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 pollutants and associated solutes cycle over time. Lake hydraulic residence time is dependent on several factors including: volume, watershed size, location within a watershed and climatic variability. The use of the stable isotopes of hydrogen (Deuterium expressed as δD) and oxygen ($\delta^{18}O$) can provide some hydrologic insight and management guidance for the development of a Total Maximum Daily Load (TMDL). 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, further explaining the relationship between hydraulic residence time and pollutant loading. 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). The deviation in amplitudes of the fractionation of lake water to water vapor was modeled to predict hydraulic residence time for each lake. Twenty-four lakes throughout Minnesota were sampled over a three year period and residence times were calculated. Each of the twenty-four lakes is part of the "Sustaining Lakes in a Changing Environment (SLICE)" project, a study led by the Minnesota Department of Natural Resources.

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 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 snap shot of what lake water quality is like at the time of sampling, however, when baseline water quality data is supplemented with varying modeling techniques (watershed, bathymetric, and lake cycling) the true condition of a lake can be better understood.

Some lakes are more or less resilient to water quality impairments because of their morphology and hydraulic residence time. Since lake basin morphology is relatively constant, hydraulic residence time should be explored 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. Surface water bodies present a challenge in determining how water cycles through them. Wetlands, streams, and lakes obtain a water budget from various sources including precipitation, surface water and/or groundwater (Magner and Alexander, 2008). Depending on the location of the water body, evaporation rates can drastically influence water budgets as well. 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 composition can be measured. This causes individual water bodies and end-member source waters to have their own isotopic signature (International Atomic Energy Agency, 2009; Craig 1961b). The use of stable isotopes has emerged as a vital tool for defining water sources 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 oxygen ($\delta^{18}O$), and hydrogen (δD) in a given lake is dependent on a variety of physical processes that is 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 for waters which have not undergone excessive evaporation (Craig, 1961a). Water bodies often 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 waters that contribute to the overall budget of a lake. Lake residence time will be driven by lake morphology, evaporation rates, and flow into and out of a lake. By identifying the seasonal isotopic signature and its 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.

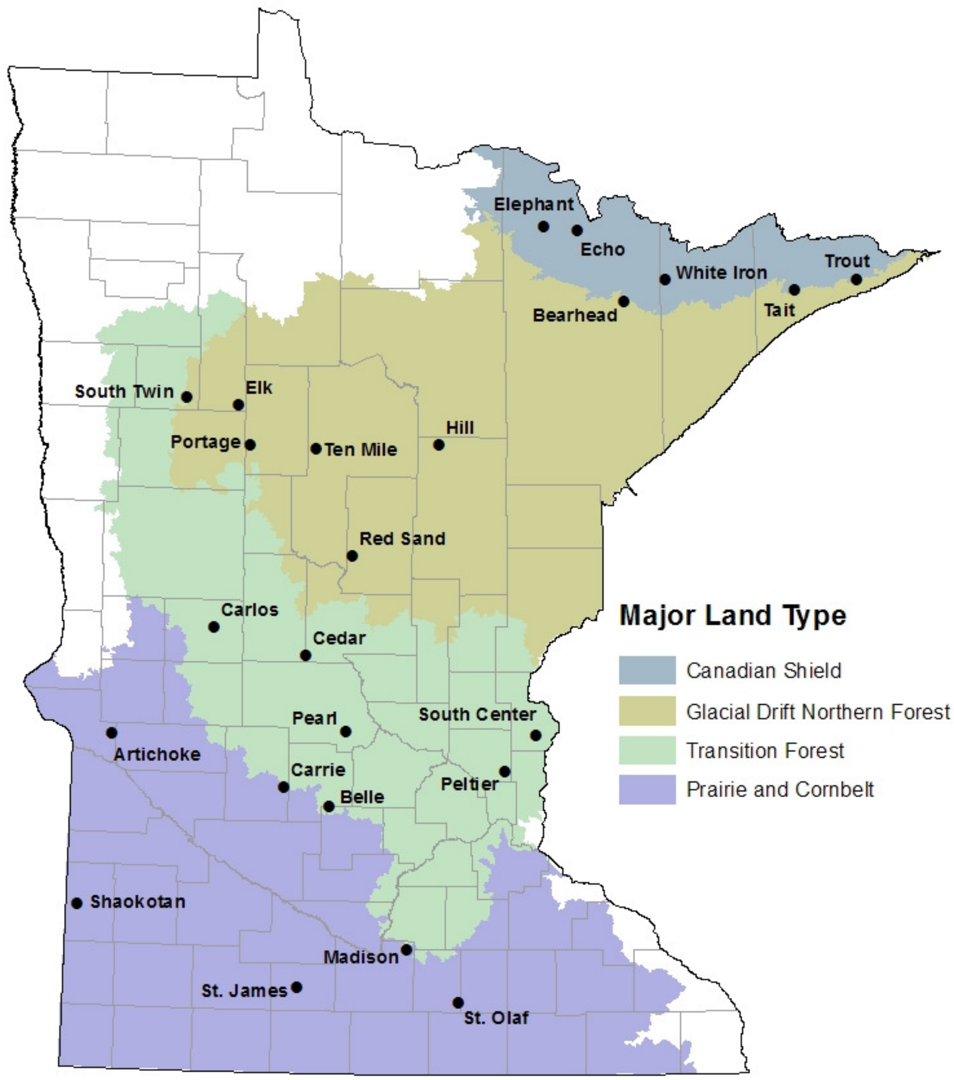
Freshwater lakes present the challenge of having many different water sources contributing to their annual water budget. Quantifying hydraulic residence time in lakes via stable isotopes will offer new insight that may explain many other lake water quality metrics. It may also be used to further explain 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). This type of 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

Stable isotope samples, δD and $\delta^{18}O$, were collected 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 address climate change on Minnesota's lakes (Valley, 2009). The SLICE study will provide many 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 and explain lake hydrology. 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. These lakes have very different water budgets and reflect a range of lakes systems found throughout the upper Midwest.

Valuable insight should be gained into the contributions of source waters and the impacts of pollutants in MN Lakes.

Figure 1. Sentinel Lakes



Over the course of a three year period (2008-2010), each of the 24 lakes were visited during the months of May, July, and October in order to collect stable isotope samples. Sampling periods were timed to correspond closely with spring and fall turnover and during mid-summer when evaporation is highest. By sampling at these key time periods, seasonal variations in lake isotopic compositions for each lake were captured. To ensure that a representative sample was taken, a composite of the top two meters of lake water were taken over the deepest part of the lake basin. An integrated water quality sampler was used for sample collection, which is a polyvinyl chloride tube 2 meters in length with an inside diameter of 3.2 centimeters. This eliminates large variations from water sources and precipitation events entering the lake within a short duration of sampling. Surface water sampling protocols were followed from the MPCA's Standard Operating Procedure for Lake Water Quality Sampling (Anderson and Lindon, 2009). Samples collected were placed in 125ml plastic water quality bottles, sealed and sent to the University of Minnesota Biometeorology Lab in the Department of Soil, Water, and Climate 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 $\delta^{18}O$.

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 in 1989 notes).

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

Where T is the air temperature in degrees Celsius.

Air temperature data used in Equation 1 was derived from the Minnesota State Climatology Working Group web page run by the State Climatology Office, Minnesota Department of Natural Resources. 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 concentrations was modeled with observed lake water isotopic concentrations 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 reservoir 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, and *B* the output amplitude.

Results

Regional Trends

Throughout the state of Minnesota regional trends in $\delta^{18}O$ and δD were similar in all four MLRUs studied (Figures 2 and 3). A general transition to heavier isotopic concentrations exists 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 to heavier isotopic concentrations is evident along the Glacial Drift Northern Forest MLUR. Here $\delta^{18}O$ and δD values are slightly heavier than Canadian Shield values. The heaviest isotopic compositions were found in the Transition Forest and Prairie and Corn Belt MLURs. Heavier $\delta^{18}O$ and δD values are a result of higher annual evaporation rates and higher annual mean temperatures.

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 isotopic composition. As a result, Canadian Shield lakes plotted lowest on the evaporative line representing a lighter isotopic composition than the other three MLUR's studied.

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

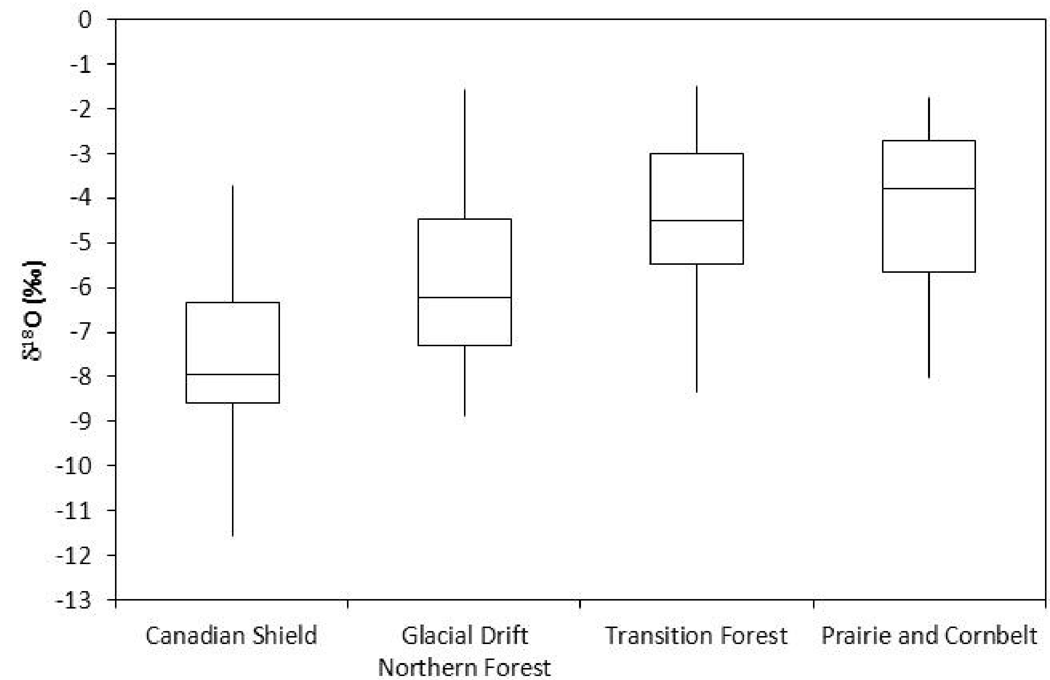


Figure 3. δD values for lakes within the MLUR's.

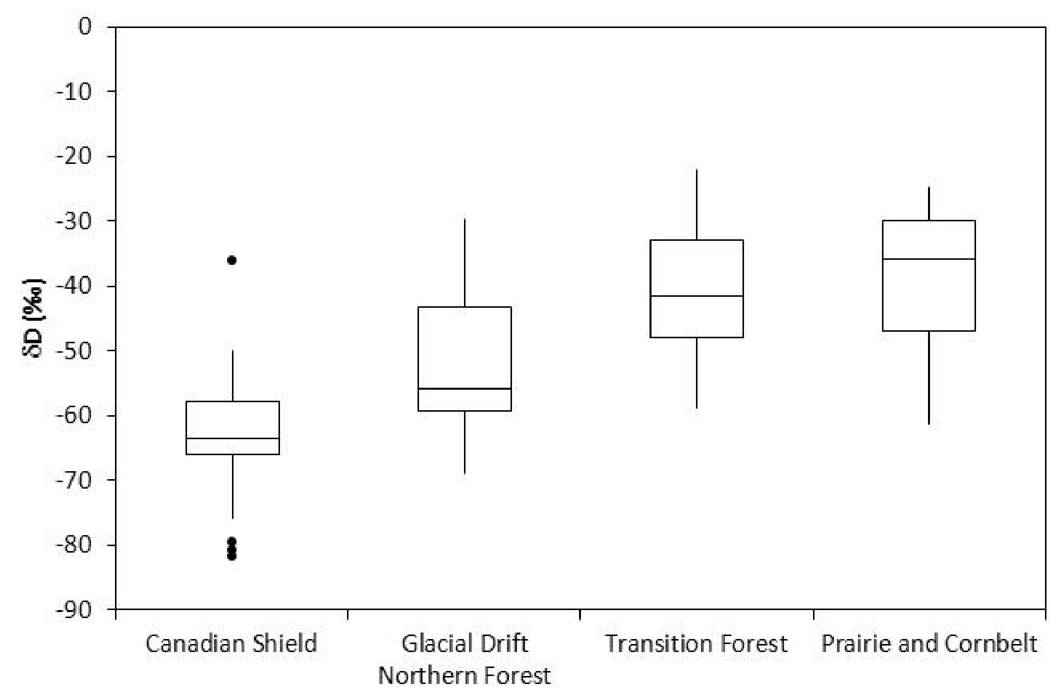
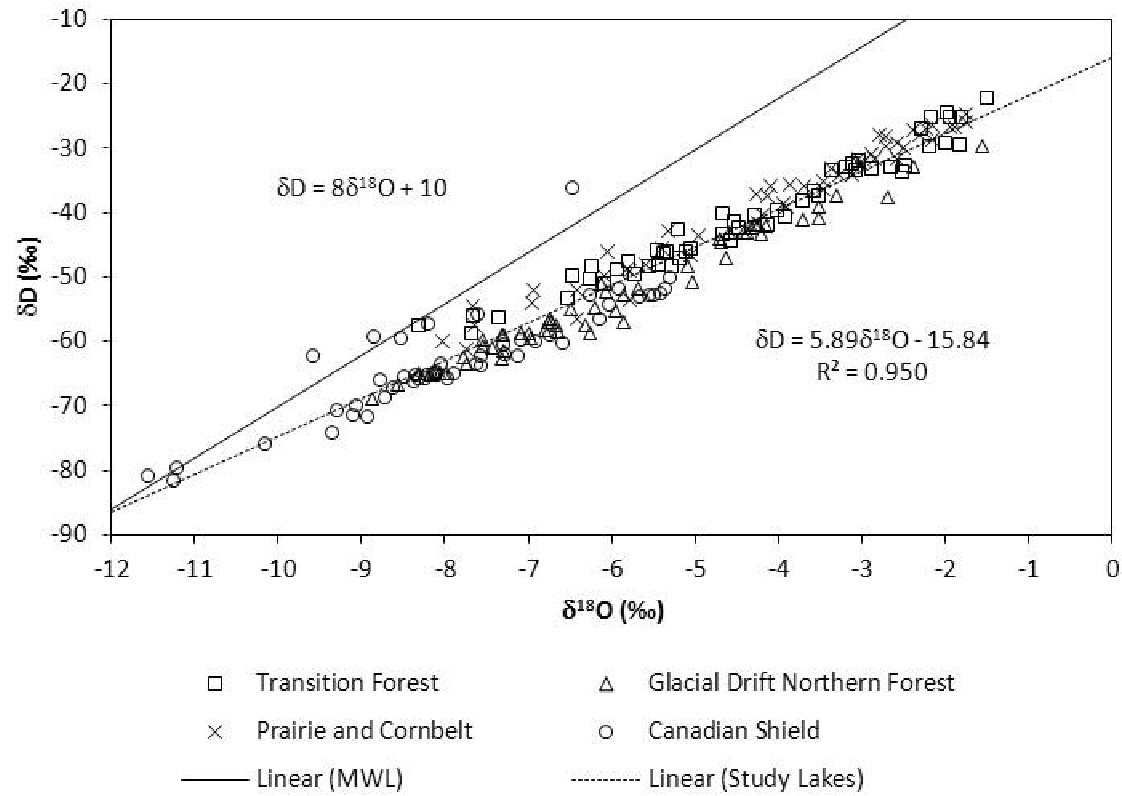


Figure 4. MLUR's $\delta^{18}O$ vs. δD compared to the MWL.



Canadian Shield

Stable isotope $\delta^{18}O$ concentrations in the Canadian Shield are lighter than in the other three major land use regions (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 relatively strong 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 are well connected to their watersheds through many tributaries. As a result residence times were shorter because direct flow 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 this lake has a large watershed and is an impoundment on the Kawishiwi River (Table 1). Large volumes of water move through White Iron resulting is a very short residence time.

Annual climate variation also has an effect on $\delta^{18}O$ amplitudes and residence times. 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.

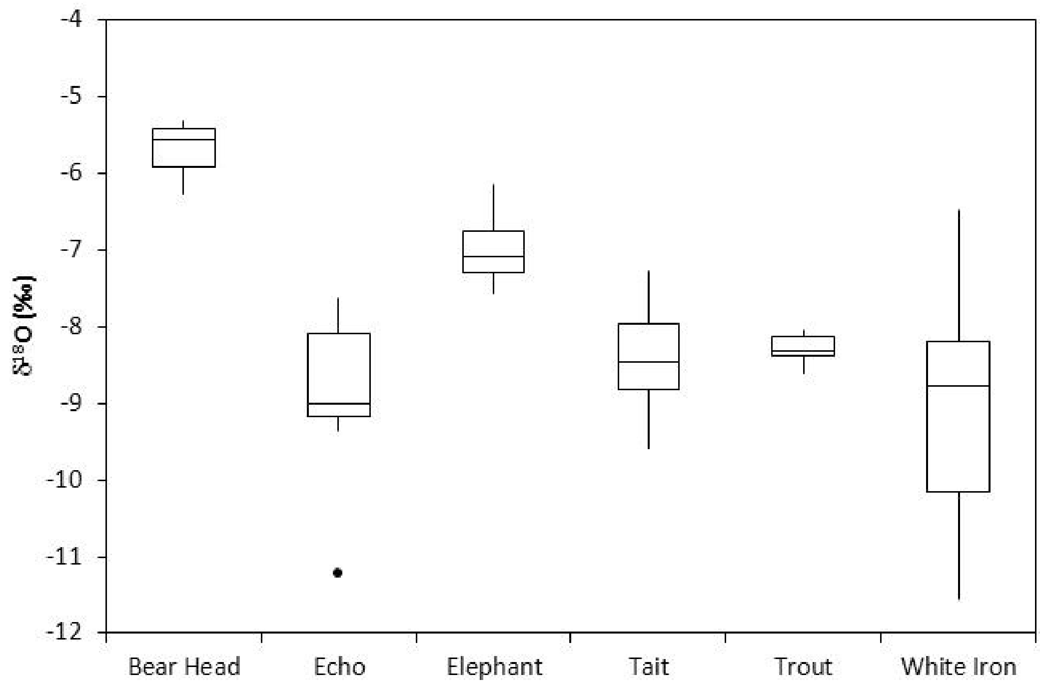


Figure 6. Canadian Shield $\delta^{18}O$ vs. δD compared to the MWL.

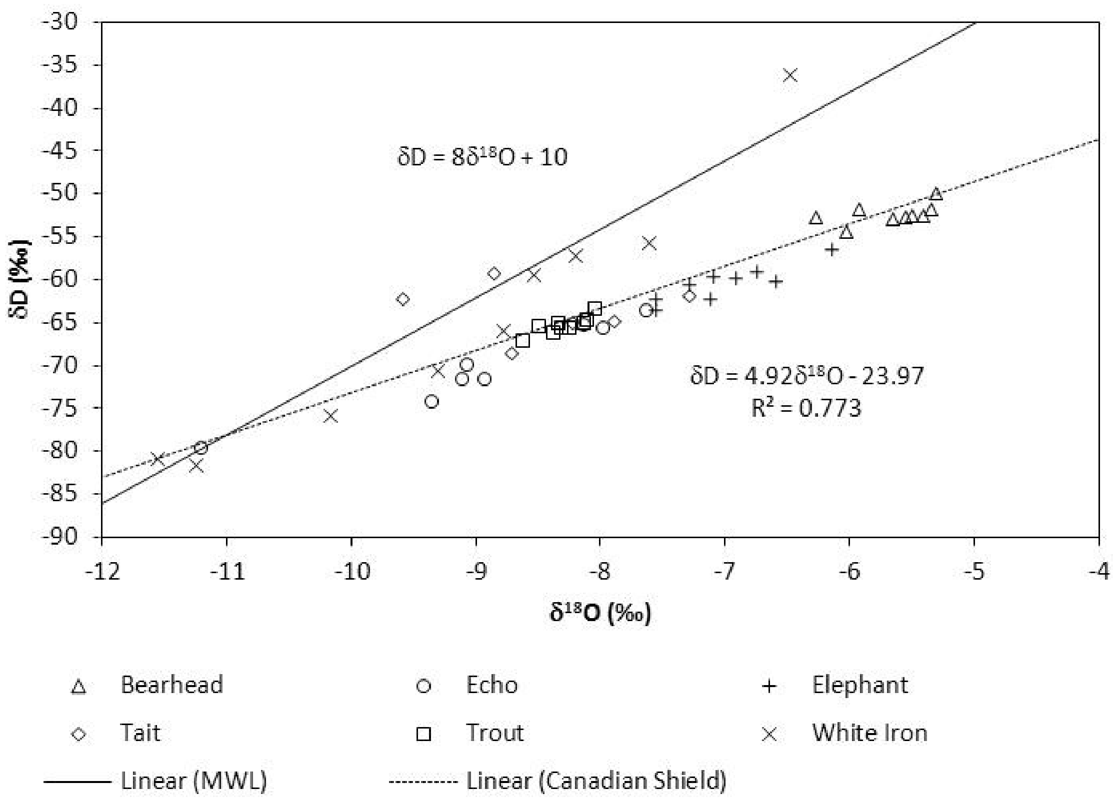


Table 1. Canadian Shield lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

Lake Name	Min. 2008	Max. 2008	Min. 2009	Max. 2009	Min. 2010	Max. 2010	Range (Yr)	Residence Time (Yr)
Bearhead	2.5	2.6	3.9	3.8	17.7	17.3	15.2	2.5-17.7
Echo	0.7	0.7	**2.8***	**2.7***	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

*** Values omitted because of missing data.**

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. Differences in residence time calculations are explained by lake basin 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. 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. 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 a wetter year than 2010, resulting in more frequent flushing of the lake water. The 2009 spring sampling event was not collected, therefore the maximum isotopic range 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 then 2010's (Table. 1).

Elephant Lake

Elephant Lake's $\delta^{18}O$ values range from -7.6 to -6.1 per mil. 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 lakes 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. 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 77 ft. and a mean depth of 35 ft. 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. 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. This reduction in source waters, snow melt, and precipitation decreased variation in $\delta^{18}O$ amplitudes and increased residence time in Trout Lake.

White Iron

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 592,000 acres (931 square miles). White Iron Lake's $\delta^{18}O$ values ranged from -6.5 to -11.6 per mil. 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 the White Iron Lake system.

Glacial Drift Northern Forest

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

Many lakes in this MLUR have important groundwater contributions because of glacial depositional sediment. Elk and Ten Mile lakes are deep and known to have high groundwater contributions. As a result, these two lakes had the highest calculated residence times (Table 2). Portage and Red Sand Lakes have similar morphology and watershed characteristics but have the heaviest and lightest isotopic composition of all Glacial Drift Northern Forest Lakes. This suggests that source waters for the two lakes are different.

Red Sand Lake is much further south than Portage Lake and may receive heavier isotopic precipitation from storms originating in the Gulf of Mexico. It is likely that Portage Lake receives lighter isotopic precipitation from arctic storms and receives higher snowmelt contributions in the spring. Hill Lake has two distinct basins. Isotope samples were collected in the deeper northern basin resulting in higher residence times as compared to what would likely be observed in the shallow basin of Hill Lake.

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

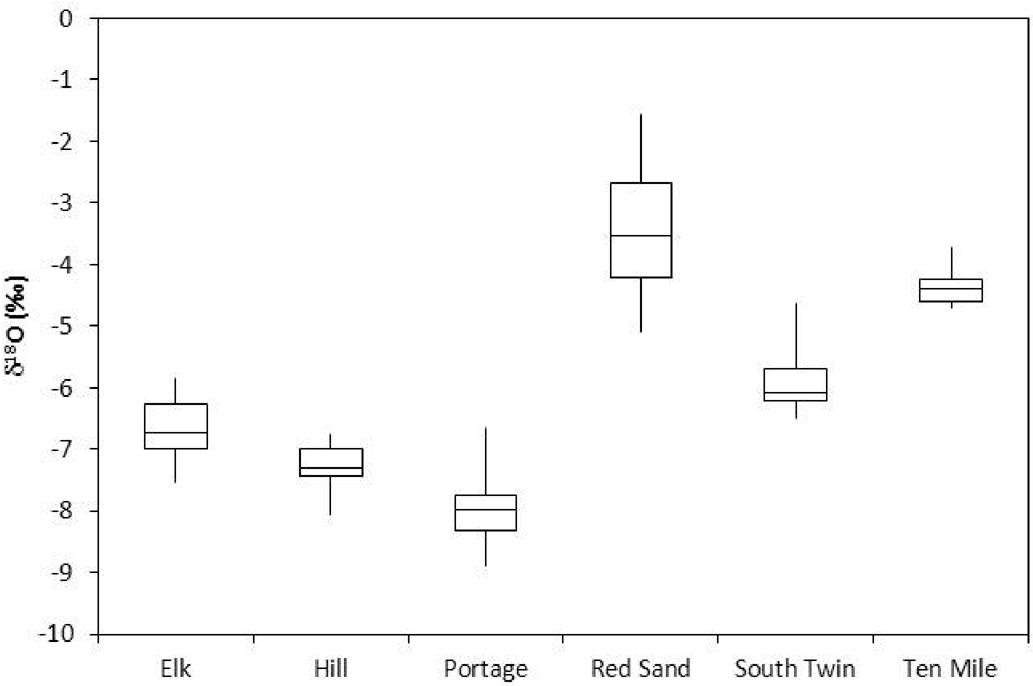


Figure 8. Glacial Drift Northern Forest δ^{18}O vs. δD compared to the MWL.

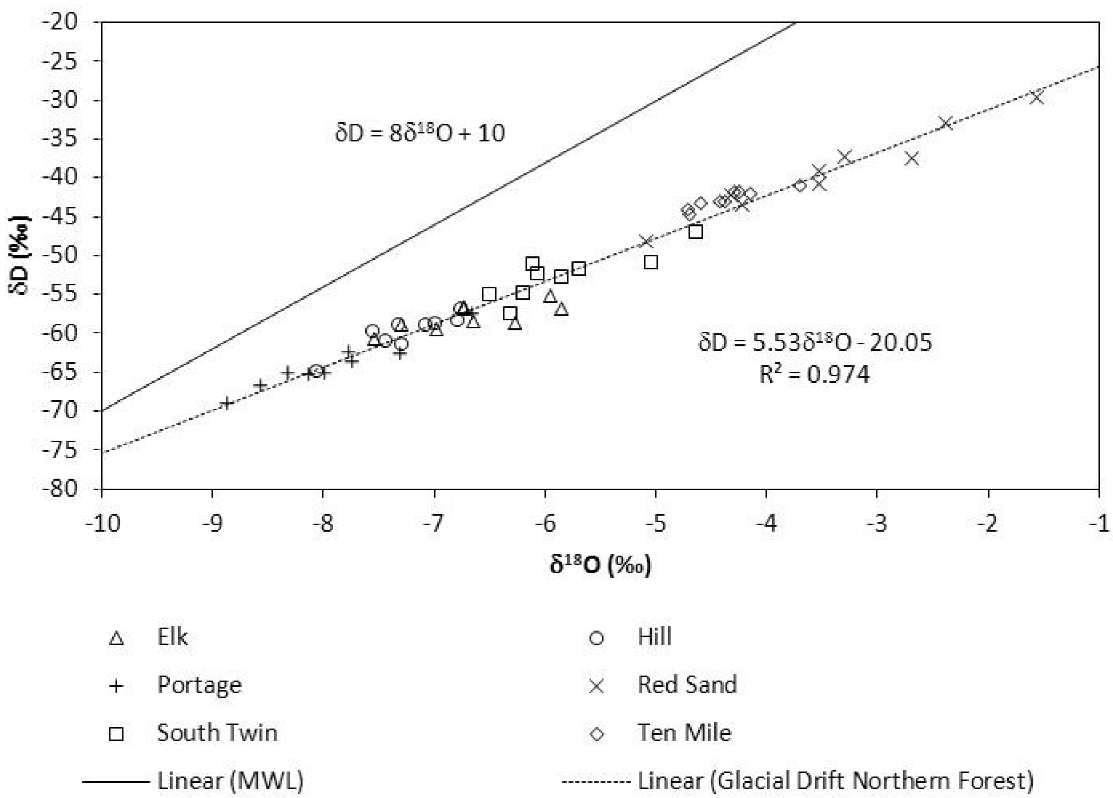


Table 2. Glacial Drift Northern Forest lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

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

*** Values omitted because of missing data.**

Elk Lake

Elk Lake had variable $\delta^{18}O$ and δD concentrations resulting from a large watershed, depth, and many different source water inputs. Large contributions of groundwater flow along with many 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. 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 is likely related to reduced outflow to Lake Itasca which forms the headwaters of the Mississippi River.

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. Hill Lake's $\delta^{18}O$ values range from -6.8 to -8.1 per mil. 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. Residence time calculations ranged from 2.0-3.4 years (Table 2). Short residence times are expected in a shallow lake with a 17 ft. maximum depth and mean depth of 7.5 ft. Source water inputs from the watershed, which is primarily forested, are consistent and supported by similar annual $\delta^{18}O$ amplitudes. Slight shifts in isotope concentrations occurred along the evaporative line which can be attributed to seasonal variability in precipitation and evaporation. Portage Lake's isotopic concentration shifts from light water in the spring to increasingly heavier water 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. 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 change.

South Twin Lake

South Twin Lake's $\delta^{18}O$ values ranged from -4.6 to -6.5 per mil. and residence time calculations ranged from 2.5-6.4 years (Table 2). Annual precipitation and evaporation fluctuations affect $\delta^{18}O$ amplitudes and how they plot on the evaporative line. Higher evaporation rates and limited source water contributions caused isotope concentrations to 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 region.

Ten Mile Lake

Ten Mile Lake's $\delta^{18}O$ values ranged from -3.7 to -4.7 per mil. and residence time calculations ranged from 3.8-22.9 years (Table 2). Residence times in Ten Mile Lake show the highest variability of all lakes in the Glacial Drift Northern Forest region. The lake is very complex with a maximum depth of 208 ft. and a mean depth of 53 ft. Groundwater is also known to make up a large portion of the lakes annual water budget. As precipitation values increased form 2008-2010, $\delta^{18}O$ amplitudes decreased and residence times increased. This suggests that wetter years are influenced by lighter isotopic snow melt and arctic weather systems may have a large influence on annual water budgets

Transition Forest

A wide range of lake types were sampled in the Transition Forest MLUR. Measured $\delta^{18}O$ compositions for each lake in the region are shown in Figure 9. The isotopic composition of lakes sampled in this region show a strong correlation to the evaporative line, $R^2 = 0.961$ (Figure 10). In general, a shift towards lighter isotopic concentrations was observed from 2008 to 2010. Lakes in the western portion of the Transition Forest region received an annual surplus of 8-12 in. of precipitation in 2010. Lakes without an outlet, such as Belle, showed a shift to a lighter isotopic composition that was more pronounced. This may result in an over estimate of residence time since lake water is being displaced and lake levels have not stabilized. 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 and residence time increased (Table 3). South Center Lake has a relatively short residence time for a deep lake due to complex hydrology. During drought years water levels can drop relatively fast. In addition, a groundwater sink in the lake bed increases annual lake water loss. Pearl and Peltier Lakes may receive large watershed contributions during wet periods but 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.

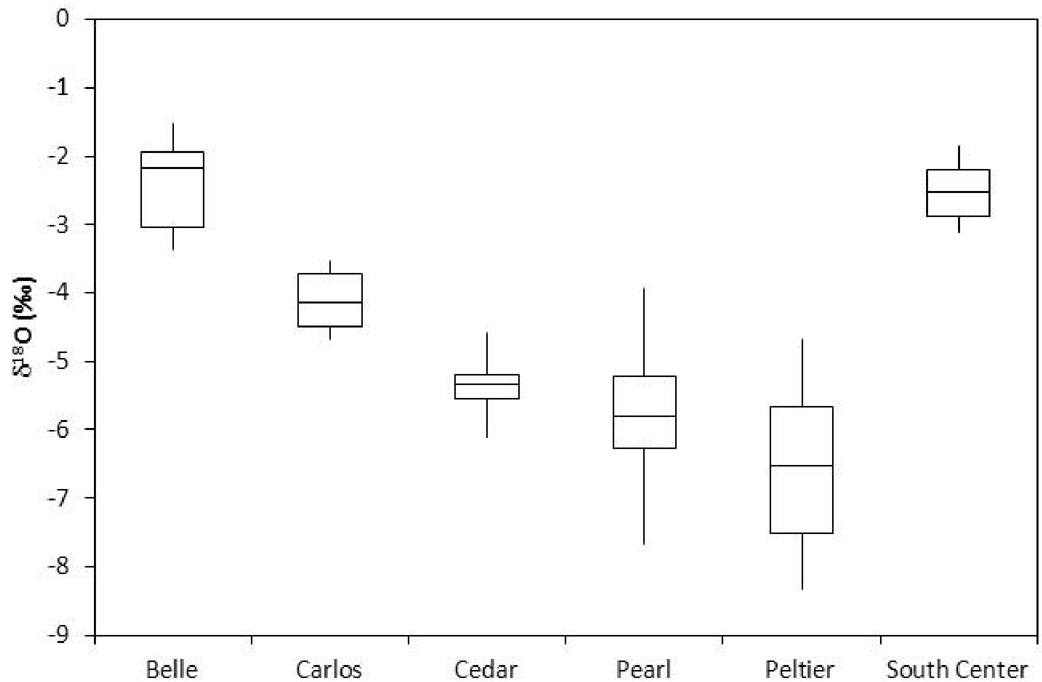


Figure 10. Transition Forest $\delta^{18}O$ vs. δD compared to the MWL.

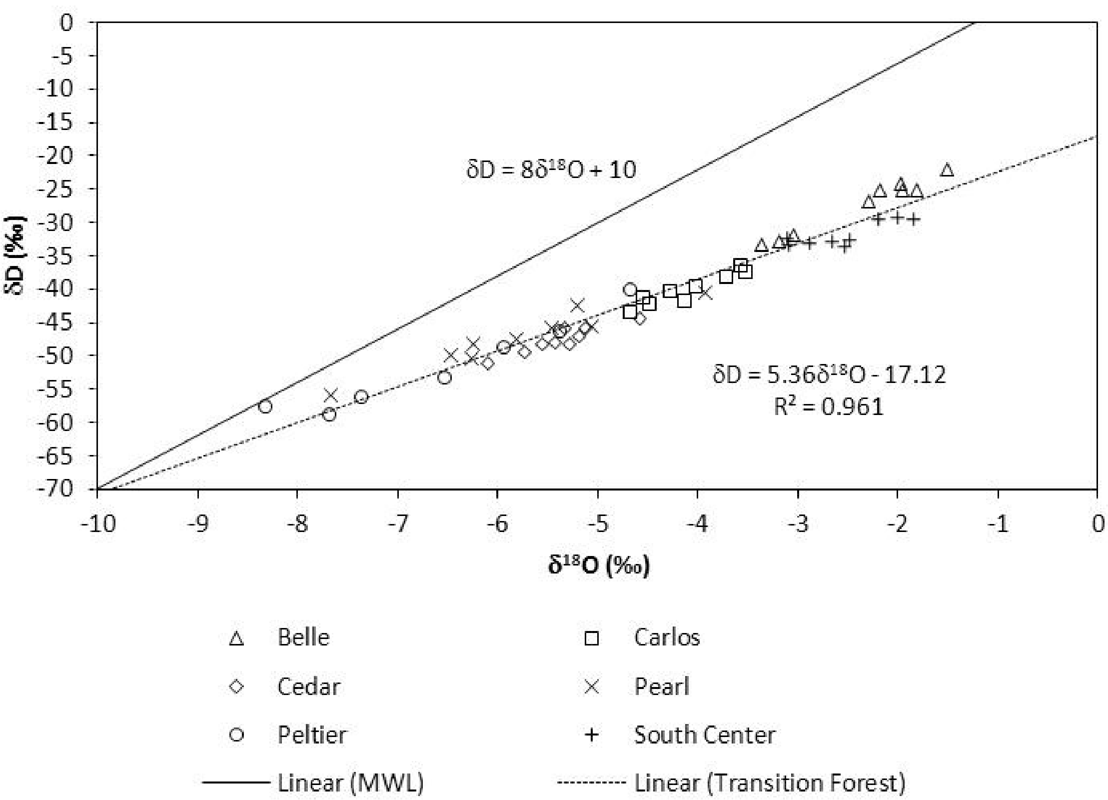


Table 3. Transition Forest lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

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

*** Values omitted because of missing data.**

Belle Lake

Belle Lake's $\delta^{18}O$ values ranged from -3.4 to -1.5 per mil. and residence time calculations ranged from 3.9-9.0 years (Table 3). Isotopic $\delta^{18}O$ values parallel the MWL which, suggest that Belle Lake's water budget consists of primarily unaltered 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. 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 160 ft. and a mean depth of 45.7ft. 2008 residence time calculations were the greatest, 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. and residence time calculations ranged from 2.6-8.5 years (Table 3). The lake is deep, with a maximum depth of 88 ft. and a mean depth of 37 ft. 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. 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 12 in. higher than normal. This caused a slight shift in Pearl Lake towards a lighter isotopic composition. Pearl Lake, lies on top of an outwash plain and is suspected to have significant groundwater contributions, increased precipitation did not have a significant effect on residence time. Further investigation into surface and groundwater interactions will occur on Pearl Lake in the future.

Peltier Lake

Peltier Lake's $\delta^{18}O$ values ranged from -8.3 to -4.7 per mil. 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 and 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. 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 isotopic patterns. The lake has a deep complex basin, is known to be a groundwater sink, and has had highly variable precipitation and water levels. As a result, higher resolution and spatial isotope data is needed to interpret South Center Lake's hydrology.

Prairie and Cornbelt

A wide range of lake types were sampled in the Prairie and Cornbelt MLUR. Measured $\delta^{18}O$ compositions for each lake in the region are shown in Figure 11. The isotopic composition of lakes sampled in this region show a strong correlation to the evaporative line (Figure 12). In general, a shift towards lighter isotopic concentrations was observed from 2008 to 2010. This shift is driven by precipitation patterns in the region. In 2008 and 2009, precipitation levels were below normal. 2010 was a wet year and lakes in this region received 13-20 in. of precipitation above normal. As a result, lake waters were reflective of the change in source water inputs and a shift to a lighter $\delta^{18}O$ composition was observed. However, annual $\delta^{18}O$ amplitudes increased in some lakes and decreased in others depending on lake outflow and the affect of evaporation in shallow lake basins.

Carrie Lake's isotopic composition showed the least deviation as a result of above normal precipitation. This is likely because of limited inflow or runoff to the lake which allows precipitation to infiltrate and enter the lake via groundwater. Other lakes have well connected watersheds which quickly transport water from the watershed to the lake itself. These lakes tend to have fluctuating isotopic compositions.

Wet years cause large inputs of source waters with similar isotopic compositions to enter the lake. This resulted in a shift to lighter isotopic concentrations 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 isotopic concentrations, but large evaporative losses to these shallow lakes increased annual $\delta^{18}O$ amplitudes and decreased residence times. Artichoke's isotopic composition also parallels the MWL, suggesting that the lake is influenced by its own local climate and that source waters are likely direct precipitation.

Figure 11. $\delta^{18}O$ values for study lakes within the Transition Forest MLUR.

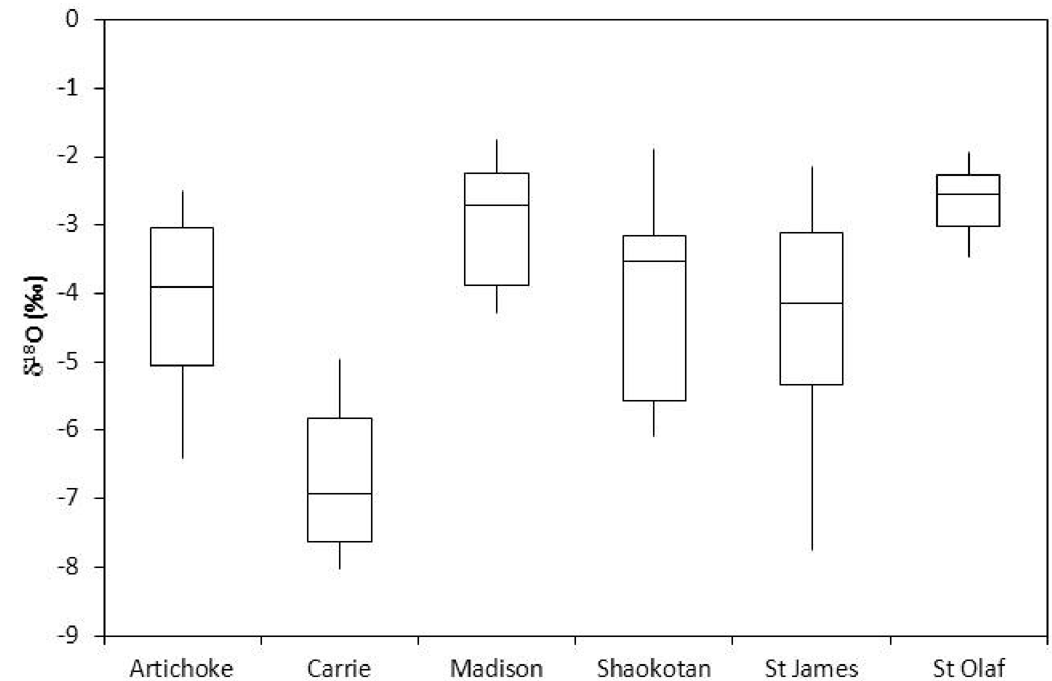


Figure 12. Prairie and Cornbelt $\delta^{18}O$ vs. δD compared to the MWL.

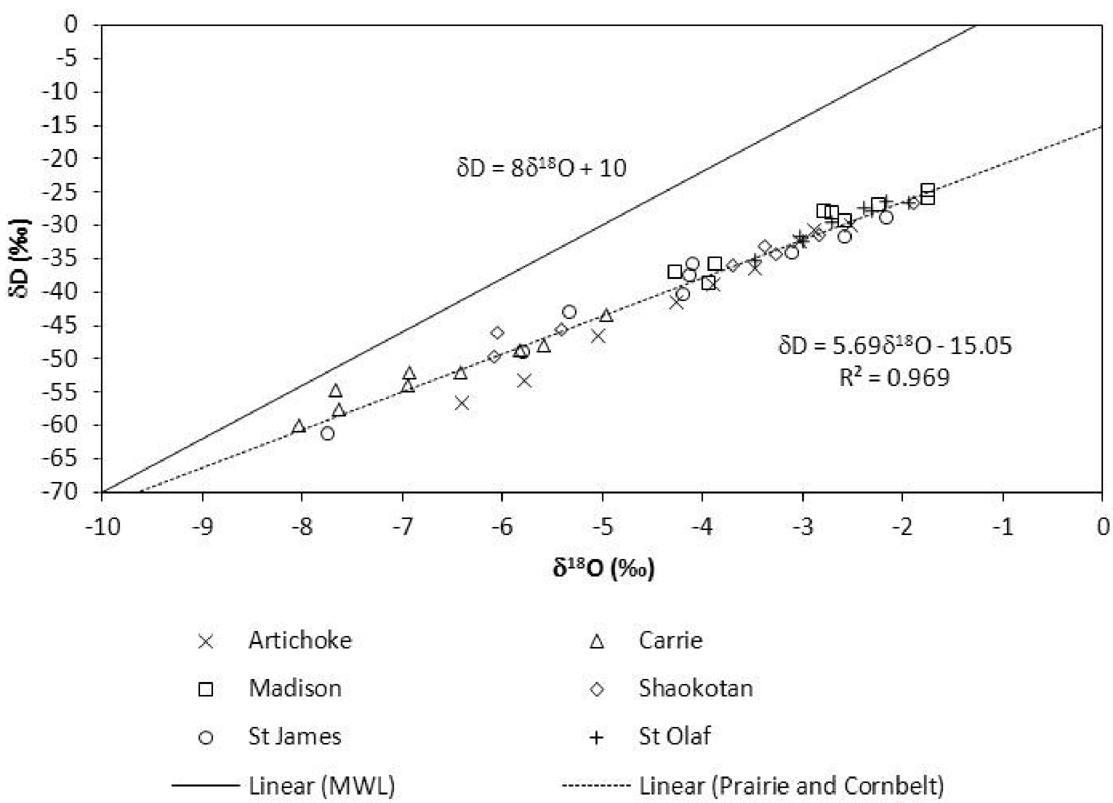


Table 4. Prairie and Cornbelt lakes modeled residence time ranges based on seasonal mean minimum and maximum air temperatures.

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	**5.8***	**5.9***	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	**17.5***	**19.0***	3.2	3.2	5.7	5.9	2.7	3.2-5.9

*** Values omitted because of missing data.**

Artichoke Lake

Artichoke Lake's $\delta^{18}O$ values ranged from -6.4 to -2.5 per mil. and residence time calculations ranged from 1.9-5.2 years (Table 4). The lake is relatively shallow and has a small outlet. Isotopic $\delta^{18}O$ values parallel the MWL which suggests that Artichoke Lake's water consists of primarily unaltered precipitation. Deviation from the MWL suggests source waters represent a localized MWL influenced by local climate. Variations along the evaporative line are caused by differences in source water contributions. This is likely a reflection of source waters during a given year (snow vs. rain). In general, 2008-2009 had slightly higher than normal precipitation levels and 2010 was a wet year. As a result 2010 had the lightest isotope 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. and residence time calculations ranged from 1.3-2.6 years (Table 4). Carrie Lake is relatively deep and has significant groundwater contributions. The lake has one outlet which drains through a diffuse wetland into Lake Elizabeth. 2008 and 2009 were both slightly below average for precipitation and residence time ranged between 1.3-1.4 years. 2010 was a very wet year, receiving approximately 14 in. 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. and residence time calculations ranged from 2.4 -7.1 years (Table 4). Madison Lake is deep with a maximum depth of 58 ft. and a mean depth of 10 ft. The lake has an outlet through a culvert to Mud Lake. In addition, strong groundwater influences are likely based on the local geology. 2008 and 2009 were both below normal precipitation levels and residence times were between 2.4 - 3.0 years. 2010 was a wet year, receiving approximately 16 in. 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 to a lighter $\delta^{18}O$ composition in 2010.

Lake Shaokotan

Lake Shaokotan's $\delta^{18}O$ values ranged from -1.9 to -6.1 per mil. and residence time calculations ranged from 1.4 -4.1 years (Table 4). One sample was not collected in spring 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 20 in. above normal. Large volumes of rain event source waters entered Lake Shaokotan and shifted the lake to a lighter $\delta^{18}O$ composition 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. 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 18 in. above normal. As a result St. James had the largest range of $\delta^{18}O$ values in the Prairie and Cornbelt region. Drainage of the St. James River causes the watershed to be highly connected to the lake. As a result, lake waters are reflective of source water inputs which shifted to a lighter $\delta^{18}O$ composition in 2010.

St. Olaf Lake
St. Olaf Lake's $\delta^{18}O$ values ranged from -1.9 to -3.5 per mil. 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, 30 ft. for a small lake and has a watershed to surface area ratio of 3:1. These characteristics limit source water inputs and as a result, St. Olaf Lake has one of the heavier $\delta^{18}O$ compositions of the Prairie and Cornbelt region. 2008 and 2009 were both below annual mean precipitation values. Precipitation values in 2010 were approximately 13 in. above normal. This caused a shift towards a lighter $\delta^{18}O$ composition in 2010.

Discussion

Hydraulic pathways and lake water budgets are complex and variable in Minnesota lakes. Examination of $\delta^{18}O$ and δD provide insight into lake and watershed processes. Once these processes are identified, lake management strategies can be developed. A variety of factors have been found to influence $\delta^{18}O$ and δD concentrations. These factors include: climate, watershed size, connectivity, and source water contributions.

Broad climatic patterns are responsible for regional differences in $\delta^{18}O$ and δD. As a result, a transition to lighter isotopic concentrations at higher latitudes was observed 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 meteoric waterline for Minnesota, however, in order to make lake management decisions $\delta^{18}O$ and δD compositions must be observed at a finer scale. By studying $\delta^{18}O$ and δD within a specific lake and its watershed, climatic differences from local weather and its impact on hydraulic residence time can be identified.

Three lakes in the study, White Iron, Artichoke, and Belle had isotopic concentrations that were parallel to the MWL suggesting that water budgets in these three lakes consist of primarily unaltered precipitation. White Iron Lake's $\delta^{18}O$ and δD values overlie the MWL, which is expected in a reservoir with a short residence time. Artichoke and Belle Lake's isotopic composition plots to the right of the MWL, suggesting a meteoric waterline influenced by localized climate specific to each lake.

Annual variations in precipitation were found to have significant impacts on $\delta^{18}O$ and δD compositions. The most dramatic changes were observed in 2010 in southwestern Minnesota in portions of the Transition Forest and Prairie and Cornbelt MLURs, due to 13-20 in. above normal precipitation. This caused a dramatic shift to lighter isotopic compositions, however residence times increased in some lakes and decreased in others. Belle Lake experienced the largest shift to a lighter isotopic composition and an increase in residence time as a result. This suggests that climate may be able to alter hydraulic residence time during wet and dry periods, but that it is not the most important factor. What is of more interest to lake managers is how a watershed transports large volumes of water into a lake.

Watershed size and connectivity have a large influence on hydraulic residence time, which varied greatly among studied lakes. Two statistical outliers were identified and associated with White Iron and Echo Lakes. Both lakes outliers were found to be a result of watershed size and connectivity. These lakes act as flow though systems with short residence times. White Iron Lake is reservoir with the largest watershed studied and Echo Lake is shallow with many tributaries and an outlet through the Echo River. As a result, large precipitation and runoff in these watersheds can have a significant affect on isotopic compositions. Both lakes had large $\delta^{18}O$ and δD amplitudes resulting in short residence times. Lakes with small watersheds and limited connectivity, Trout and St. Olaf, had short $\delta^{18}O$ and δD 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 in lakes such as Ten Mile and Elk where, groundwater contributions account for large portions of the annual water budget. By using $\delta^{18}O$ and δD amplitudes, a snap shot of all source water contributions, including groundwater, are accounted for. This was found to be important in annual hydraulic residence time variations in Bearhead and Carrie. Bearhead Lake's hydraulic residence time showed substantial variation between wet and dry years. Carrie Lake's watershed has the ability to infiltrate precipitation, buffering the affects of significantly higher than normal precipitation, opposed to other study lakes in 2010. Over time, shifts in $\delta^{18}O$ and δD amplitudes point to lakes that have a conservative isotopic composition. These are often deep or have high connectivity through under lying lake bed sediments where groundwater discharge occurs such as in Ten Mile and Pearl.

Conclusion

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 $\delta^{18}O$ and δD 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 them to their watersheds potential for contributing pollutants. 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. Through the use of isotopes, δD and $\delta^{18}O$, a better understanding of hydraulic residence time and source water contributions may be understood. Determining what source water contributions are present and how seasonal variations affect the isotopic concentration 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 being included. 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 isotopic 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 lake it is critical to capture the entire seasonal amplitude. Additional isotopic work in groundwater is needed in order to fully understand residence time and water budgets.

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