.169540	0.124753	-3.375618	0.057783	12/21/2010
Shaokotan	10/7/2008	-26.693951	0.188594	-1.894256	0.204752	12/21/2010
Shaokotan	7/21/2009	-34.219817	0.382860	-3.266347	0.169137	12/21/2010
Shaokotan	10/13/2009	-31.527229	0.407274	-2.844165	0.085158	12/21/2010
Shaokotan	4/29/2010	-49.703032	0.195744	-6.086273	0.029504	12/21/2010
Shaokotan	7/21/2010	-45.646928	0.202819	-5.404838	0.052542	12/21/2010
Shaokotan	10/4/2010	-46.161880	0.177417	-6.044600	0.056201	12/21/2010
South Center	5/14/2008	-33.426197	0.273208	-3.085699	0.064831	12/21/2010
South Center	7/14/2008	-32.848154	0.253385	-2.653359	0.088745	12/21/2010
South Center	10/10/2008	-29.611800	0.790346	-2.191031	0.228843	12/21/2010
South Center	5/6/2009	-32.370716	0.348919	-3.114438	0.115700	12/21/2010
South Center	7/23/2009	-29.498742	0.395086	-1.840138	0.091266	12/21/2010
South Center	10/7/2009	-29.234088	0.259069	-2.000423	0.091640	12/21/2010
South Center	5/24/2010	-33.159793	0.391400	-2.883917	0.038495	12/21/2010
South Center	7/19/2010	-33.546596	0.194521	-2.530006	0.070923	12/21/2010
South Center	10/14/2010	-32.515122	0.465065	-2.478715	0.325226	12/21/2010
Peltier	4/23/2008	-57.596207	0.282923	-8.323363	0.089338	12/21/2010
Peltier	5/6/2009	-56.125175	0.675699	-7.365267	0.101420	12/21/2010
Peltier	7/23/2009	-46.235323	0.425638	-5.380922	0.129110	12/21/2010
Peltier	10/7/2009	-40.072710	0.101562	-4.676502	0.126319	12/21/2010
Peltier	5/28/2010	-58.738909	1.095135	-7.674889	0.173618	12/21/2010
Peltier	7/19/2010	-53.174722	0.408318	-6.526179	0.141378	12/21/2010
Peltier	10/14/2010	-48.693478	0.119306	-5.939163	0.093165	12/21/2010
South Twin	5/21/2008	-51.714042	0.725882	-5.696343	0.400443	12/21/2010
South Twin	7/16/2008	-50.782194	0.522610	-5.040843	0.089616	12/21/2010
South Twin	10/8/2008	-46.943988	0.077108	-4.634283	0.056201	12/21/2010
South Twin	5/20/2009	-54.971313	0.653615	-6.498205	0.049032	12/21/2010
South Twin	7/15/2009	-52.353743	0.393898	-6.072880	0.117451	12/21/2010
South Twin	10/19/2009	-51.121354	0.448074	-6.120417	0.032191	12/21/2010
South Twin	5/27/2010	-57.529061	0.141583	-6.318150	0.147792	1/3/2011
South Twin	7/29/2010	-54.804255	0.058695	-6.203331	0.097087	1/3/2011
South Twin	10/11/2010	-52.683681	0.050925	-5.855249	0.205802	1/3/2011
Madison	4/22/2008	-27.844317	0.359356	-2.789388	0.234673	1/3/2011
Madison	7/9/2008	-28.193356	0.222647	-2.705591	0.111141	1/3/2011
Madison	9/9/2008	-24.709556	0.249368	-1.756826	0.041997	1/3/2011
Madison	5/28/2009	-29.232471	0.185213	-2.585099	0.057783	1/3/2011
Madison	7/14/2009	-26.885968	0.371939	-2.237857	0.078219	1/3/2011
Madison	10/15/2009	-25.915060	0.327028	-1.751220	0.094568	1/3/2011

Madison	4/29/2010	-38.700102	0.406227	-3.935485	0.105162	1/3/2011
Madison	7/21/2010	-36.981033	0.521284	-4.269036	0.072269	1/3/2011
Madison	10/6/2010	-35.637745	0.417342	-3.874500	0.172726	1/3/2011
Belle	5/21/2008	-25.125219	0.421921	-2.175996	0.040795	1/3/2011
Belle	7/23/2008	-24.336426	0.030734	-1.977541	0.036048	1/3/2011
Belle	10/7/2008	-22.063544	0.251944	-1.514478	0.065198	1/3/2011
Belle	5/5/2009	-26.949305	0.236560	-2.287474	0.051827	1/3/2011
Belle	7/8/2009	-25.245918	0.281560	-1.815836	0.083586	1/3/2011
Belle	10/12/2009	-25.135419	0.255269	-1.950590	0.059896	1/3/2011
Belle	4/29/2010	-33.281760	0.379187	-3.360514	0.059427	1/3/2011
Belle	7/26/2010	-32.797870	0.233336	-3.188130	0.081285	1/3/2011
Belle	10/4/2010	-31.845372	0.381373	-3.048225	0.045616	1/3/2011
Artichoke	5/27/2008	-30.816471	1.065581	-2.885834	0.080104	1/3/2011
Artichoke	7/30/2008	-32.424342	0.770655	-3.033235	0.180202	1/3/2011
Artichoke	10/6/2008	-29.940376	0.354931	-2.509838	0.024894	1/3/2011
Artichoke	5/27/2009	-41.528729	0.257153	-4.255283	0.077420	1/3/2011
Artichoke	7/21/2009	-38.980131	0.418915	-3.899146	0.163333	1/3/2011
Artichoke	10/12/2009	-36.459820	0.353321	-3.469831	0.133506	1/3/2011
Artichoke	4/29/2010	-56.586669	0.407274	-6.409180	0.104013	1/3/2011
Artichoke	7/21/2010	-53.382395	0.315845	-5.784720	0.145367	1/3/2011
Artichoke	10/4/2010	-46.527488	0.242666	-5.048054	0.176764	1/3/2011
Cedar	5/6/2008	-48.325669	0.543112	-5.548176	0.074972	1/4/2011
Cedar	7/15/2008	-47.023508	0.320793	-5.183164	0.174380	1/4/2011
Cedar	10/7/2008	-44.34592	0.193671	-4.580156	0.091085	1/4/2011
Cedar	5/28/2009	-47.912707	0.366960	-5.429794	0.106882	1/4/2011
Cedar	7/29/2009	-45.942815	0.288615	-5.120274	0.127560	1/4/2011
Cedar	10/5/2009	-45.949476	0.154295	-5.334841	0.071736	1/4/2011
Cedar	5/20/2010	-51.001059	0.264683	-6.098703	0.146617	1/4/2011
Cedar	7/27/2010	-49.420825	0.886056	-5.72619	0.068060	1/4/2011
Cedar	10/20/2010	-48.236485	0.767976	-5.276435	0.077098	1/4/2011
Carrie	5/22/2008	-53.931006	0.976719	-6.950872	0.161470	1/4/2011
Carrie	7/23/2008	-48.06443	0.297135	-5.592883	0.084731	1/4/2011
Carrie	10/7/2008	-43.509147	0.614958	-4.959986	0.095234	1/4/2011
Carrie	5/5/2009	-57.472501	0.218937	-7.636104	0.034790	1/4/2011
Carrie	7/8/2009	-51.969795	0.181816	-6.424727	0.051021	1/4/2011
Carrie	10/12/2009	-48.71407	0.435573	-5.823885	0.030198	1/4/2011
Carrie	4/29/2010	-59.904448	1.212939	-8.02859	0.217113	1/4/2011
Carrie	7/20/2010	-52.099955	0.269595	-6.933505	0.165552	1/4/2011
Carrie	10/4/2010	-54.591844	0.412303	-7.662754	0.035847	1/4/2011
Elk	5/22/2008	-58.7559	0.463704	-6.26703	0.169755	1/4/2011
Elk	7/16/2008	-56.883579	0.224644	-5.851323	0.098990	1/4/2011
Elk	10/8/2008	-55.161445	0.273717	-5.948672	0.079844	1/4/2011
Elk	5/20/2009	-59.425062	0.469486	-6.978731	0.153245	1/4/2011

Elk	7/15/2009	-56.569857	0.292075	-6.741936	0.207841	1/4/2011
Elk	10/20/2009	-56.903604	0.159903	-6.731411	0.192905	1/4/2011
Elk	5/27/2010	-60.70654	0.398204	-7.544141	0.133032	1/4/2011
Elk	7/22/2010	-58.847018	0.104447	-7.294308	0.067463	1/4/2011
Elk	10/12/2010	-58.523695	0.118076	-6.647277	0.087900	1/4/2011
Pearl	5/6/2008	-47.542459	0.247043	-5.806826	0.196825	1/4/2011
Pearl	7/15/2008	-45.528813	0.558847	-5.063086	0.099824	1/4/2011
Pearl	10/7/2008	-40.456169	1.541960	-3.9256	0.175942	1/4/2011
Pearl	5/22/2009	-50.279485	0.477124	-6.25846	0.019687	1/19/2011
Pearl	7/29/2009	-45.733583	0.570161	-5.459492	0.105113	1/11/2011
Pearl	10/5/2009	-42.559479	0.144738	-5.205003	0.122732	1/11/2011
Pearl	4/29/2010	-55.919092	0.133273	-7.667151	0.067463	1/11/2011
Pearl	7/27/2010	-49.795249	0.610315	-6.473686	0.095016	1/11/2011
Pearl	10/20/2010	-48.166953	0.252217	-6.241763	0.057926	1/11/2011
Portage	5/20/2008	-65.025602	0.216666	-7.986491	0.129879	1/11/2011
Portage	7/15/2008	-62.625083	0.276606	-7.316078	0.061265	1/11/2011
Portage	10/8/2008	-57.48038	0.159387	-6.666215	0.035585	1/11/2011
Portage	6/1/2009	-66.733664	0.414501	-8.563148	0.037871	1/11/2011
Portage	7/6/2009	-64.999956	0.286446	-8.32555	0.037843	1/11/2011
Portage	10/20/2009	-62.392554	0.207598	-7.77201	0.051264	1/11/2011
Portage	5/13/2010	-68.978261	0.243458	-8.876828	0.123607	1/11/2011
Portage	7/22/2010	-65.172143	0.290967	-8.141745	0.064447	1/11/2011
Portage	10/12/2010	-63.501906	0.427458	-7.740317	0.077527	1/11/2011
Carlos	5/20/2008	-38.102481	0.363267	-3.714303	0.220837	1/11/2011
Carlos	7/24/2008	-37.427638	0.764191	-3.521409	0.085836	1/11/2011
Carlos	10/6/2008	-36.523348	0.270885	-3.573542	0.067693	1/11/2011
Carlos	5/20/2009	-41.205137	0.931871	-4.545425	0.102891	1/11/2011
Carlos	7/9/2009	-40.234975	0.158522	-4.277945	0.061011	1/11/2011
Carlos	10/5/2009	-39.487642	0.953737	-4.021408	0.165270	1/11/2011
Carlos	5/25/2010	-43.320294	0.287715	-4.669438	0.180684	1/11/2011
Carlos	7/20/2010	-41.75021	0.435103	-4.132047	0.055905	1/11/2011
Carlos	10/20/2010	-42.231862	0.151691	-4.48585	0.021690	1/11/2011
Ten Mile	5/21/2008	-41.964415	0.469402	-4.150632	0.077420	1/11/2011
Ten Mile	7/15/2008	-42.975758	0.233520	-4.386589	0.133094	1/11/2011
Ten Mile	10/7/2008	-41.045164	0.485400	-3.707174	0.041325	1/11/2011
Ten Mile	5/19/2009	-43.101339	0.246228	-4.416232	0.076882	1/11/2011
Ten Mile	7/14/2009	-41.855578	0.116672	-4.286989	0.024558	1/11/2011
Ten Mile	10/20/2009	-41.745067	0.195041	-4.246675	0.024218	1/11/2011
Ten Mile	5/19/2010	-44.588046	0.110020	-4.699716	0.065705	1/13/2011
Ten Mile	7/28/2010	-44.095207	0.437712	-4.711597	0.062071	1/13/2011
Ten Mile	10/11/2010	-43.156625	0.148949	-4.59754	0.060035	1/13/2011
Hill	5/8/2008	-58.828249	1.134724	-7.083039	0.155979	1/13/2011
Hill	7/7/2008	-58.705459	0.489655	-6.991555	0.104807	1/13/2011

Hill	10/8/2008	-56.887167	0.357477	-6.759876	0.067078	1/13/2011
Hill	5/27/2009	-61.024654	0.526748	-7.443503	0.069863	1/13/2011
Hill	7/21/2009	-64.908794	0.522663	-8.061589	0.102163	1/13/2011
Hill	10/19/2009	-58.295119	0.437371	-6.796698	0.083287	1/13/2011
Hill	5/13/2010	-61.340326	0.401566	-7.302404	0.118190	1/13/2011
Hill	7/22/2010	-59.696772	0.342034	-7.555882	0.042194	1/13/2011
Hill	10/12/2010	-58.905876	0.524005	-7.327377	0.111178	1/13/2011
Red Sand	5/8/2008	-40.818668	0.407531	-3.525855	0.111402	1/13/2011
Red Sand	7/16/2008	-37.541327	0.235154	-2.686027	0.043165	1/13/2011
Red Sand	10/7/2008	-29.61454	0.287548	-1.568934	0.026817	1/13/2011
Red Sand	5/21/2009	-42.284363	0.166707	-4.318804	0.163359	1/13/2011
Red Sand	7/28/2009	-37.354145	0.620607	-3.29949	0.104639	1/13/2011
Red Sand	10/1/2009	-32.923635	0.599449	-2.384653	0.088230	1/13/2011
Red Sand	5/13/2010	-48.278881	0.820916	-5.086739	0.183439	1/19/2011
Red Sand	7/22/2010	-43.354386	0.660003	-4.215393	0.227530	1/13/2011
Red Sand	10/11/2010	-39.144015	0.057989	-3.528991	0.118111	1/13/2011
St James	4/22/2008	-37.35503	0.503817	-4.130201	0.154269	1/13/2011
St James	7/10/2008	-35.765573	0.555787	-4.098559	0.059340	1/13/2011
St James	9/11/2008	-28.749979	0.458249	-2.161054	0.092170	1/13/2011
St James	4/28/2009	-40.317658	0.732484	-4.199317	0.133226	1/13/2011
St James	7/14/2009	-34.14427	0.474033	-3.115126	0.076720	1/13/2011
St James	10/15/2009	-31.559623	0.470509	-2.588124	0.096305	1/13/2011
St James	4/29/2010	-61.245885	1.294173	-7.743134	0.130587	1/19/2011
St James	7/21/2010	-49.002139	0.826960	-5.790385	0.129046	1/13/2011
St James	10/6/2010	-42.835593	0.576178	-5.323756	0.099324	1/13/2011
St Olaf	4/22/2008	-27.866228	0.693880	-2.307581	0.197539	1/18/2011
St Olaf	7/15/2008	-26.473624	0.942272	-2.166081	0.042803	1/18/2011
St Olaf	4/29/2009	-29.58316	0.271847	-2.706466	0.154752	1/18/2011
St Olaf	7/15/2009	-27.237634	0.673115	-2.38687	0.161720	1/18/2011
St Olaf	10/15/2009	-26.542168	0.144275	-1.947731	0.042972	1/18/2011
St Olaf	4/29/2010	-35.213759	0.330388	-3.47008	0.118182	1/18/2011
St Olaf	7/21/2010	-32.454244	0.933808	-3.000952	0.151340	1/18/2011
St Olaf	10/6/2010	-31.634838	0.184143	-3.031049	0.063262	1/18/2011
Trout	5/14/2008	-66.201201	0.754821	-8.378353	0.127820	1/18/2011
Trout	8/14/2008	-64.982292	0.317780	-8.133812	0.070527	1/18/2011
Trout	10/15/2008	-63.39108	0.166181	-8.047282	0.040592	1/18/2011
Trout	5/19/2009	-65.390295	0.366529	-8.494981	0.049369	1/18/2011
Trout	7/14/2009	-67.190288	0.473159	-8.619342	0.110917	1/18/2011
Trout	10/12/2009	-65.099148	1.190509	-8.345541	0.191704	1/18/2011
Trout	5/24/2010	-65.556209	0.842401	-8.318407	0.202492	1/18/2011
Trout	7/19/2010	-65.66446	0.548320	-8.24564	0.099938	1/18/2011
Trout	10/11/2010	-64.640369	0.713153	-8.105039	0.012468	1/18/2011
Elephant	5/13/2008	-59.916297	0.894012	-6.916841	0.191444	1/18/2011

Elephant	8/11/2008	-60.248087	0.954816	-6.594168	0.112291	1/18/2011
Elephant	10/13/2008	-56.544622	0.607746	-6.143453	0.147792	1/18/2011
Elephant	5/21/2009	-63.633139	0.409125	-7.558923	0.038279	1/18/2011
Elephant	7/20/2009	-62.190916	0.353107	-7.119383	0.066831	1/18/2011
Elephant	10/13/2009	-59.078303	0.625549	-6.748132	0.064703	1/18/2011
Elephant	5/25/2010	-62.303297	0.302497	-7.560165	0.132571	1/18/2011
Elephant	7/20/2010	-60.483796	0.837926	-7.292883	0.099356	1/18/2011
Elephant	10/12/2010	-59.691599	0.582085	-7.09504	0.055887	1/18/2011
Echo	5/13/2008	-79.632592	0.168643	-11.207698	0.112651	1/18/2011
Echo	8/11/2008	-71.505677	0.373524	-9.110564	0.192776	1/18/2011
Echo	10/13/2008	-63.563034	0.239496	-7.629215	0.051082	1/18/2011
Echo	7/20/2009	-71.590064	0.147384	-8.936215	0.142720	1/18/2011
Echo	10/13/2009	-65.562082	1.266519	-7.97489	0.121979	1/19/2011
Echo	5/25/2010	-74.100782	1.216457	-9.35302	0.108757	1/19/2011
Echo	7/20/2010	-69.93974	1.214784	-9.069357	0.200905	1/19/2011
Echo	10/12/2010	-65.263186	0.393623	-8.134451	0.115279	1/19/2011
Bearhead	5/13/2008	-52.756552	0.260550	-6.272911	0.200409	1/19/2011
Bearhead	8/11/2008	-51.84475	0.438183	-5.919514	0.115315	1/19/2011
Bearhead	10/13/2008	-50.011535	0.159903	-5.312933	0.100517	1/19/2011
Bearhead	5/20/2009	-54.332642	0.460593	-6.030395	0.102406	1/19/2011
Bearhead	7/15/2009	-52.879986	0.136040	-5.660582	0.137506	1/19/2011
Bearhead	10/13/2009	-51.879714	0.551967	-5.352598	0.057206	1/19/2011
Bearhead	5/25/2010	-52.64039	0.351191	-5.498423	0.025265	1/19/2011
Bearhead	7/20/2010	-52.667198	0.305766	-5.559087	0.050449	1/19/2011
Bearhead	10/12/2010	-52.463756	0.591710	-5.410389	0.049432	1/19/2011
White Iron	5/28/2008	-81.631909	0.494836	-11.243688	0.080966	1/19/2011
White Iron	8/12/2008	-70.602882	0.366604	-9.300082	0.083685	1/19/2011
White Iron	10/14/2008	-65.96133	0.355700	-8.777568	0.152710	1/19/2011
White Iron	5/19/2009	-80.840948	0.762085	-11.55397	0.176477	1/19/2011
White Iron	7/14/2009	-75.809895	0.811599	-10.161425	0.082387	1/19/2011
White Iron	10/13/2009	-57.281577	0.376674	-8.193951	0.053924	1/19/2011
White Iron	5/14/2010	-59.395897	1.037873	-8.532121	0.091719	1/19/2011
White Iron	7/19/2010	-36.131458	0.967582	-6.479108	0.167320	1/19/2011
White Iron	10/12/2010	-55.709319	0.394651	-7.604438	0.027429	1/19/2011
Tait	5/19/2009	-62.180882	1.414879	-9.580906	0.144617	1/19/2011
Tait	7/14/2009	-59.221663	0.442601	-8.855439	0.078377	1/19/2011
Tait	10/12/2009	-65.108591	0.691638	-8.225677	0.060447	1/19/2011
Tait	5/24/2010	-68.598603	0.355623	-8.717548	0.112033	1/19/2011
Tait	7/19/2010	-64.919262	0.303738	-7.889706	0.154430	1/19/2011
Tait	10/11/2010	-61.968753	0.333724	-7.284234	0.154115	1/19/2011

Appendix D

Study lakes seasonal mean air temperatures (°C).

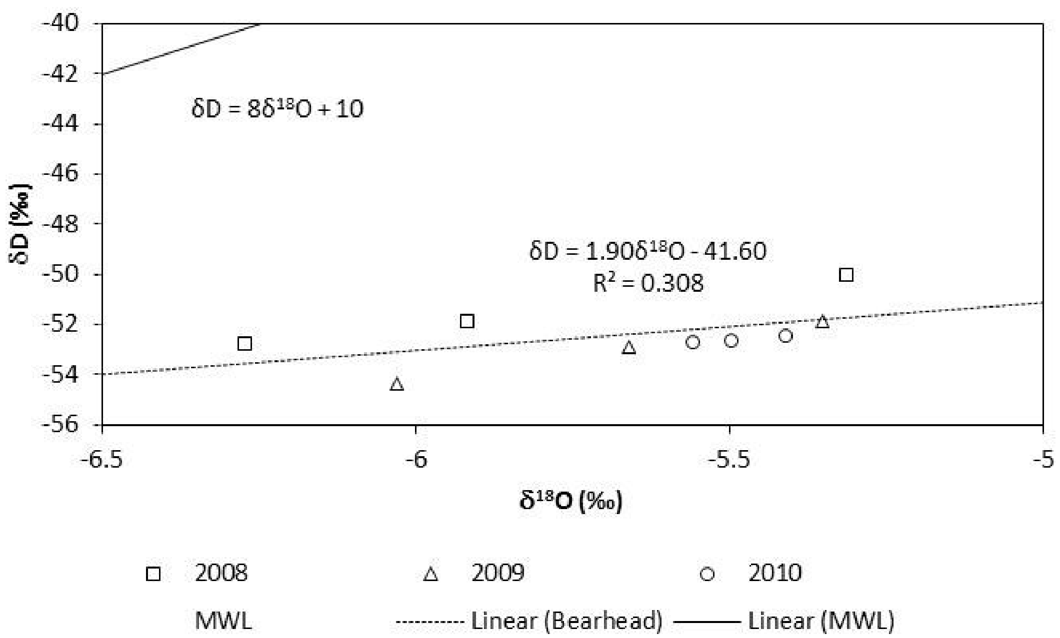
	2008				2009				2010			
Lake Name	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Artichoke	-17.28	-1.32	14.21	2.37	-18.60	-0.73	12.93	3.79	-16.19	3.13	15.70	2.43
Bearhead	-19.77	-5.71	9.74	0.03	-23.04	-4.11	8.60	1.23	-20.37	-0.65	11.44	-0.95
Belle	-16.59	-0.60	14.74	2.96	-17.35	0.30	13.61	4.00	-15.63	3.40	16.15	2.66
Carlos	-18.03	-2.16	13.57	2.37	-19.64	-1.32	12.55	3.70	-16.19	2.71	15.24	2.03
Carrie	-16.77	-0.88	14.38	2.59	-17.85	-0.11	13.29	3.94	-15.96	3.10	15.78	2.35
Cedar	-17.75	-2.21	13.05	2.20	-19.44	-1.39	12.14	3.32	-16.05	2.49	14.75	1.92
Echo	-20.38	-5.64	9.92	0.59	-22.89	-4.35	9.27	1.55	-20.47	-1.20	11.30	-0.66
Elephant	-20.38	-5.62	9.53	0.31	-22.76	-4.47	8.87	1.30	-20.40	-1.32	10.99	-0.91
Elk	-20.08	-4.77	11.04	0.59	-22.11	-3.45	10.52	2.45	-17.94	0.79	13.00	-0.11
Hill	-18.83	-3.66	11.17	1.41	-20.68	-2.61	10.38	2.79	-17.05	0.86	13.27	0.75
Madison	-15.16	0.14	14.70	3.74	-15.76	1.07	13.51	4.18	-15.67	3.34	16.36	2.84
Pearl	-16.64	-1.11	14.07	2.96	-18.02	-0.22	12.96	3.91	-15.22	3.04	15.48	2.50
Peltier	-15.47	-0.85	14.35	3.72	-17.04	0.52	13.38	4.41	-14.75	3.23	16.02	2.93
Portage	-19.54	-3.70	11.91	1.27	-21.63	-2.75	11.13	2.78	-17.60	1.37	13.69	0.53
Red Sand	-18.47	-2.72	12.54	1.97	-20.22	-1.86	11.60	3.19	-16.59	1.84	14.48	1.49
Shaokotan	-15.92	-1.12	14.25	2.28	-16.84	-0.74	12.91	3.62	-15.78	2.89	15.53	2.25
South Center	-15.84	-1.34	13.81	3.37	-17.73	-0.09	12.83	4.38	-15.14	2.94	15.71	2.62
South Twin	-19.98	-3.88	11.79	1.28	-21.91	-2.74	11.12	2.99	-17.59	1.55	13.79	0.72
St. James	-15.09	0.29	14.87	3.36	-15.49	0.98	13.66	3.97	-15.58	3.42	16.46	2.93
St. Olaf	-15.25	0.16	14.57	3.48	-15.89	1.13	13.44	4.08	-15.78	3.30	16.32	2.93
Tait	-17.50	-5.67	10.29	0.62	-20.20	-4.42	9.07	1.66	-16.66	-0.43	11.91	-0.17
Ten Mile	-18.74	-3.31	12.13	1.86	-20.77	-2.15	11.35	3.34	-16.81	1.77	14.26	1.32
Trout	-17.33	-5.37	10.28	0.33	-19.55	-4.74	9.26	1.49	-15.37	-0.31	11.72	-0.24
White Iron	-20.12	-5.84	10.00	0.21	-23.48	-4.38	9.00	1.88	-20.37	-0.36	11.88	-0.40

Appendix E

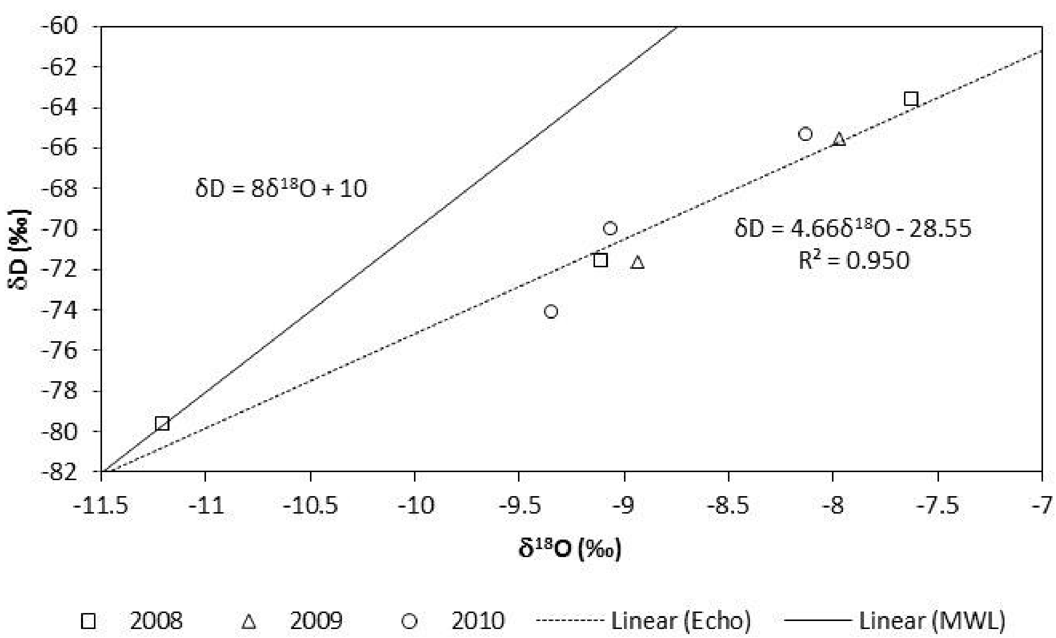
Study lakes $\delta^{18}O$ vs. δD compared to the MWL.

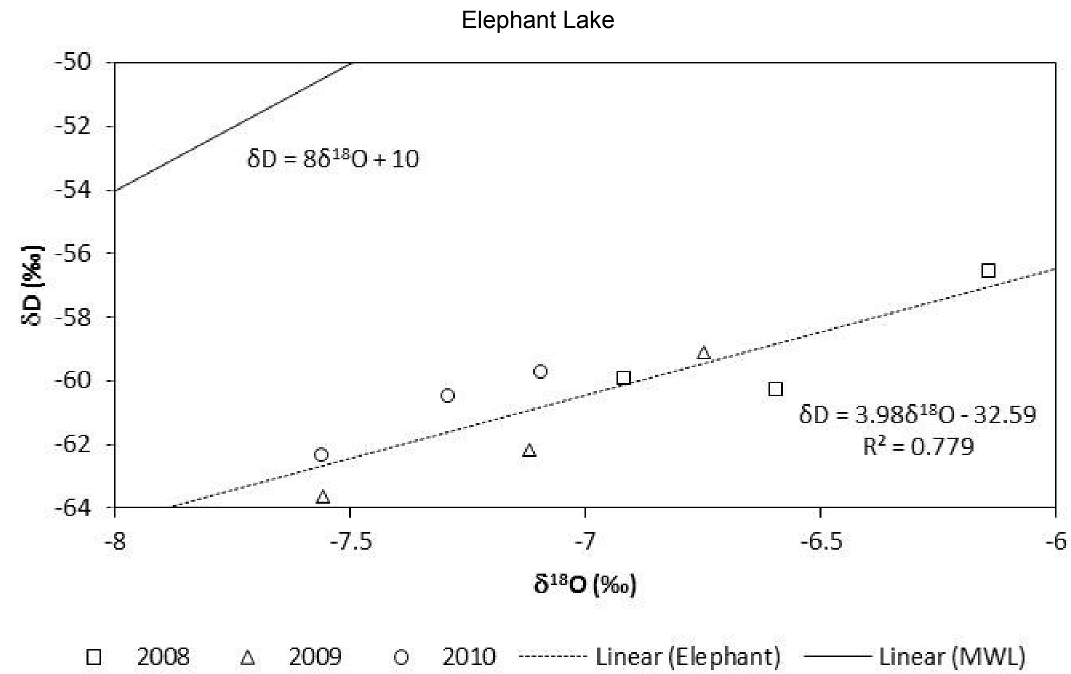
Canadian Shield

Bearhead Lake

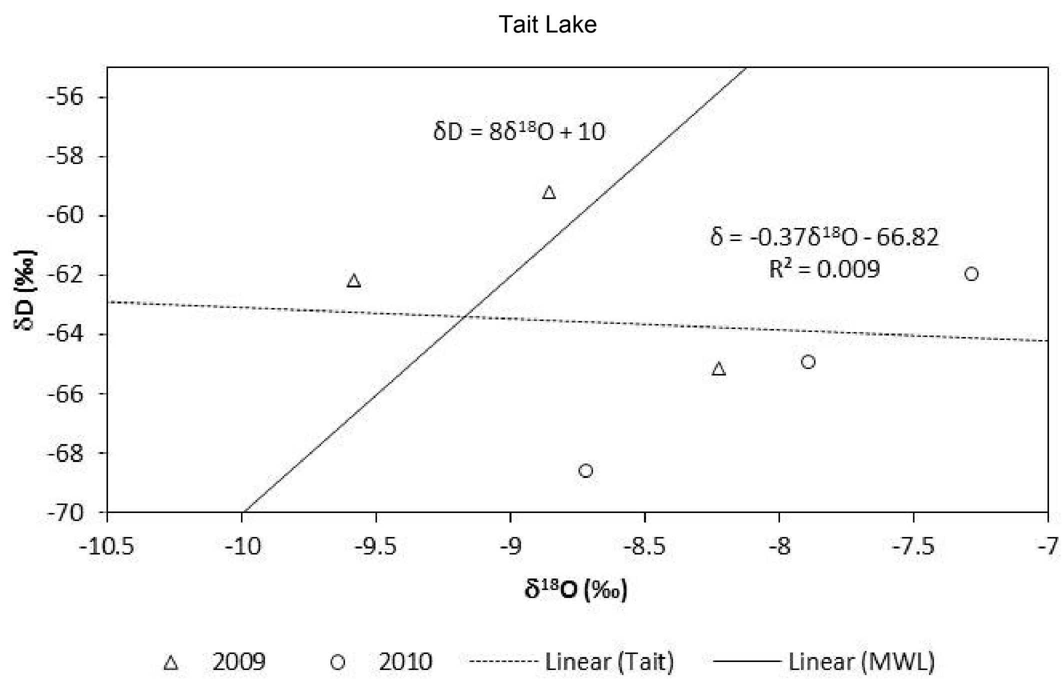


Echo Lake

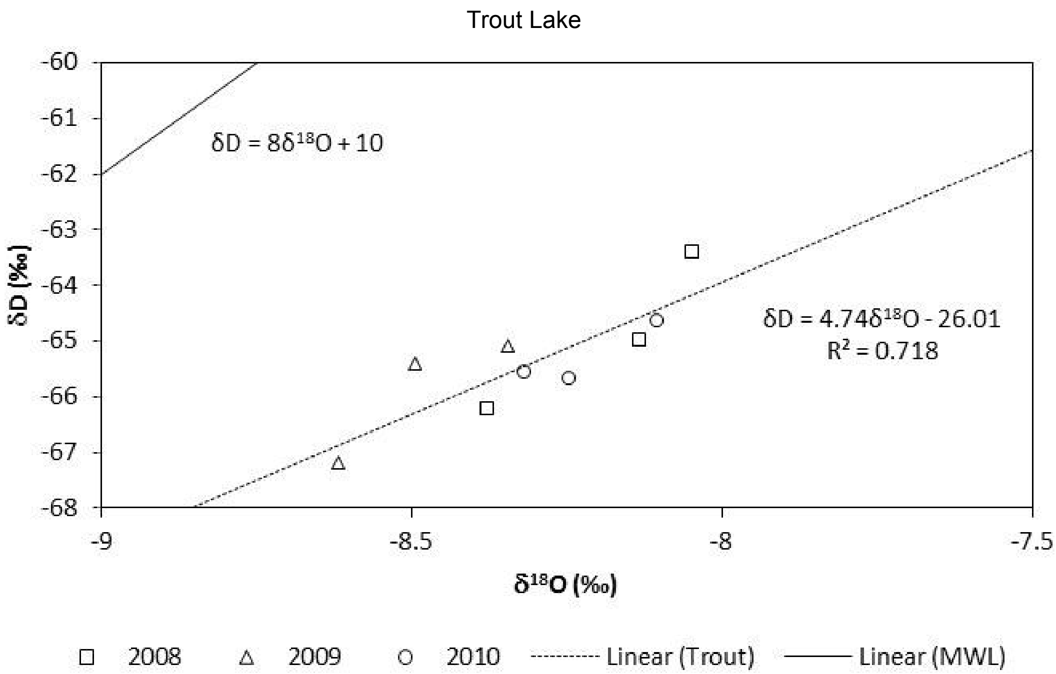


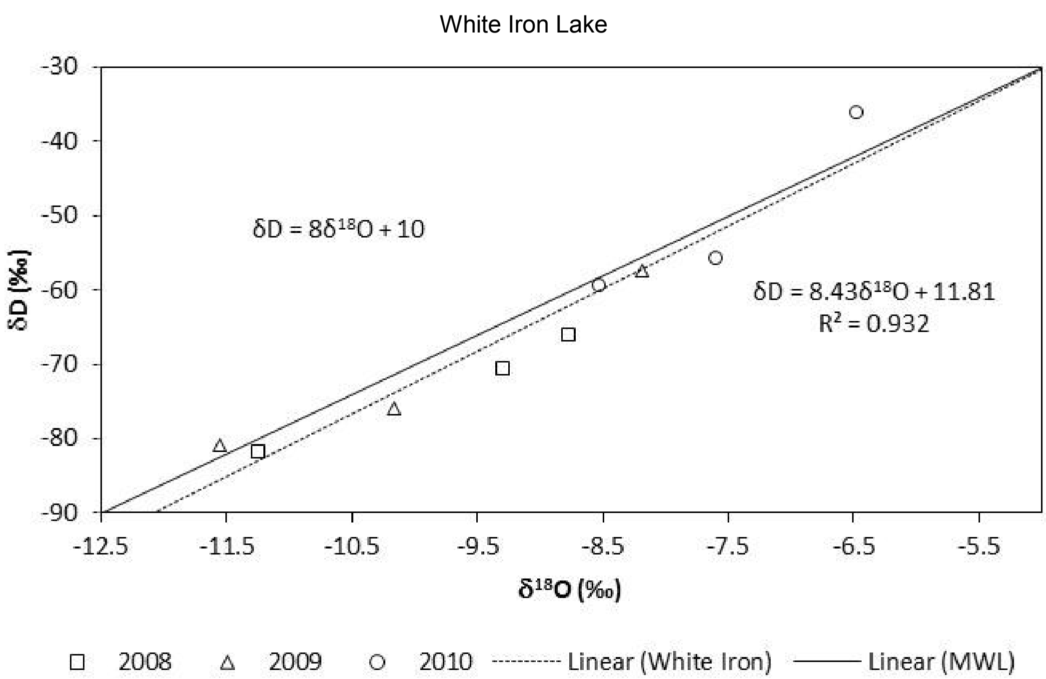


Elephant Lake
-50
-52
-54
-56
-58
-60
-62
-64
δD (‰)
δD = 8δ18O + 10
δD = 3.98δ18O - 32.59
R² = 0.779
-8
-7.5
-7
-6.5
-6
δ18O (‰)
2008
2009
2010
Linear (Elephant)
Linear (MWL)

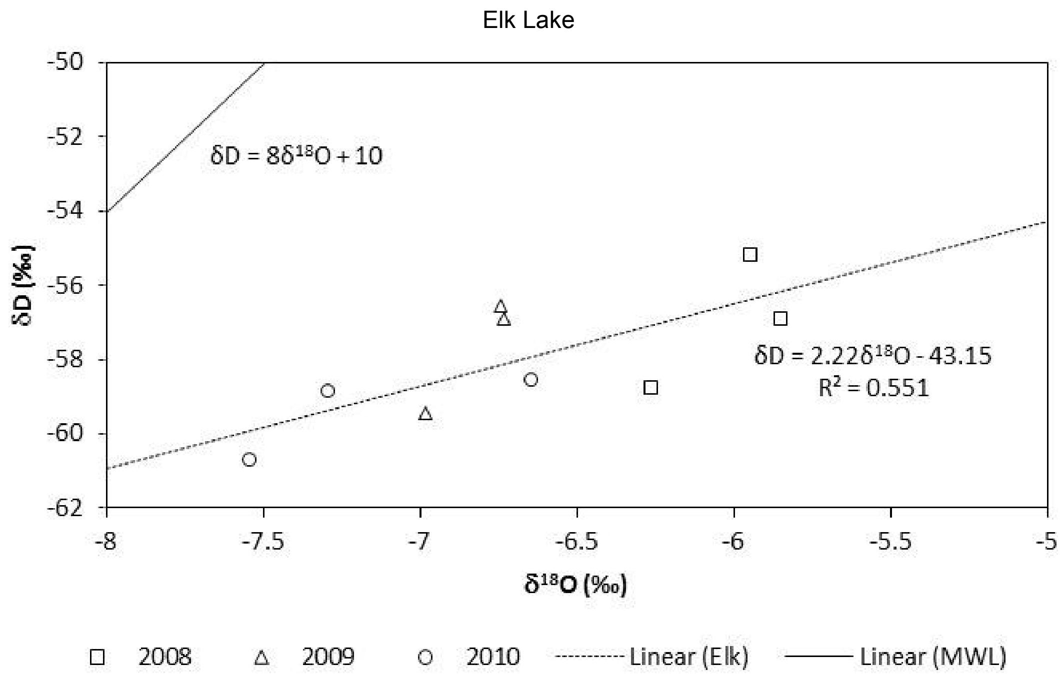


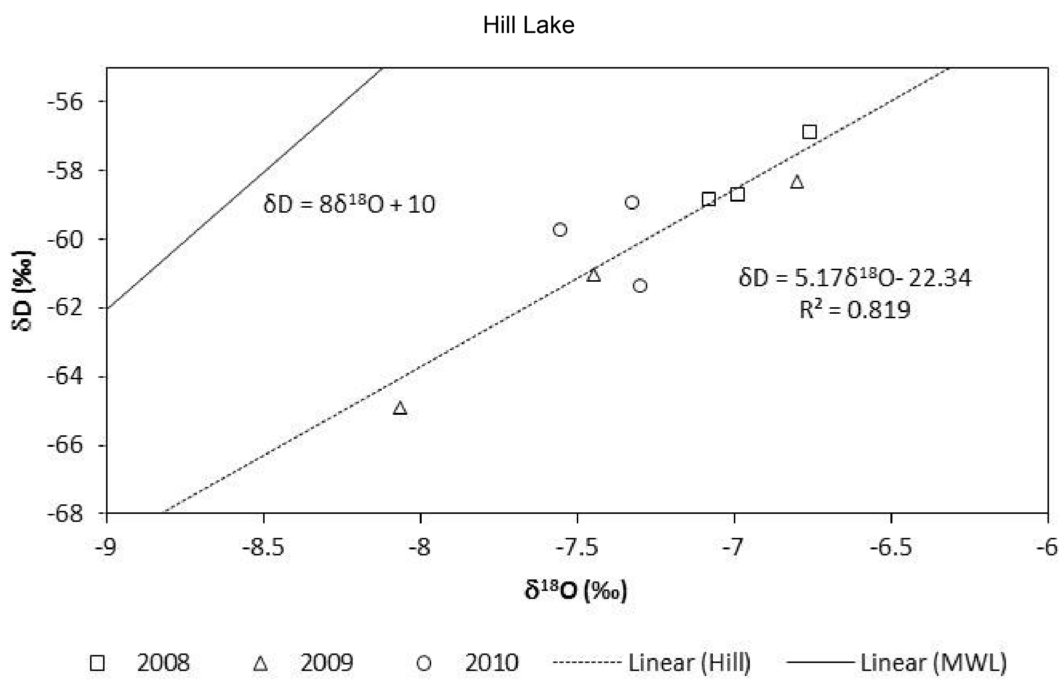
Tait Lake
-56
-58
-60
-62
-64
-66
-68
-70
δD (‰)
δD = 8δ18O + 10
δ = -0.37δ18O - 66.82
R² = 0.009
-10.5
-10
-9.5
-9
-8.5
-8
-7.5
-7
δ18O (‰)
2009
2010
Linear (Tait)
Linear (MWL)

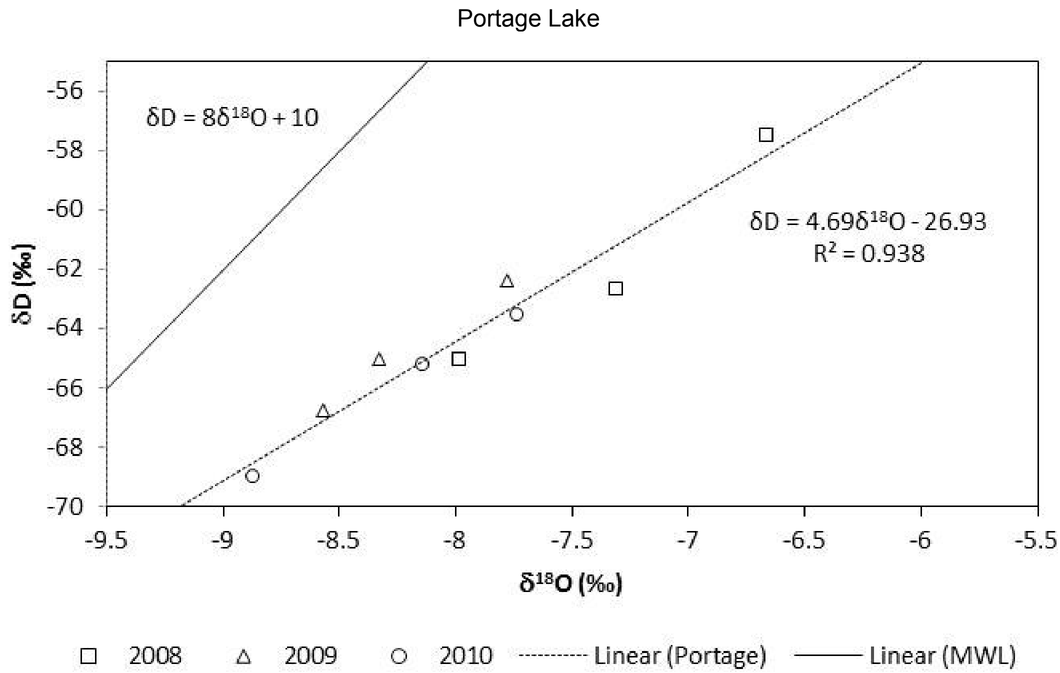

Trout Lake
-60
-61
-62
-63
-64
-65
-66
-67
-68
δD (‰)
δD = 8δ18O + 10
δD = 4.74δ18O - 26.01
R2 = 0.718
-9
-8.5
-8
-7.5
δ18O (‰)
2008
2009
2010
Linear (Trout)
Linear (MWL)

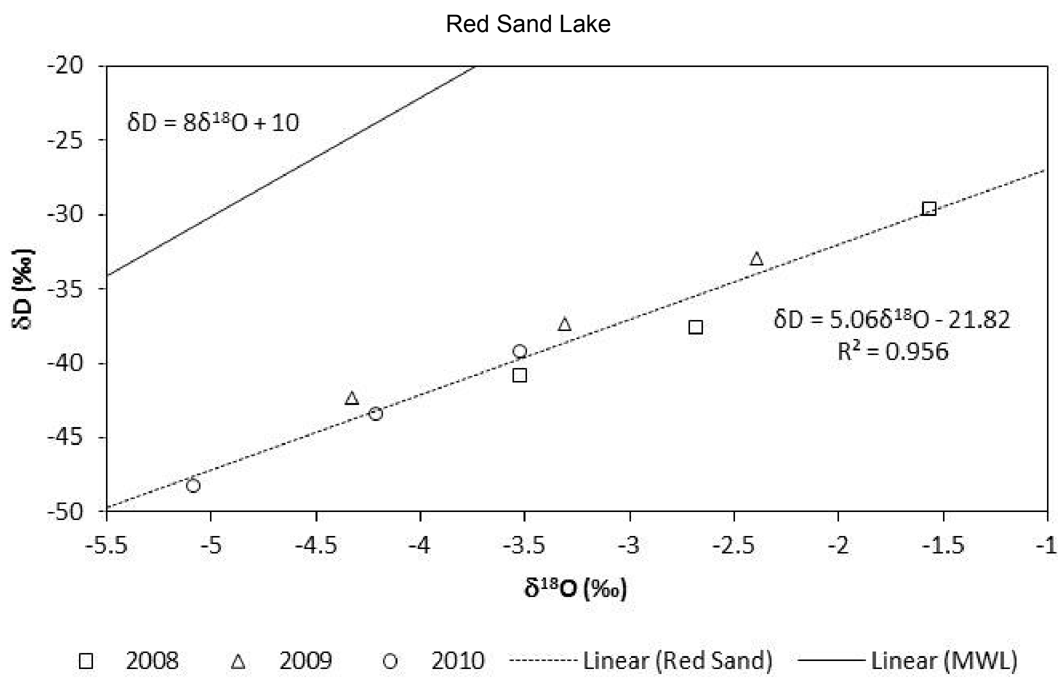

White Iron Lake
-30
-40
-50
-60
-70
-80
-90
δD (‰)
δD = 8δ18O + 10
δD = 8.43δ18O + 11.81
R2 = 0.932
-12.5
-11.5
-10.5
-9.5
-8.5
-7.5
-6.5
-5.5
δ18O (‰)
2008
2009
2010
Linear (White Iron)
Linear (MWL)

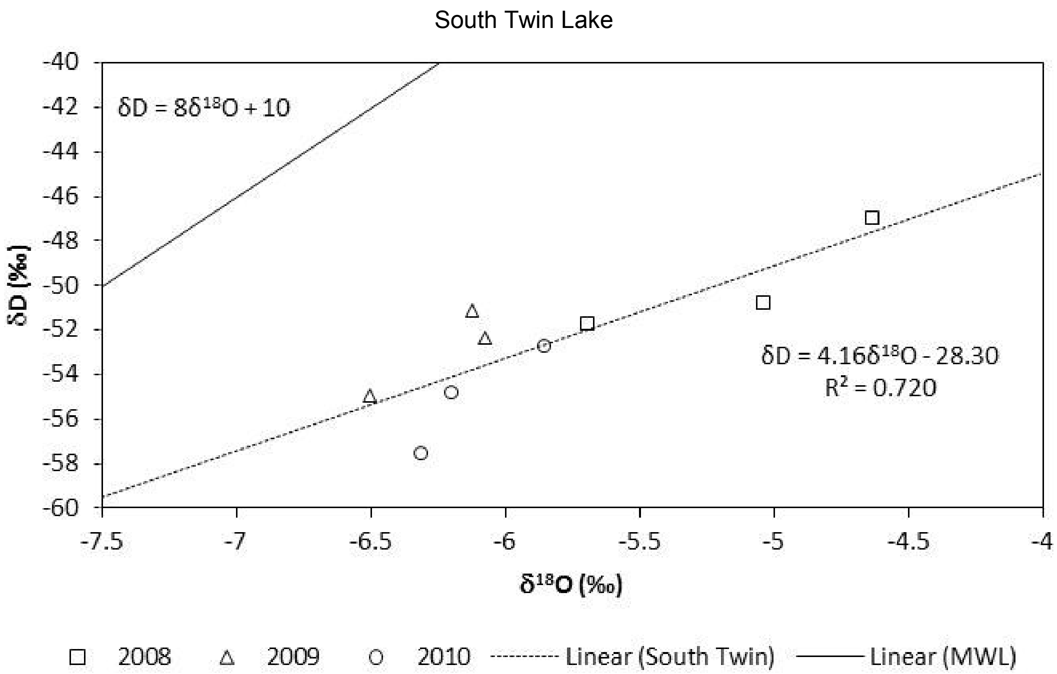
Glacial Drift Northern Forest

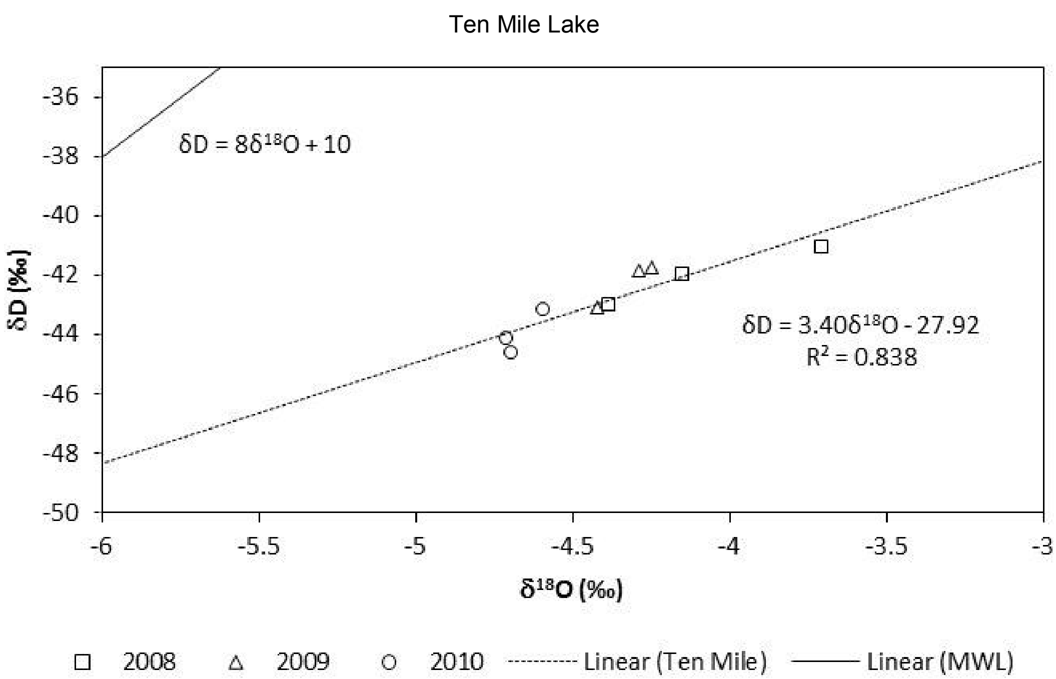




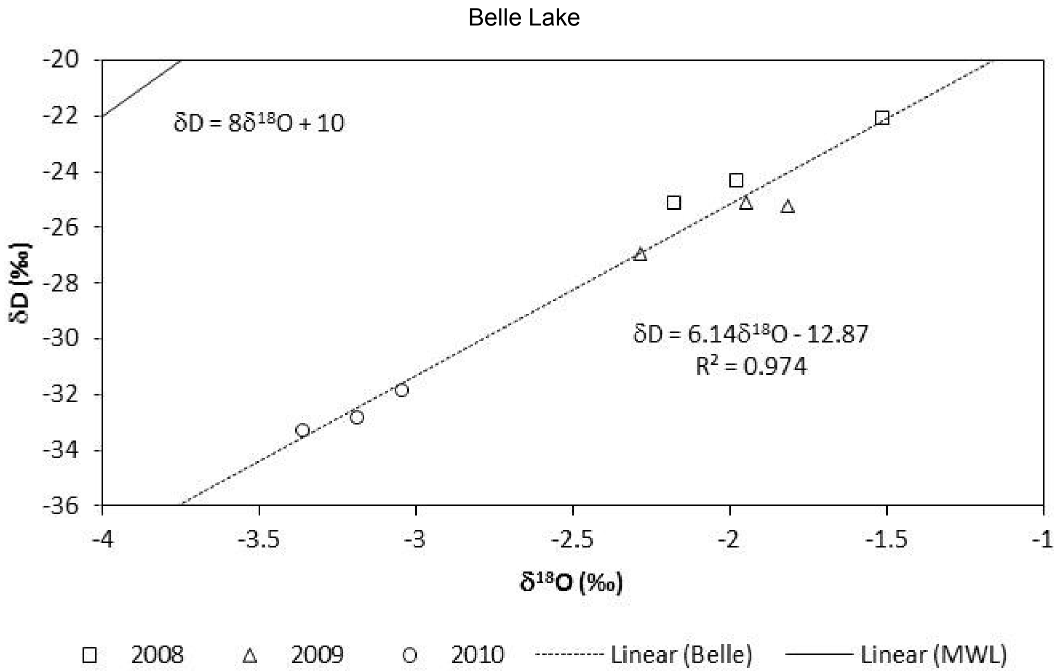

Portage Lake
δD = 8δ18O + 10
δD = 4.69δ18O - 26.93
R2 = 0.938
δD (‰)
δ18O (‰)
-56
-58
-60
-62
-64
-66
-68
-70
-9.5
-9
-8.5
-8
-7.5
-7
-6.5
-6
-5.5
2008
2009
2010
Linear (Portage)
Linear (MWL)

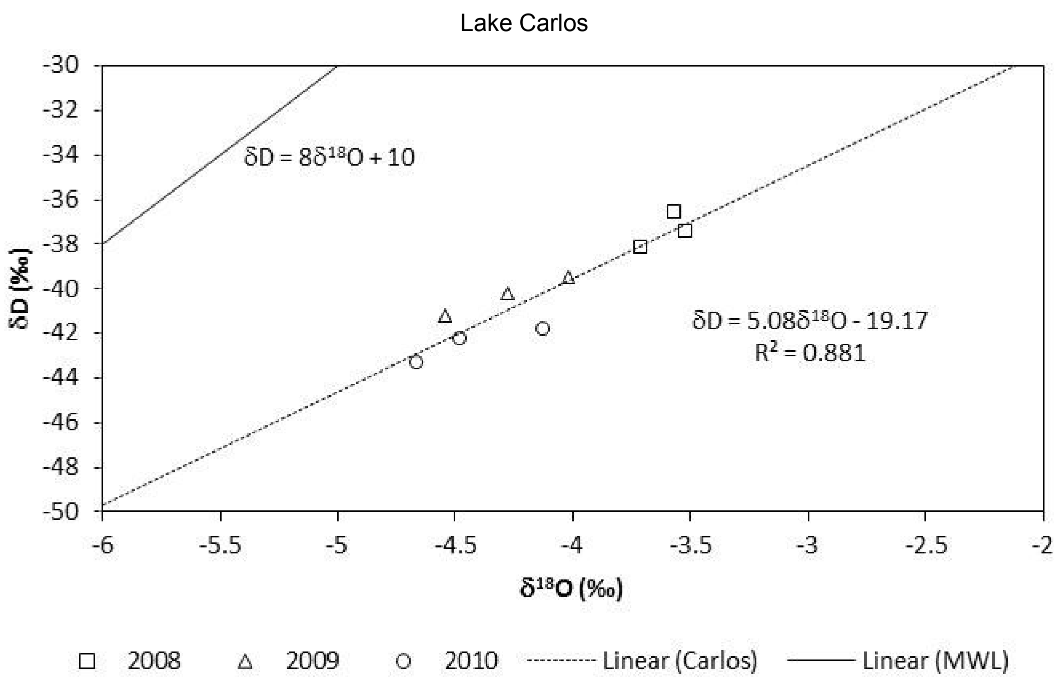

Red Sand Lake
δD = 8δ18O + 10
δD = 5.06δ18O - 21.82
R2 = 0.956
δD (‰)
δ18O (‰)
-20
-25
-30
-35
-40
-45
-50
-5.5
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
2008
2009
2010
Linear (Red Sand)
Linear (MWL)

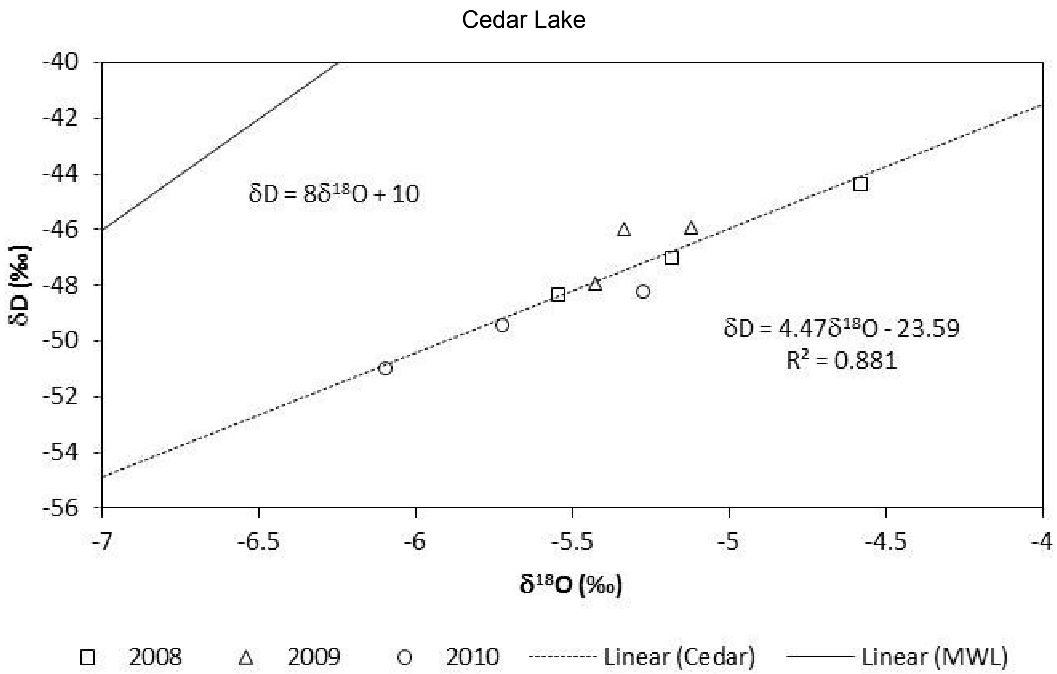

South Twin Lake
δD = 8δ18O + 10
δD = 4.16δ18O - 28.30
R2 = 0.720
δD (‰)
δ18O (‰)
-40
-42
-44
-46
-48
-50
-52
-54
-56
-58
-60
-7.5
-7
-6.5
-6
-5.5
-5
-4.5
-4
2008
2009
2010
Linear (South Twin)
Linear (MWL)


Ten Mile Lake
δD = 8δ18O + 10
δD = 3.40δ18O - 27.92
R2 = 0.838
δD (‰)
δ18O (‰)
-36
-38
-40
-42
-44
-46
-48
-50
-6
-5.5
-5
-4.5
-4
-3.5
-3
2008
2009
2010
Linear (Ten Mile)
Linear (MWL)

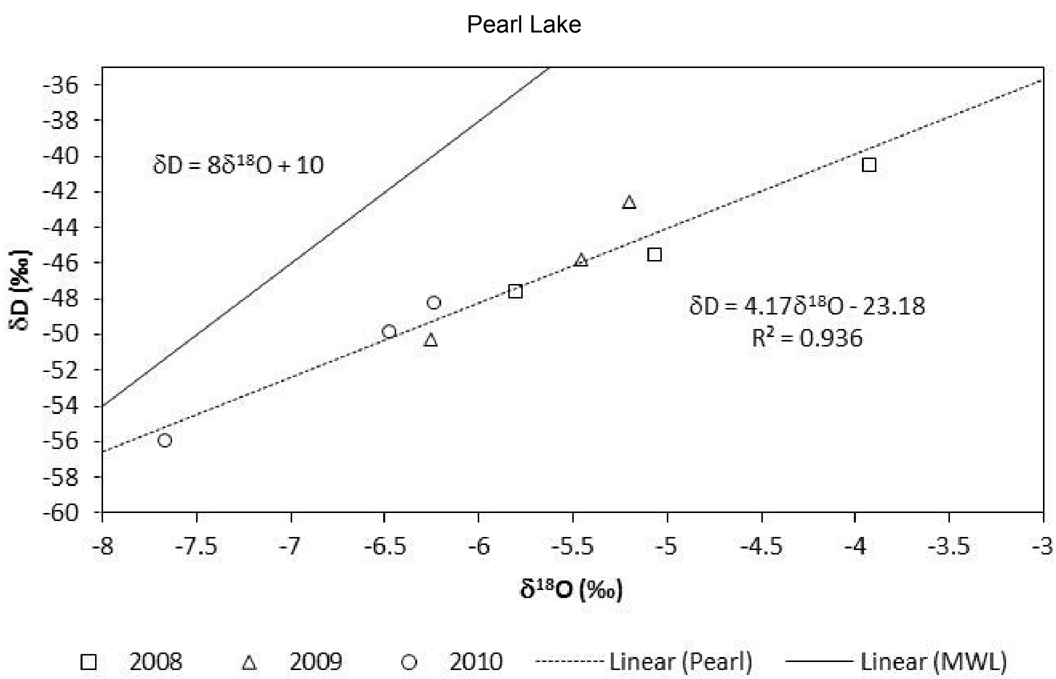
Transition Forest



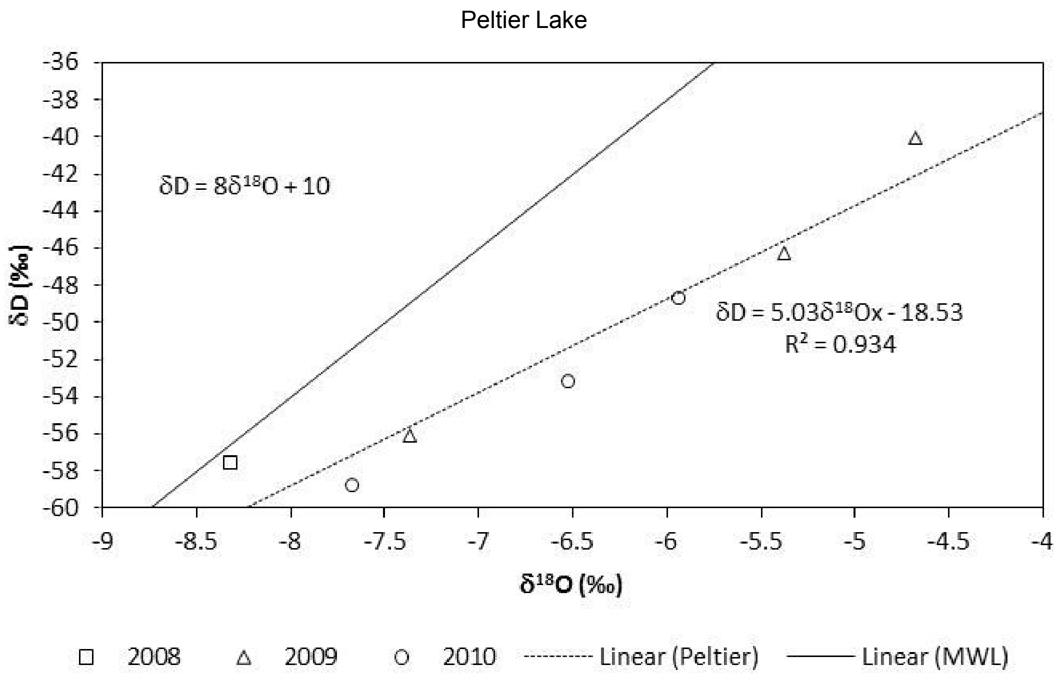


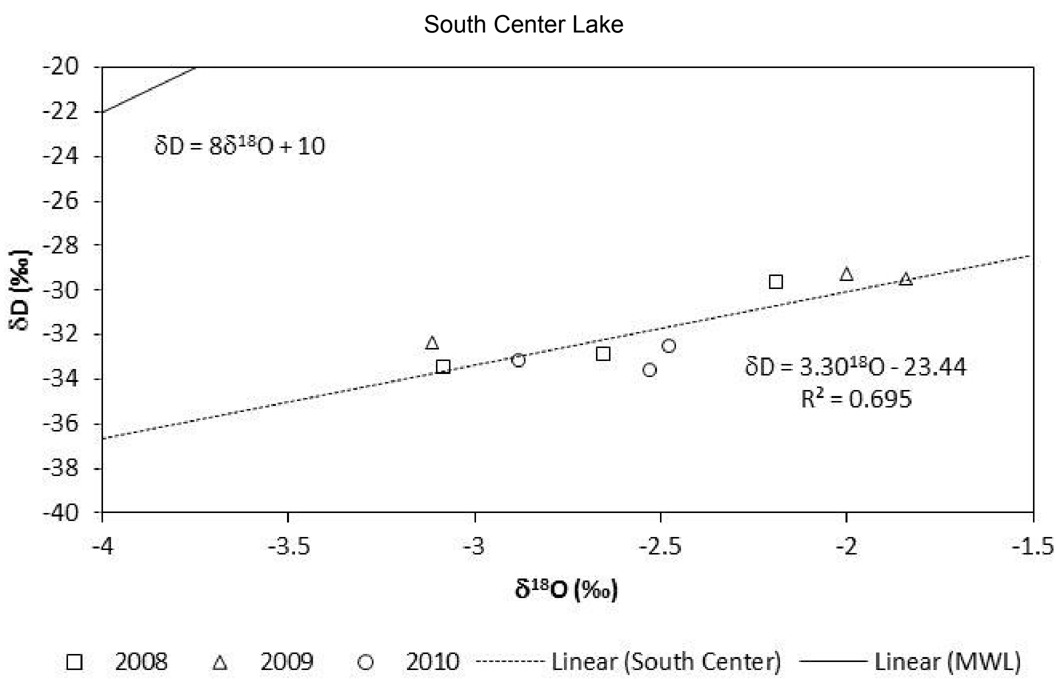


Cedar Lake
-40
-42
-44
-46
-48
-50
-52
-54
-56
δD (‰)
δD = 8δ18O + 10
δD = 4.47δ18O - 23.59
R² = 0.881
-7
-6.5
-6
-5.5
-5
-4.5
-4
δ18O (‰)
2008
2009
2010
Linear (Cedar)
Linear (MWL)

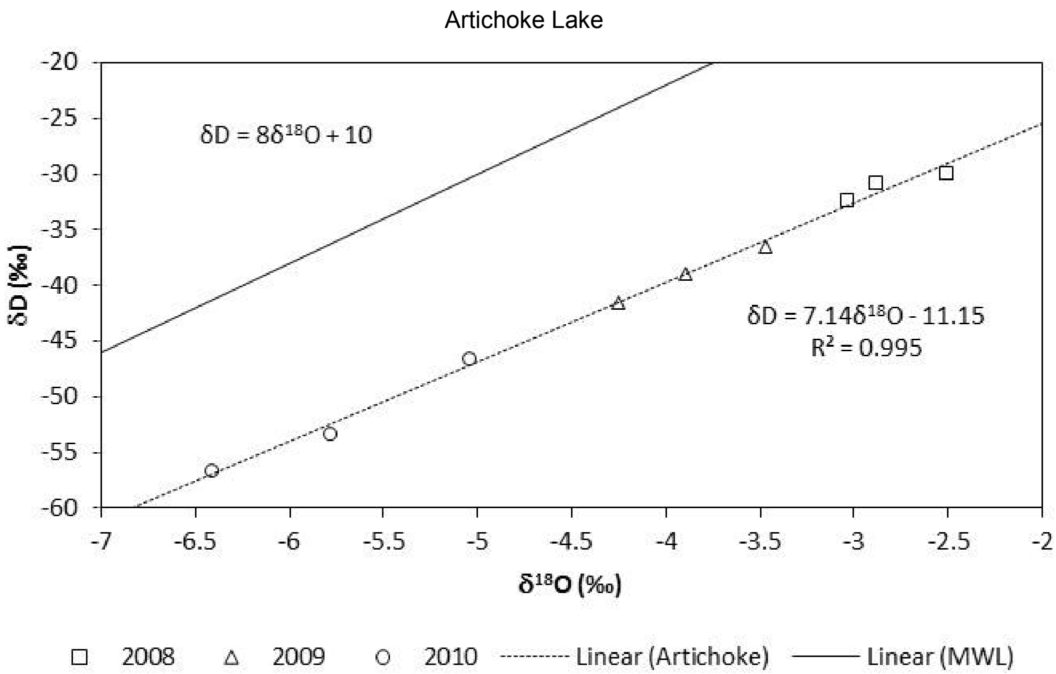


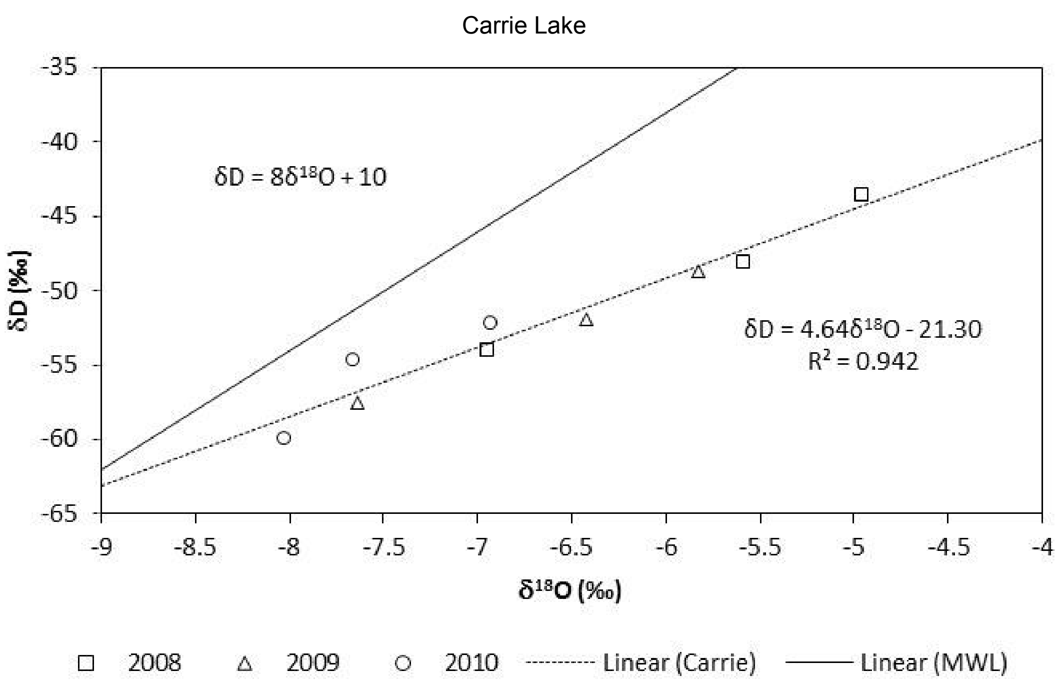
Pearl Lake
-36
-38
-40
-42
-44
-46
-48
-50
-52
-54
-56
-58
-60
δD (‰)
δD = 8δ18O + 10
δD = 4.17δ18O - 23.18
R² = 0.936
-8
-7.5
-7
-6.5
-6
-5.5
-5
-4.5
-4
-3.5
-3
δ18O (‰)
2008
2009
2010
Linear (Pearl)
Linear (MWL)

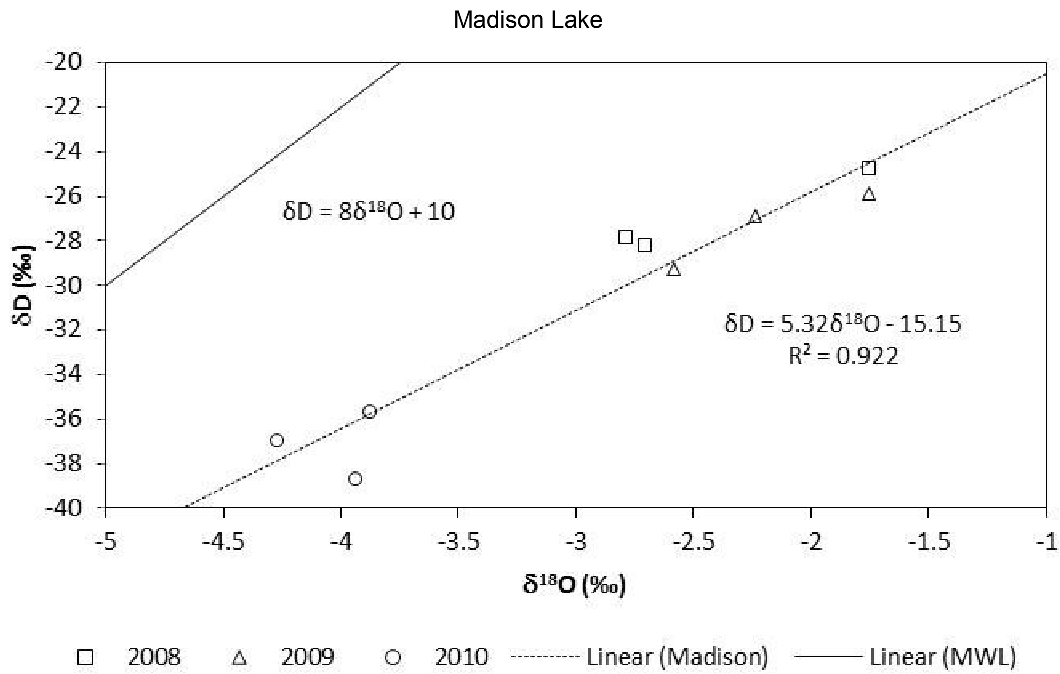

Peltier Lake
δD = 8δ18O + 10
δD = 5.03δ18Ox - 18.53
R2 = 0.934
δD (‰)
δ18O (‰)
2008
2009
2010
Linear (Peltier)
Linear (MWL)

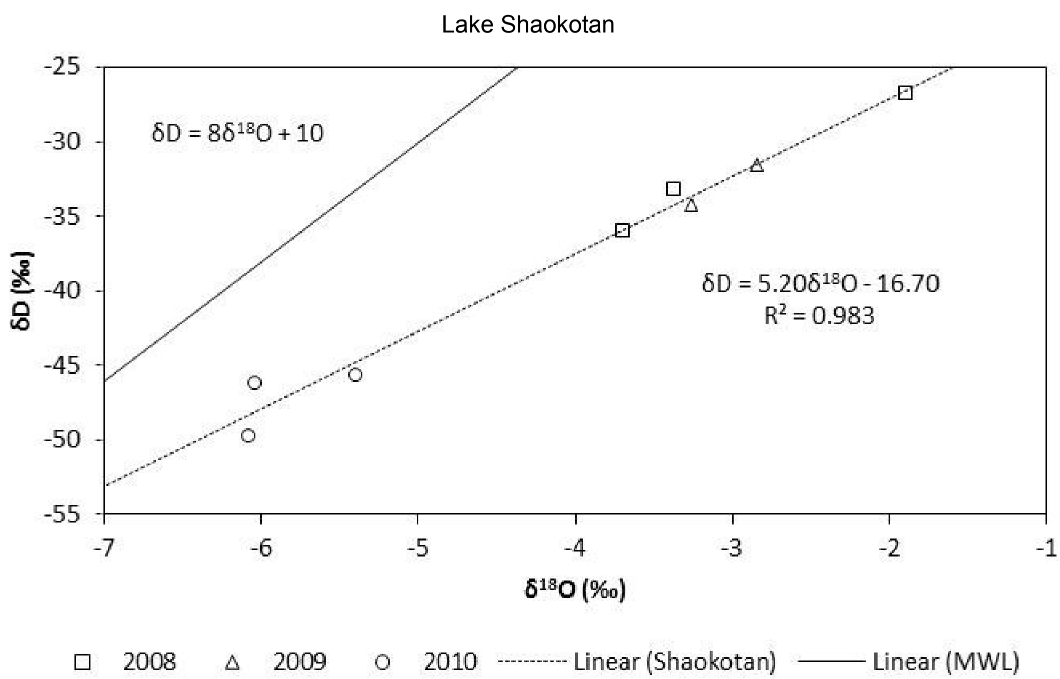

South Center Lake
δD = 8δ18O + 10
δD = 3.3018O - 23.44
R2 = 0.695
δD (‰)
δ18O (‰)
2008
2009
2010
Linear (South Center)
Linear (MWL)

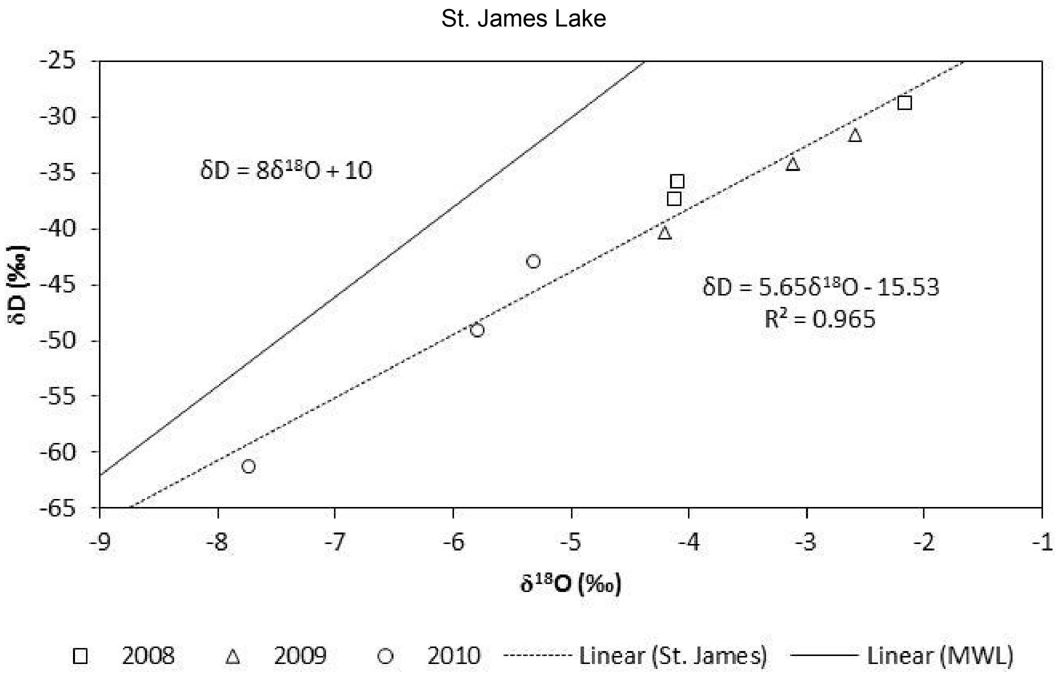
Prairie and Cornbelt

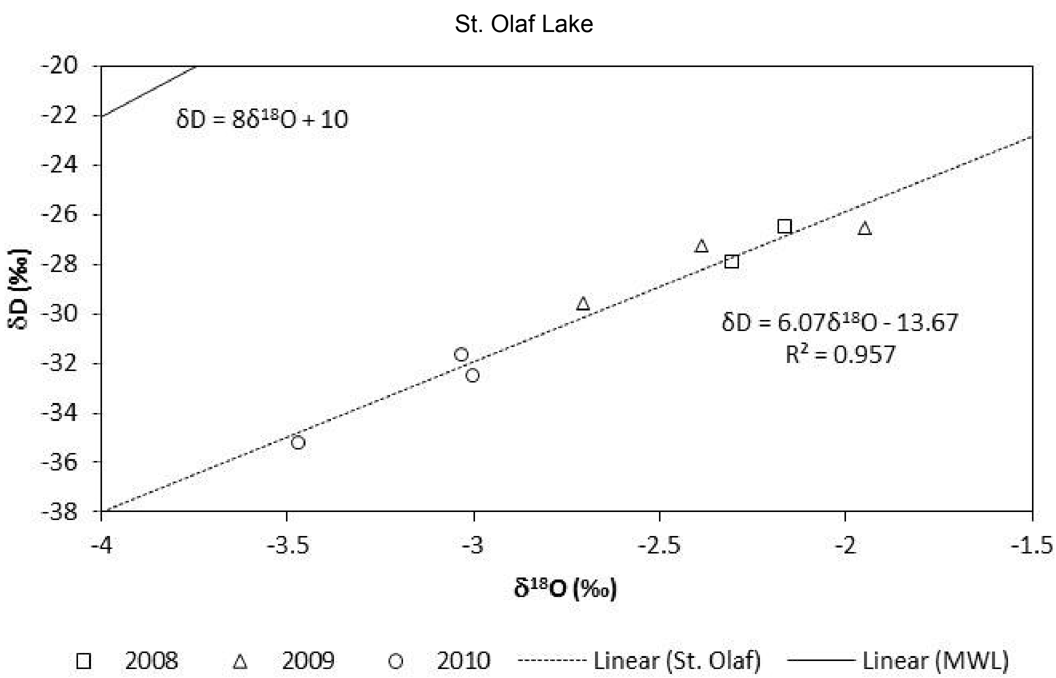





Madison Lake
δD = 8δ18O + 10
δD = 5.32δ18O - 15.15
R2 = 0.922
δD (‰)
δ18O (‰)
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
-5
-4.5
-4
-3.5
-3
-2.5
-2
-1.5
-1
2008
2009
2010
Linear (Madison)
Linear (MWL)


Lake Shaokotan
δD = 8δ18O + 10
δD = 5.20δ18O - 16.70
R2 = 0.983
δD (‰)
δ18O (‰)
-25
-30
-35
-40
-45
-50
-55
-7
-6
-5
-4
-3
-2
-1
2008
2009
2010
Linear (Shaokotan)
Linear (MWL)


St. James Lake
δD = 8δ18O + 10
δD = 5.65δ18O - 15.53
R2 = 0.965
δD (‰)
δ18O (‰)
-25
-30
-35
-40
-45
-50
-55
-60
-65
-9
-8
-7
-6
-5
-4
-3
-2
-1
2008
2009
2010
Linear (St. James)
Linear (MWL)


St. Olaf Lake
δD = 8δ18O + 10
δD = 6.07δ18O - 13.67
R2 = 0.957
δD (‰)
δ18O (‰)
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-4
-3.5
-3
-2.5
-2
-1.5
2008
2009
2010
Linear (St. Olaf)
Linear (MWL)

Appendix F

Water year departure from normal precipitation (cm).

Lake ID #	Lake Name	2008	2009	2010	Range
06-0002-00	Artichoke	8.9	5.2	33.5	28.4
69-0254-00	Bearhead	6.6	-5.1	-4.2	11.7
47-0049-01	Belle	-5.6	-6.0	31.9	38.0
21-0057-00	Carlos	-0.6	-2.4	26.3	28.7
34-0032-00	Carrie	-3.8	-2.0	36.1	39.9
49-0140-00	Cedar	-7.0	-4.4	20.8	27.8
69-0615-00	Echo	5.2	3.5	7.3	3.8
69-0810-00	Elephant	4.2	4.7	12.0	7.8
15-0010-00	Elk	3.1	8.4	21.7	18.6
01-0142-01	Hill (North Basin)	-7.9	-10.7	9.0	19.7
07-0044-00	Madison	-7.1	-14.6	41.0	55.6
73-0037-00	Pearl	-2.0	3.5	31.2	33.2
02-0004-00	Peltier	-6.4	-22.0	11.9	33.9
29-0250-00	Portage	-0.2	2.5	18.4	18.6
18-0386-00	Red Sand	-3.4	-0.8	14.4	17.8
41-0089-00	Shaokotan	-7.8	-2.3	51.2	59.0
13-0027-00	South Center	-5.4	-29.4	18.3	47.7
44-0014-00	South Twin	3.5	14.7	20.9	17.5
83-0043-00	St. James	-2.8	-12.0	44.8	56.8
81-0003-00	St. Olaf	-9.6	-16.5	34.0	50.5
16-0384-00	Tait	15.4	-2.8	-10.6	26.0
11-0413-00	Ten Mile	-9.5	-2.2	12.0	21.5
16-0049-00	Trout	30.4	-2.2	-7.7	38.0
69-0004-00	White Iron	17.8	1.5	-9.9	27.7