Isotope-Inferred Water Balances of Slave River Delta Lakes, NWT, Canada.

By

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Authors' Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

The use of the stable isotopes, ^{18}O and ^{2}H, has proven to be a valuable tool in determining the importance of various hydrological controls on the modern water balances of Slave River Delta lakes, NWT, Canada. Samples collected during the 2002 and 2003 field season have shown that delta lakes exhibit highly systematic isotopic variability over the entire delta. The major influences observed to be affecting Slave River Delta lakes include spring snowmelt runoff, flood events from the Slave River, seiche events from Great Slave Lake and thaw season precipitation events. An important component of Slave River Delta lake modern water balances is evaporation, the main controlling factor of water loss in the study lakes, as well as isotopic variability experienced throughout the entire delta during the ice-off season.

Flood events from Great Slave Lake and the Slave River play a key role in controlling modern water balances and isotopic compositions of lakes in the delta. Levee height throughout the delta seems to strongly affect local hydrology, with areas having the greatest levee heights also having the most enriched lake water compositions, and areas having the lowest levee heights having the most depleted isotopic signatures. Outer delta and mid-delta lakes experience the greatest amount of flooding during the spring. Lakes that are affected by spring flood events have a more depleted isotopic signature than those lakes in the upper delta.

Discrepancies between $\delta^{18}O$- and $\delta^{2}H$-derived E/I ratios have been effectively reconciled by incorporating site-specific information into the mass balance equations, and allowing mixing between Great Slave Lake (GSL) vapour δ_E, a large body of water adjacent to the delta and advected atmospheric vapour δ_A. The use of locally derived parameters also ensures a more accurate depiction of local conditions.

Good correlation can be observed during July 2003, between mixing of GSL vapour and atmospheric moisture, when the lakes water balances were solely affected by evaporation. The mixing ratios obtained from two of the study lakes suggest that 5 – 16% of ambient atmospheric moisture was derived from Great Slave Lake.

Acknowledgments

I would like to thank those individuals who contributed to this work over the years. Special thanks go to my supervisors Dr. Brent Wolfe and Dr. Tom Edwards for their infinite patience, and support, and for giving me the opportunity of a lifetime. I wouldn't be where I am today without them. I would also like to thank Michael Sokal and Gabriel Lafferty for their invaluable assistance collecting samples over the years up in the delta. Others who contributed to this thesis through funding and logistical support were the Deninu School, the Deninu Ku'e First Nation, the NSERC Northern Research Chair Program, the INAC Northern Scientific Training Program, the Polar Continental Shelf Project, and the employees of the University of Waterloo Environmental Isotope Laboratory.

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1 INTRODUCTION

The Slave River Delta (SRD) is one of three major fluvio-deltaic complexes in the Mackenzie Drainage Basin. The Slave River basin encompasses the lower reaches of the Slave River on the southeastern shore of Great Slave Lake and extends southwards upstream to Fort Smith, NWT, Canada. This high-latitude delta provides extensive habitat for wildlife, including large populations of migratory waterfowl and other animals which have historically been an important natural resource to the First Nations community of Fort Resolution (English *et al.*, 1997, Wolfe et al., 2007).

The northern environment and northern deltas in particular, can act as very sensitive indicators of climate change and can be strongly influenced by anthropogenic effects. This sensitivity can be profoundly observed and recorded in the numerous small lakes that are part of a deltaic environment.

The hydro-ecology of the Slave River Delta is intimately linked to varying fluxes of water and sediment carried by the Slave River, especially during periods of flooding when river water levels rise above the levees throughout the SRD (English *et al.*, 1997). These events usually occur during the spring thaw season when snowmelt-enhanced discharge raises Slave River water level. Other natural and anthropogenic factors that can influence the flood regime of the Slave River include climate variability and flow regulation due to hydroelectric power production on a major upstream tributary (the Peace River).

Understanding the controls on lake water balances and the hydrologic variability in the Slave River Delta is important, since changes in regional hydrology can strongly affect wildlife habitat and the natural resources used by residents of Fort Resolution.

Very little research has been undertaken on the modern water balances of the numerous lakes in the Slave River Delta and only limited meteorological and hydrometric data are available, so an understanding of how deltaic lakes may have reacted to past climate variability is difficult to ascertain.

As part of a larger multidisciplinary study in the Slave River Delta, being undertaken by researchers from the University of Waterloo and Wilfrid Laurier University, stable isotope tracers (^{18}O and ^{2}H) will be used to determine isotope-inferred hydrologic controls on modern lake water balances within the delta. These isotope tracers can be used due to natural partitioning of $^{1}H^{1}H^{16}O$, $^{1}H^{2}H^{16}O$ and $^{1}H^{1}H^{18}O$ in the hydrologic cycle. The development of a local isotopic framework from 42 lakes throughout the delta will help to assess the importance of the multiple hydrologic influences that can affect the water balance of lakes. Through analysis of the dataset, potential hydrological influences that can affect modern water balances of Slave River Delta lakes are snowmelt runoff, evaporation, precipitation, Slave River flood events, and Great Slave Lake seiche events.

Fieldwork commenced in September 2002 with an initial reconnaissance sampling of 42 lakes and three river sites. This work was undertaken to obtain water and sediment samples from lakes with varying hydrological characteristics, from the outer, mid and upper zones of the delta. This was to initially characterize the hydrology of the lakes for further follow-up studies in 2003. From this set of 42 lakes, six were chosen to represent variable hydrological characteristics within the three delta zones defined by English *et al.* (1997). A temporal sampling of the six lakes and three river sites was undertaken from mid-May to mid-August 2003 to determine how these water bodies react during the thaw season to the myriad hydrological influences experienced in the delta.

Terminology for geographic divisions of the delta was modified from English *et al*. (1997). The SRD was divided into three different zones based on flood frequency, geomorphology, and vegetation. These zones are termed the outer zone, mid-zone, and upper zone of the delta. Another factor influencing the zonation of the delta was levee height. The lowest levees are present in the outer delta, and increase in height upstream, with the highest levees in the upper delta.

The objective of this thesis is to characterize the temporal and spatial variability of seasonal water balances in Slave River Delta lakes. This will be done by:

1. characterizing cumulative 2002 thaw season water balances from 42 lakes using water isotope tracers (^{2}H and ^{18}O);

2. identifying the hydrological relationships between previously identified geomorphological zones described by English *et al*. (1997) and lake water balances;

3. assessing the importance of various hydrological processes on the water balances of six shallow lakes during 2003;

4. quantitatively evaluating the sensitivity of varying isotopic composition of input water, δ_I, and ambient moisture, δ_A to achieve best fit between $\delta^{18}O$ and $\delta^{2}H$ estimated lake water balances, by using a vapour mixing model developed for the 2002 reconnaissance sampling; and

5. applying the vapour mixing model derived from the 2002 dataset on a seasonal basis, performed on the subset of the six study lakes sampled during 2003.

This research is spearheading a broader research program being conducted by the Mackenzie Basin Delta (MBD) research group at the University of Waterloo and

Wilfrid Laurier University, focused on improving knowledge of the past and present hydro-ecology of the Slave River Delta (Wolfe *et al.*, 2007). Understanding the hydrologic evolution of the system to its present state is needed to predict how it may evolve in the future, and aid in northern water resource management and stewardship.

2 SITE DESCRIPTION

The Slave River Delta is located at the mouth of the Slave River on the south shore of Great Slave Lake, Northwest Territories (61°15' N; 113°30' W) (Figure 1). The active and relict portions of the delta are 170 km long and 70 km wide in total, extending from the mouth of the Slave River rapids at Fort Smith, to Great Slave Lake, and cover a total area of 8,300 km^2 (Milburn and Prowse, 1998)

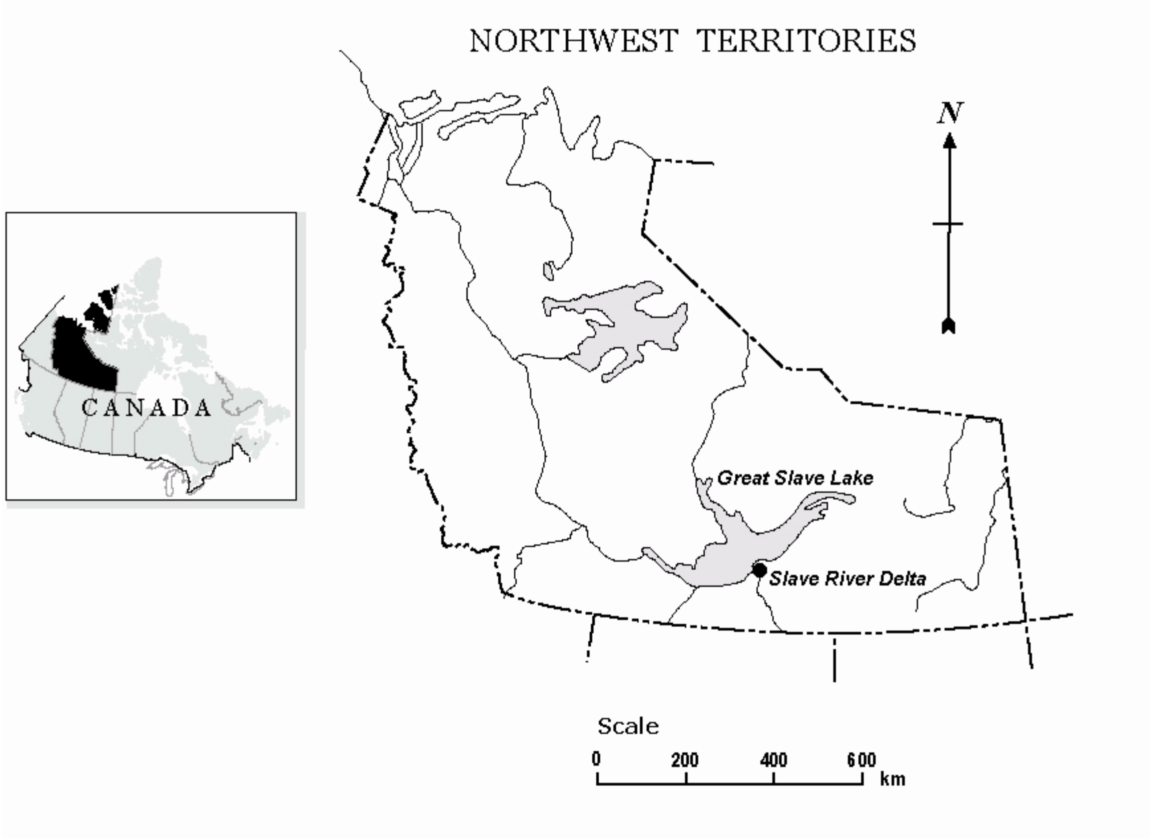


Figure 1 Location of the Slave River Delta (http//atlas.gc.ca).

2.1 History of the Slave River Delta

The Slave River Delta formed during the retreat of the Keewatin Ice Sheet approximately 10,000 years ago. Glacial Lake McConnell formed during the recession of the ice sheet, and occupied Great Slave Lake, Lake Athabasca, and Great Bear Lake basins over time. The separation between Great Slave Lake and Lake Athabasca occurred around 8,780 years ago. Infilling of the southern arm of Great Slave Lake with lacustrine and deltaic sediments then occurred from the beginning of the delta at Fort Smith to today's Slave River Delta outer fringe (Vanderburg and Smith, 1988).

Relict Slave River Delta morphology comprises point bar deposits, abandoned distributary channels, closely spaced strandlines, and areas which have no morphological patterns.

2.2 Modern Delta

Major tributaries in the drainage basin Mackenzie Drainage Basin that directly affect the SRD are the Peace River, the Athabasca River, and the Slave River. The Slave River forms at the confluence of the Peace River and Rivière des Rochers near the Peace-Athabasca Delta, in northern Alberta, and flows north to Great Slave Lake (Prowse *et al.*, 2002). The Peace River contributes approximately 66% of the total flow of the Slave River (English *et al.*, 1997). This large contribution from the Peace River has a major influence on the flow of the Slave River.

The active part of the SRD is an arcuate delta, and spans an area of approximately 400 km^2, approximately 5% of the entire delta. The Slave River is the source of the sediment deposited in the SRD. At the mouth of the Slave River, an area of approximately 630,000 km^2 has been drained, and water from Lake Athabasca, the Peace-Athabasca Delta, the Peace River, and the Athabasca River flows into Great Slave Lake with a mean flow of 3,400 m^3 s^{-1} (Prowse *et al.*, 2002).

2.3 Delta Divisions

English *et al.* (1997) divided the Slave River Delta into three distinct zones based on vegetation patterns and geomorphological differences: the outer delta, mid-delta, and apex, termed the upper delta here (Figure 2).

The outer delta is influenced by annual spring flooding and seiche events, with levees that are at or within 0.10 m of summer water levels on Great Slave Lake. The mid-delta is a transitional area between the outer delta and upper delta, and floods approximately every 5 to 7 years. The mid-delta exhibits levees that are approximately 1.5 m above Great Slave Lake summer water levels. The upper delta is the driest area of the SRD, exhibiting the highest levees which are approximately 2.5 m or greater above Great Slave Lake summer water levels.

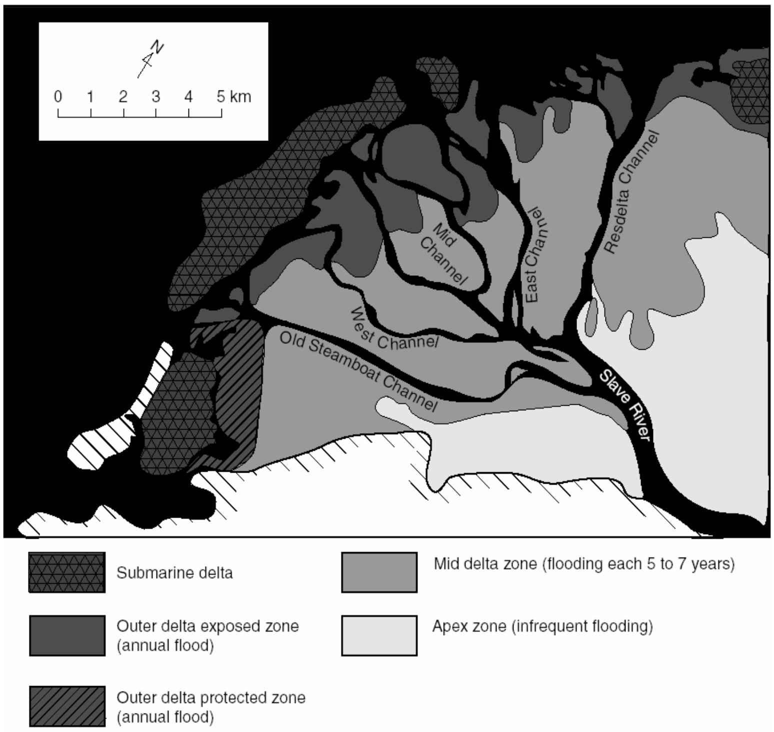


Figure 2 Divisions of the Slave River Delta into the outer delta, mid-delta, and apex (upper Delta) (Prowse *et al*., 2002).

The height of the levees restricts flooding from the Slave River, thereby only receiving infrequent flooding from very high water events (English *et al*., 1997).

Ice-jam flooding is believed to play a significant role in maintaining the water balances of northern delta lakes, likes those found in the Peace-Athabasca Delta, the Slave River Delta, and the Mackenzie Delta (English *et al*., 1997; Prowse and Conly, 1998, 2002; Marsh and Hey, 1989). Flooding of the delta zones can be attributed to both open-water floods and ice-jam flooding.

2.4 Delta Ecology

The ecology of the Slave River Delta is dependent upon the flood regime and deposition of alluvial substrate provided by flooding of the Slave River. Observations made in the field are consistent with previous research conducted on ecology in the delta.

The outer delta is very wet, with many areas having standing water. The outer zone is influenced by annual spring flooding, and supports aquatic and emergent vegetation such as horsetail, (*Equisetum*), sedges (*Carex*), and small willow (*Salix*) (English *et al*., 1997; Prowse *et al*., 2002a).

The mid-delta is slightly drier than the outer delta, and is a transitional zone between the low outer delta levees and the high upper delta levees. The mid-delta is dominated by plant species such as poplar (*Populus*), alder (*Alnus*), and willow (*Salix*) (English *et al*., 1997; Prowse *et al*., 2002a).

The upper delta is the driest area of the SRD, and rarely receives flooding due to the height of the levees. Plant communities that thrive in this environment range from wetlands to climax forest stage supporting white spruce (*Picea glauca*) (Prowse *et al*., 2002a).

2.5 Climate

Climate in the Slave River Delta region is dry with cool summers and cold winters. The climate experienced during 2002 and 2003 is consistent with 30 year climate normals for temperature, relative humidity and precipitation. Relative humidity and temperature vary greatly in the area throughout the year (Figure 3). Average ice-free season (May to October) temperature and relative humidity are 11.4^{o}C and 69.2% respectively, based on 1971 to 2000 climate normals measured in Hay River, NWT (Environment Canada, 2002). 2002 experienced greater amounts of precipitation than 2003. Hay River, located approximately 150 km to the west of Fort Resolution, experienced 325.5 mm and 307.7 mm of precipitation in 2002 and 2003 respectively (Figure 4).

The Great Slave Lake region undergoes greater amounts of precipitation during the summer months than the winter. All delta lakes are completely covered by ice during the winter, and usually begin to thaw in May. The Slave Delta region is underlain by discontinuous permafrost.

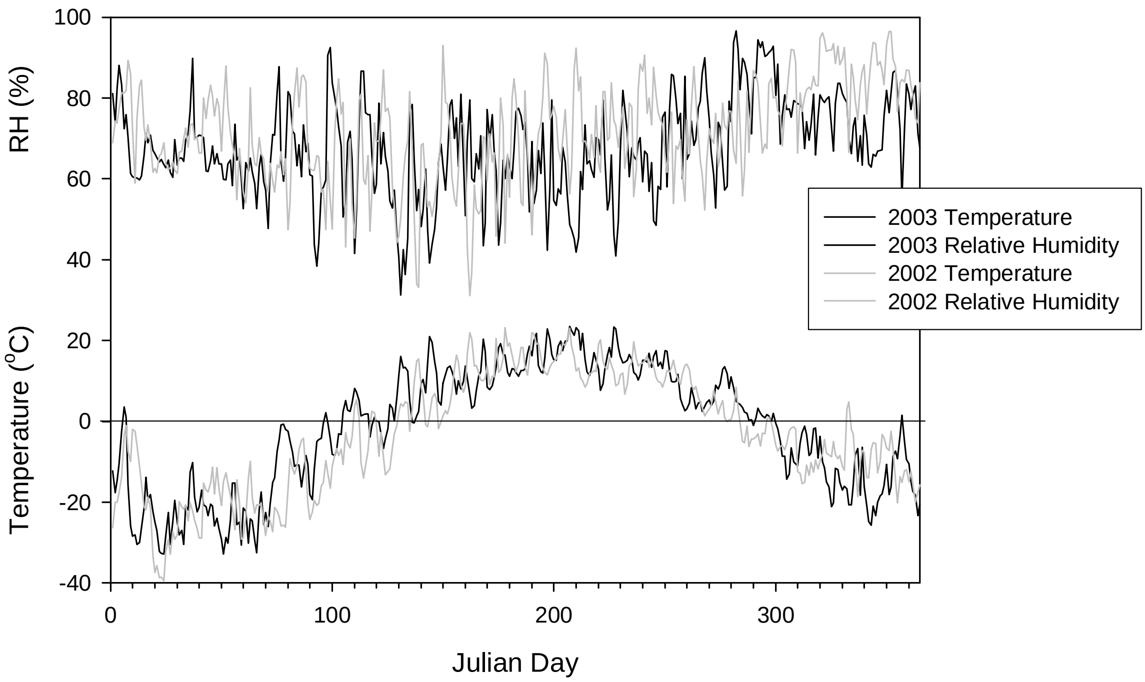


Figure 3 Temperature and Relative Humidity at Hay River during 2002 and 2003 (Environment Canada, 2004).

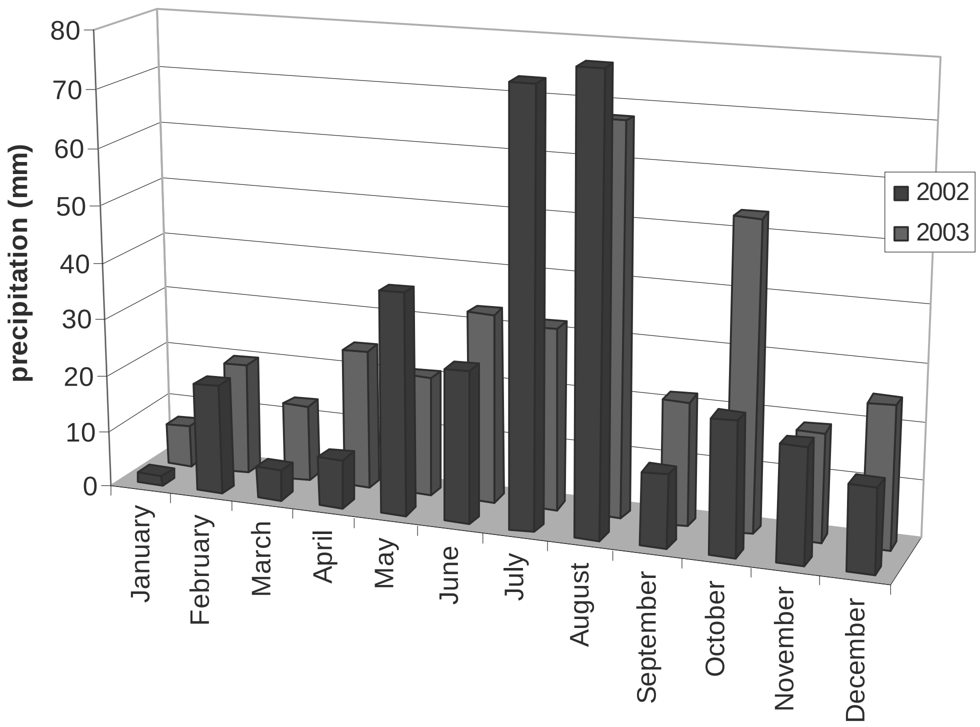


Figure 4 Monthly precipitation amounts experienced at Hay River during 2002 and 2003 (Environment Canada, 2004).

The high amount of precipitation received during October 2003 should be noted and will be discussed in Section 9.

3 METHODOLOGY

3.1 Sampling

Water samples were collected from 42 lakes and three river sites during a week long sampling period in September 2002. The samples were obtained by field personnel with the aid of a helicopter. A more detailed temporal sampling of six lakes was undertaken during May 23 to August 15, 2003. Samples were collected bi-weekly by boat and once a month by helicopter to continue the regional data set of 42 lakes. Two more sampling events were conducted in early September and October 2003 by Gabriel Lafferty from Fort Resolution.

Samples of local thaw season precipitation were collected from each of the six study lake sites. Rain was collected in buckets with a thin layer of oil covering the bottom so that when rain was collected the oil prevented evaporation of the water sample.

3.2 Sampling Protocol

Water samples were collected from the deepest part of each lake, at a depth of 10 cm below the water surface. Samples were collected in 30 ml HDPE (high density polyethylene) bottles, and tightly sealed to prevent evaporation.

Water samples were submitted to the University of Waterloo Environmental Isotope Laboratory to undergo oxygen and hydrogen stable isotope analysis using continuous flow isotope ratio mass spectrometry. Results are reported in standard δ–notation, where $\delta = \delta^{18}O$ or $\delta^{2}H = 1000\ ((R_{sample}/R_{standard})-1)$, where R represents the $^{2}H/^{1}H$ or $^{18}O/^{16}O$ ratios in the water sample and standard, respectively. Analytical uncertainties are ±0.2‰ for $\delta^{18}O$ and ±2‰ for $\delta^{2}H$.

3.3 Continuous Water Level Recorders

Water level recorders were installed at the deepest part of each of the six lakes that were selected for the 2003 temporal sampling. Metal poles were pounded into the substrate until they were stable. The water level recorders were then securely attached to the poles. Data was downloaded at the end of the 2003 field season.

4 STUDY LAKES SELECTION CRITERIA

4.1 2002 Reconnaissance - 42 Study Lakes

The September 2002 spatial dataset was analyzed to assess the variability of lake water balances throughout the SRD. Forty-two lakes and three river sites were sampled to obtain a broad geographic and hydrological snapshot of the active delta. Of the 42 study lakes, two are in the outer delta, 14 in the mid-delta, and 24 lakes are in the upper delta (Figure 5). Table 1 lists all the study lakes with their respective location, geomorphological zone, and depth at the sample point from the September 2002 sampling.

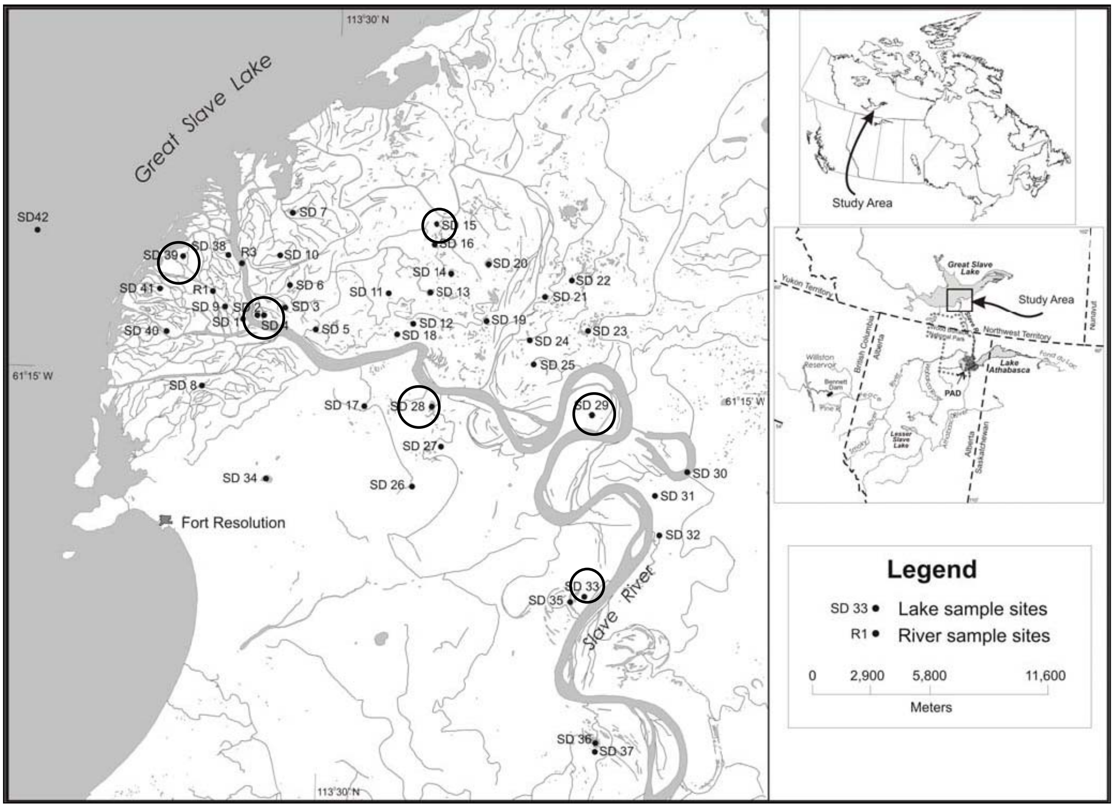


Figure 5 Map of the Slave River Delta indicating the locations of the 42 study lakes and three river sites sampled in September 2002. The circles show the location of the six study lakes sampled in detail during 2003.

Depth of the study lakes varied between 0.15 m and 4 m, with surface areas varying between 1,000 and 200,000 m^2. Lake water temperatures varied between 5^oC and 10^oC.

Table 1 Geomorphologic zones and initial depth of the lake where samples were collected for the September 2002 sampling of 42 lakes and three river sites.

Lake ID	Geomorphologic Zone	Sampling Point Depth (m)	Lake ID	Geomorphologic Zone	Sampling Point Depth (m)
1	**Mid**	**1.00**	25	**Upper**	**0.90**
2	**Mid**	**0.60**	26	**Upper**	**0.70**
3	**Mid**	**1.00**	27	**Upper**	**0.30**
4	**Mid**	**1.20**	28	**Upper**	**2.80**
5	**Mid**	**2.40**	28 C1	**Channel**	**1.50**
6	**Mid**	**1.20**	28 C2	**Channel**	**1.35**
7	**Mid**	**1.40**	29	**Upper**	**0.40**
8	**Mid**	**1.45**	30	**Upper**	**10.0**
9	**Mid**	**1.25**	31	**Upper**	**0.90**
10	**Mid**	**1.90**	32	**Upper**	**1.30**
11	**Upper**	**1.50**	33	**Upper**	**1.25**
12	**Upper**	**0.50**	34	**Upper**	**1.75**
13	**Upper**	**1.30**	35	**Upper**	**1.25**
14	**Upper**	**0.95**	36	**Upper**	**1.85**
15	**Upper**	**1.50**	37	**Upper**	**1.60**
16	**Upper**	**2.35**	38	**Upper**	**1.90**
17	**Upper**	**1.40**	39	**Outer**	**1.10**
18	**Upper**	**1.35**	40	**Outer**	**1.50**
19	**Upper**	**0.49**	41	**Mid**	**1.50**
20	**Upper**	**1.35**	42	**GSL**	**---**
21	**Upper**	**0.75**	R1	**River**	**5.5**
22	**Upper**	**0.90**	R2	**River**	**---**
23	**Upper**	**0.75**	R3	**River**	**---**
24	**Upper**	**0.80**			

4.2 2003 Temporal Sampling – Six Study Lakes

Using the information garnered from the September 2002 data set, a more detailed sampling of six lakes was undertaken during the 2003 ice-off season. Criteria that were considered in choosing the six lakes (SD 39, SD 2, SD 28, SD 15, SD 29 and SD 33) for the detailed temporal sampling from the original 42 lakes were to achieve a geographic spacing of lakes throughout the SRD, and to obtain a broad span of hydrological conditions as reflected by the isotopic data and basin type.

4.2.1 Geographic Distribution

One lake was selected to represent hydrological conditions in the outer delta, one adjacent to the Slave River in the mid-delta susceptible to flooding, and four lakes spaced throughout the upper delta. Another factor in choosing the six lakes was ability to access them by boat from the Slave River.

4.2.2 Hydrological Variability

A key consideration in the selection of the six study lakes was selecting lakes with variable basin types. This meant choosing sites that were considered to have open, restricted, and closed drainage. Open basins were considered to have a continuous inflow and outflow of water, restricted basins were considered to have the potential for inflow and outflow dependent on summer Slave River and GSL water levels, and closed basin lakes were considered to have no river or GSL influence.

Another consideration was to obtain a variable distribution of the lakes' isotopic compositions that were obtained from the 2002 sampling, along the local evaporation line (LEL). To achieve variability along the LEL, two lakes were selected that were extremely depleted, two lakes that plotted along the mid-point of the LEL, and two lakes that had very enriched isotopic compositions plotting near the end of the LEL.

5 SITE DESCRIPTIONS

Table 2 lists the six lakes chosen for detailed sampling, with their geomorphologic zone and depth as determined from initial water sampling in September 2002. Figure 5 shows the six study lakes chosen for the temporal sampling in the circles.

Table 2 Location, geomorphologic zone, and lake depth at time of September 2002 sampling of the six lakes sampled for the more detailed temporal sampling.

Lake ID	Northing	Easting	Geomorphologic Zone	Depth (m)
39	6800378	357341	Outer	1.4
2	6796800	361650	Mid	2.8
15	6802209	372375	Upper	3.2
28	6791339	372046	Upper (connected)	0.5
29	6790800	381718	Upper	1.7
33	6779992	381208	Upper	1.6
Slave River	6798437	358872	River	5.5

5.1 SD 39

SD 39 is located in the outer zone of the SRD, adjacent to Great Slave Lake. For the exact location see Table 2 and Figure 5. Levees along the channels surrounding SD 39 average approximately 0.1 m in height. Due to the low lying levees, SD 39 is prone to frequent flooding. The lake was underlain by ice, at an average depth of 0.4 m in the sediment. The ice underlying SD 39 was found when the water level loggers were being installed, and numerous sites had to be tried until the stake was able to penetrate the lake bottom. The maximum depth of SD 39 is 1.4 m.

SD 39 is surrounded by a horsetail flooded meadow approximately 1 m in depth. This flooded area extends from the lake to the levees in the south, approximately 1 km away. Sedges and cattail are also abundant in the area. Small live willows line the north side of the lake, separating SD 39 from Great Slave Lake. The presence of the willows now in standing water suggests that at some earlier time water levels were lower. Approximately 100 m north of SD 39 is the shoreline and beach of Great Slave Lake.

5.2 SD 2

SD 2 is situated in the mid-delta geomorphologic zone, east of Resdelta Channel. Levee heights along the channel in this area are approximately 1 m high. For the exact location see Table 2 and Figure 5. There is no connection to the river, but overbank flooding entering from the south end of the lake was observed during the 2003 spring thaw. Flooding was observed as very turbid river water entering the lake. The maximum depth of SD 2 is 2.8 m.

Levee vegetation adjacent to SD 2 is mainly composed of high poplar stands and shrubs. The lake is surrounded by 10 to 15 m of mostly living willows on the shoreline, followed by a 10 to 15 m ring of bulrush, cattail and horsetail surrounding the lake.

5.3 SD 15

SD 15 is located halfway along the Jean River, in the eastern part of the upper delta. For the exact location see Table 2 and Figure 5. It is a very irregular and sinuous lake that exhibits qualities of a relict channel. At the northern end of the sinuous relict channel is a large open area of water. The shoreline is steep sided throughout most of the lake. The large open area of the lake has a maximum depth of 1.5 m, while the relict channel, which comprises the narrow portions of the lake, has a maximum depth of 3.2 m.

The shore is mainly composed of bulrush, cattail, sedges and dead willows. Dead birch, poplar, and spruce trunks are submerged in the growth position along the edge of the lake suggesting lower water levels in the past. The surrounding catchment is populated by mature spruce and poplar forest that is very wet.

5.4 SD 28

SD 28 is the largest of the study lakes and is located in the upper zone of the SRD. It is connected to the west side of the Slave River via a channel that is approximately 900 m long and 10 m wide along most of its length. For the exact location see Table 2 and Figure 5. Water depth is mainly controlled by the Slave River water levels. However, during extremely low summer river levels, the mouth of the channel becomes separated from the river. This separation of the channel from the river allows SD 28 to become a closed basin lake. Where the channel enters SD 28, it narrows considerably to a 1 m wide open water channel, with an approximate depth of 0.5 to 1 m. The rest of the channel at the entrance to the lake is constricted by extensive horsetail growth. This horsetail growth acts as a sediment filter, allowing the sediment to settle out of the river water entering the lake. On one occasion during the mid to late 2003 sampling season, a stratified water column was noted as clear lake water was flowing into the channel and on top of the more turbid channel water.

The shoreline of the lake consists of a horsetail fringe surrounding the entire lake, 2 to 15 m in width depending on lake water level, followed by a zone of old cattails and sedges. Interspersed within the horsetail and sedge fringe are small live willows. The surrounding catchment is very wet and consists mainly of mature willows and some birch trees. There is a small inlet channel to the southwest of the lake that provides inflow from the surrounding catchment. The water's edge in SD 28 was observed to recede by approximately 15 m over the 2003 sampling season.

5.5 SD 29

SD 29 is located in the center of a large bend of the Slave River and is in the upper zone of the delta. For the exact location see Table 2 and Figure 5. Levees along this bend are from 1 to 3 m in height. The lake sits in a depression with higher ground on the west side of the lake. SD 29 is the shallowest lake in the sample set, with an average depth of 0.5 m. The lake is a closed-drainage water body with no surface inflow or outflow. The area surrounding the lake is composed of a compressed mat of water-saturated sedge. Directly around the edge of the lake is a narrow 1 m fringe of horsetail and cattail. Floating algae mats within the lake were very abundant from July onwards.

5.6 SD 33

SD 33 is located on the west bank of the Slave River in the upper zone of the delta, and is the furthest south of the study lakes. For the exact location see Table 2 and Figure 5. The levee along the Slave River is approximately 3 m in height during low summer river water levels. SD 33 is a closed basin with no surface inflow or outflow and an average depth of 1.6 m, with shallower water levels on the south side of the lake. During the 2003 sampling season, the water's edge receded by approximately 12 m from its location in the spring.

The area surrounding SD 33 is composed of matted sedge and dead willow trees. The surrounding forest is composed of mature spruce, with some willows mixed throughout.

Extensive growth of floating duckweed mats was present in the lake from July onwards. The lake is underlain by very stiff clay.

6 STABLE ISOTOPE THEORY

6.1 Terminology

Isotopic data are expressed as delta (δ) values, which represent deviations in per mil (‰) from the standard VSMOW (Vienna Standard Mean Ocean Water) and are defined by:

$$\delta_{sample} = (R_{sample} / R_{standard} - 1) * 1000,$$

where R refers to the ratio of $^2H/^1H$ or $^{18}O/^{16}O$.

When making comparisons between δ values, the common terminology used is enriched vs. depleted, which is generally with respect to the rare or heavy isotope, for example ^2H and ^{18}O. When a body of water is evaporating, molecules containing only the light ^1H and ^{16}O preferentially leave the system compared to molecules containing heavy ^2H and ^{18}O. ^2H and ^{18}O will then be concentrated, or enriched in the water.

6.2 Use of Isotopes in Hydrological Studies

Variations in the isotopic composition of water in the numerous components of the water cycle allows for the identification of different water masses, which enables the tracing of their interrelationships in nature (Gat, 1996).

The oxygen and hydrogen stable isotope composition of lake water and input waters can be used in evaluating modern water balances in the Slave Delta due to the preferential evaporation of water molecules containing the lighter isotopes compared to those containing the heavier isotopes. The techniques used in this thesis apply to changes occurring in a lake during the ice-free season for shallow well-mixed lakes (Gibson, 2002). The degree of lake water evaporative enrichment is dependent on environmental factors and atmospheric conditions. These environmental and atmospheric conditions include relative humidity, temperature, the isotopic composition of atmospheric moisture, and the mass water balance factors of the study lakes, with regard to inflow and outflow volumes, and isotopic compositions (Gibson *et al*., 1996).

Factors potentially influencing the isotopic signature of lakes in the Slave Delta are the input of isotopically different waters from precipitation, snowmelt runoff, flood events, ground water inflow, and river water dilution. River water has a more isotopically depleted signature than lake water because of shorter residence times, effectively limiting the amount of evaporative enrichment that can occur on the river water.

The isotopic signatures of lake waters, δ_L, and precipitation in δ^2H vs. $\delta^{18}O$ space (Figure 6), in simple catchments, typically define two distinct linear trends.

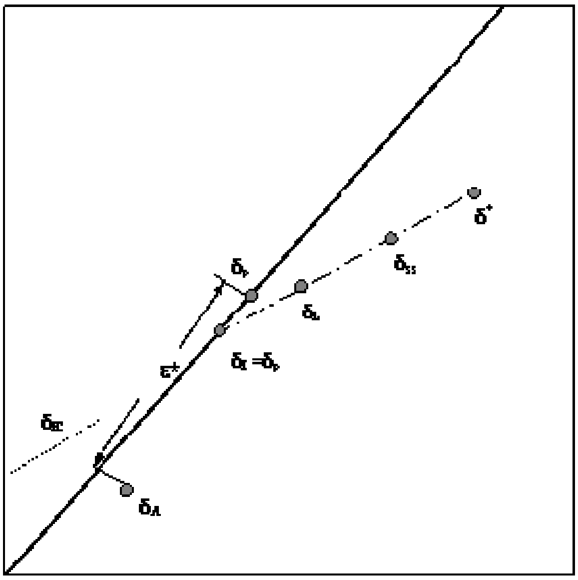


Figure 6 Schematic relationship of δ^2H vs. $\delta^{18}O$ space. δ^* - non-steady state limiting isotopic composition, δ_{ss} – steady-state isotopic composition, δ_L – isotopic composition of lake water, δ_I – isotopic composition of input water, δ_p – isotopic composition of precipitation, δ_E – isotopic composition of lake evaporation, δ^* - equilibrium isotopic fractionation, δ_A – isotopic composition of ambient atmospheric moisture.

Precipitation in the Slave River Delta region that has not undergone evaporation generally plot along a Local Meteoric Water Line (LMWL), defined by $\delta^2H = 6.7*\delta^{18}O – 19.2$, as constructed from Fort Smith data (CNIP, 2004). The LMWL often has a slightly lower slope than the Global Meteoric Water Line, described by the equation $\delta^2H = 8*\delta^{18}O + 10$ reflecting the isotopic composition of precipitation throughout the world. The GMWL and LMWL are a function of the distribution of precipitation, and are controlled by isotopic rainout effects. Surface water that has undergone evaporation usually plots along a separate line of lower slope, ranging between 4 and 6, called a local evaporation line (LEL).

The LEL can be calculated from local hydroclimatic information. The point where the LEL and LMWL intersect can be used to estimate the mean annual isotopic composition of precipitation, δ_p, or can be obtained from the Global Network for Isotopes in Precipitation (GNIP) or the Canadian Network for Isotopes in Precipitation (CNIP) stations. The LEL extends from δ_I through δ_{SSL} (calculated isotopic steady state composition, where E/I = 1), and δ^* (calculated non-steady state limiting isotopic composition; the theoretical isotopic composition of the last drop of water present in a lake if its entire volume was evaporated). Small deviations in lake water isotopic compositions from the LEL can easily be observed. Lakes plotting above the LEL can often be attributed to input of thaw season precipitation, while deviations below the LEL may reflect snowmelt contributions. Relative humidity, h, has a strong influence on all the following parameters used in constructing the predicted LEL (Gibson and Edwards, 2002).

δ_{SSL} is calculated by:

$$\textbf{(1)} \quad \delta_{SSL} = \frac{\delta_I + m\delta^*}{1 + m}$$

(Gonfiantini, 1986).

m, as defined by Welhan and Fritz (1977); Allison and Leaney (1982); and Gibson and Edwards (2002), is the enrichment slope:

$$\textbf{(2)} \quad m = \frac{h - 10^{-3}\varepsilon}{1 - h + 10^{-3}\varepsilon_K}$$

and δ^*, the limiting isotopic composition under local climatic conditions, is given by:

$$\textbf{(3)} \quad \delta^* = \frac{h\delta_A + \varepsilon}{h - \varepsilon \times 10^{-3}}$$

(Gonfiantini, 1986, Gibson and Edwards, 2002).

Water molecules are affected by both equilibrium and kinetic effects during evaporation. Equilibrium fractionation (α^*) and separation ($\varepsilon^* = 1000 (\alpha^* - 1)$) are inversely dependent on temperature. The respective α^* and ε^* values are calculated using equations of Horita and Wesolowski (1994) for *T* in Kelvin:

(4) $^{18}O: 10^3 \ln\alpha^* = -7.685 + 6.7123 (10^3/T) - 1.6664 (10^6/T^2) + 0.35041 (10^9/T^3)$

(5) $^2H: 10^3 \ln\alpha^* = 1158.8 (T^3/10^9) - 1620.1 (T^2/10^6) + 794.84 (T/10^3) - 161.04 + 2.9992 (10^9/T^3)$

Kinetic fractionation occurs during one-way reactions due to physical and chemical processes and is not temperature-dependent. Kinetic effects during evaporation of water are controlled by relative humidity deficit, with respective kinetic separation values (ε_k) defined as:

(6) $\varepsilon_k = C_k (1 - h)$

using empirically-determined values of C_k for open-water evaporation of 14.2‰ for ^{18}O and 12.5‰ for ^2H (Gonfiantinin, 1986).

Following the convention of Gonfiantini (1986), the respective total isotopic separations are then determined by:

(7) $\varepsilon = \varepsilon^*/\alpha^* + \varepsilon_k$

(Gibson and Edwards, 2002).

The isotopic composition of atmospheric moisture, δ_A, is calculated by;

(8) $$\delta_A = \frac{(\delta_{ps} - \varepsilon^*)}{\alpha^*}$$

where δ_{ps} is the isotopic composition of thaw season precipitation (Gibson and Edwards, 2002).

The water balances of lakes can be represented by evaporation/inflow ratio, or E/I, which characterizes the degree, or amount of evaporation compared to the inflow experienced by a lake, thereby affecting the degree of isotopic enrichment occurring over the ice-off season. E/I ratios are calculated using:

$$\textbf{(9)} \quad E/I = \frac{\delta_I - \delta_L}{\delta_E - \delta_L}$$

where, δ_I, δ_L, and δ_E, are the isotopic compositions of the input water, lake water, and evaporation respectively obtained from the lake (Gibson and Edwards, 2002).

The evaporation flux, δ_E, as defined by Craig and Gordon (1965), is the isotopic composition of vapour being released from a water body and is isotopically depleted with respect to its source, and is calculated by:

$$\textbf{(10)} \quad \delta_E = \frac{(\delta_h - \varepsilon^*)/\alpha^* - h\delta_A - \varepsilon_K)}{(1 - h + 10^{-3}\varepsilon_K)}$$

and is dependent on temperature during evaporation, relative humidity, ambient atmospheric moisture isotopic composition, and boundary layer conditions. Evaporation occurs in a series of steps as described by Craig and Gordon (1965), but will be explained using a series of four steps as illustrated in Gonfiantini (1986).

Step 1, at the water-vapour interface, vapour is in equilibrium with the water when it is first released. As equilibrium fractionation occurs, a virtually saturated layer of water vapour forms that is depleted in heavy isotopes. Step 2, as the vapour moves upwards in the atmosphere, away from the water, transportation is influenced by molecular diffusion processes, further depleting the heavier isotopes in vapour form. Step 3, upon further migration of the vapour, it reaches a turbulent layer, where mixing of the original vapour occurs with other sources. No fractionation of the vapour occurs in this turbulent layer. It is this step that will become important when discussing the proposed mixing model of Great Slave Lake vapour with ambient atmospheric moisture δ_A in Section 9. Step 4, continuous molecular exchange of the vapour and the liquid from the turbulent layer then occurs, allowing for the condensation of the mixed vapour to occur on the liquid's surface (Gonfiantini, 1986).

7 RESULTS AND INTERPRETATION

7.1 2002 Initial Sampling

7.1.1 Construction of LEL

Results from isotope analysis of 42 lakes and three river locations sampled in September 2002 in the Slave River Delta show a broad distribution along the predicted Local Evaporation Line for the region represented by $\delta^2H = 4.16\ \delta^{18}O - 69.03$. Parameters used in the construction of the predicted LEL in the Slave River Delta were δ_p, mean annual isotopic composition of precipitation input, of –18.8‰ and –142‰, for $\delta^{18}O$ and δ^2H respectively. These values were obtained from precipitation data measured at Fort Smith, NWT (CNIP, 2004). Flux-weighted relative humidity during the ice-off season for the area was obtained from Canadian Climate Normals (1971 - 2000) for Hay River at 69.2%, and an average flux-weighted temperature of 11.4°C was used. The limiting isotopic composition, δ^*, was determined to be –3.49‰ and –82.79‰, for $\delta^{18}O$ and δ^2H respectively using equation (3). Lake water isotopic compositions for the 42 lakes sampled range from –18‰ to –9.5‰ for $\delta^{18}O$, and –142‰ to –106‰ for δ^2H, reflecting varying degrees of evaporative enrichment.

All three river samples, collected from different areas within the delta have approximately the same isotopic compositions averaging -17.68‰ and –140.27‰ for $\delta^{18}O$ and δ^2H respectively.

7.1.2 2002 Initial Sampling – Isotopic Results

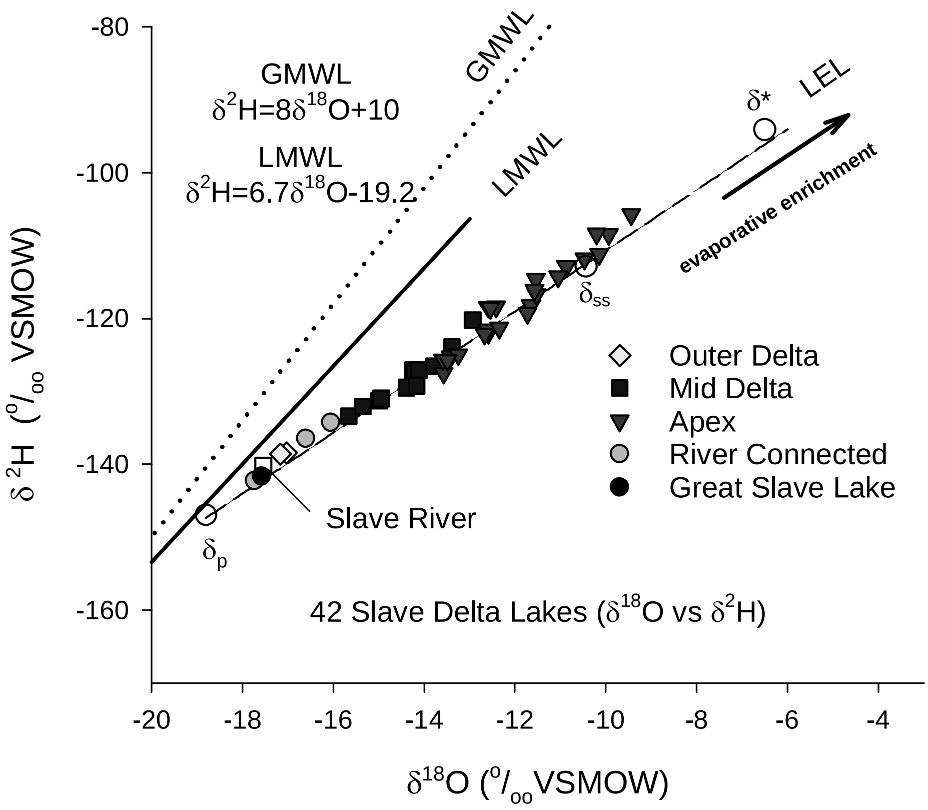


Figure 7 δ^2H and δ^{18}O compositions of 42 lakes sampled and 3 river sites at the end of the 2002 thaw season.

The isotope compositions from the 2002 sampling event, reveals strong clustering along the calculated local evaporation line (LEL). The isotopic variability of lakes observed in Figure 7 encompasses lakes maintaining their water balances through a variety of influences. These influences are direct river influence, along with initial snowmelt input and summer precipitation, obtaining depleted isotopic water signals, to lakes with enriched isotopic water values that maintain their water balances by the input of snowmelt runoff, precipitation, and groundwater.

The isotopic composition of the Slave River during September 2002, is one of the most depleted samples collected, and is slightly offset from the calculated LEL, plotting above it reflecting a strong precipitation signal (Figure 7). This offset from the LMWL can be explained due to the isotopic composition of the river reflecting precipitation that has undergone evaporative enrichment, as well as an isotopic signature of the Slave River and its tributaries.

The Slave River has a strong influence on Great Slave Lake isotopic composition at the outer fringe of the delta. Water discharging from the river collects on the outer fringes of the delta, and mixes with Great Slave Lake water. This mixing is shown by Slave River water having only a slightly more depleted isotopic composition than GSL water.

All the lakes plot reasonably close to the predicted LEL, exhibiting very little scatter around the calculated LEL, with an r^2 of 0.98. The outer part of the Slave River Delta contains lakes that receive river water, and water input from Great Slave Lake during seiche events. These lakes are dependent on river water, and precipitation to maintain their water balances, and exhibit the most depleted isotopic compositions in the delta (Figure 7). An example of a lake that maintains its water balance from inputs of Great Slave Lake water is SD 39. This lake plots directly below the position of Great Slave Lake in δ^2H vs. $\delta^{18}O$ space, with a composition of –17 ‰ and –138.4‰ for $\delta^{18}O$ and δ^2H respectively. It is on the extreme outer fringe of the delta, and is separated from Great Slave Lake only by flooded terrain composed of a horsetail dominated marsh interspersed with willows. Like the Slave River, other lakes sampled in the outer delta plot slightly above the LEL, and exhibit very little scatter along it. This indicates that the lake water balances are dominated mainly by the Slave River, allowing river water isotopic compositions to overwhelm any signal that would be obtained from precipitation.

Three lakes, SD 17, 28 and 30, exhibiting very depleted signals (Figure 7, grey circles), are located in the upper section of the delta, and have direct connections to the Slave River by channels. These lakes all exhibit depleted isotopic signals like the outer delta, as their water balances are also maintained by Slave River water.

The upper delta comprises 25 of the 42 lakes sampled, and shows the most enriched isotopic compositions, excluding the three lakes previously mentioned having direct river influences. These lakes rely solely on precipitation sources, snowmelt and rain, and possibly groundwater inputs to maintain their water balances. There is a greater amount of scatter along the LEL for lakes in the upper delta. This reflects varying inputs of the source waters, and individual lake catchment size, affecting the lake water balances. The lakes also experience more evaporative enrichment than lakes in the outer delta. This is reflected by lakes plotting further along the LEL compared to lakes experiencing continuous river water influence. The lakes in the upper delta also plot above the LEL indicating an influence from summer precipitation inputs. The summer mean isotopic composition of precipitation is –17‰ and –133‰ for $\delta^{18}O$ and $\delta^{2}H$ respectively. This input of precipitation draws the lake water isotopic compositions back towards the LMWL, offsetting some of the evaporative enrichment that has occurred over the ice-off season.

Five lakes sampled in September 2002 are more enriched than the calculated steady-state value (δ_{SSL}) of –8.5‰ and –105.7% for $\delta^{18}O$ and $\delta^{2}H$ respectively. Climate data collected from Hay River, the closest meteorological station to the delta, approximately 150 km away, indicate that the climate experienced in 2002 was a representative year for precipitation when compared to the last 5 years. The area experienced a total of 69 cm of snow and 212 mm of rain. In the month prior to the September 2002 sampling, a total of 90.4 mm of rain was recorded. This amount of rain in September gives a possible explanation as to why none of the lakes sampled surpassed steady state conditions after the precipitation events when the water samples were collected. The lakes water balances were reset slightly due to the large input of isotopically depleted rain water entering the lakes.

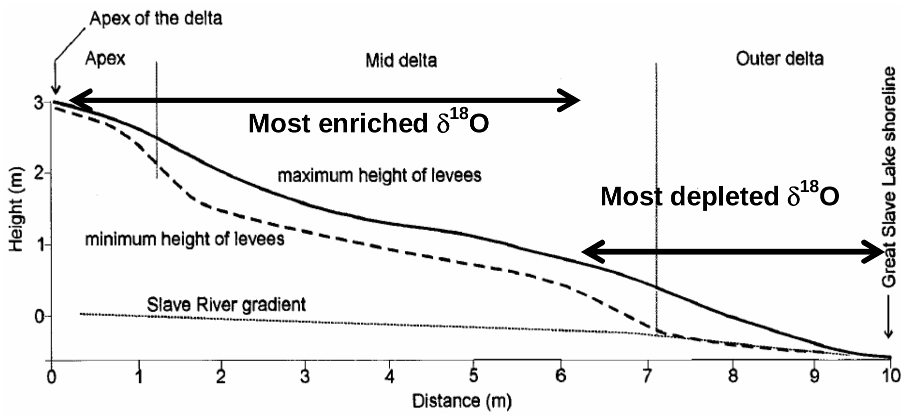


Figure 8 Schematic of levee height with respect to distance from Great Slave Lake (modified from English *et al.*, 1997).

Levees in the outer delta area as observed and previously defined by English *et al.* (1997), are approximately 10 cm above GSL summer water levels (Figure 8). This allows seasonal river flooding to occur as well as periodic flooding from seiche events that occur throughout the summer and mainly in the fall on Great Slave Lake. These flood events strongly influence the water balances of lakes in this area (English *et al.*, 1997). As shown by a spatial representation of $\delta^{18}O$ from the 42 lakes, there is a definite spatial distribution of $\delta^{18}O$ present within the delta (Figure 9). The most depleted signals observed from the sample lakes are represented by the lighter gray, while the most enriched lakes are darker.

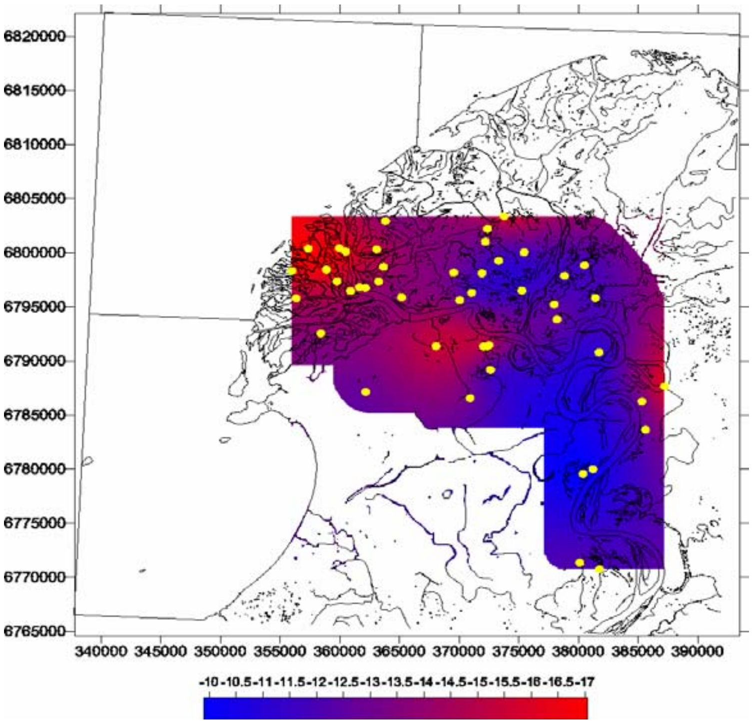


Figure 9 Spatial representation of $\delta^{18}O$ compositions of the 42 sample lakes and three river sites.

The spatial plot indicates that all but three of the lakes with the most depleted isotopic compositions are situated within the outer delta, which exhibits the lowest levees. The other three lakes, SD 17, 28, and 30 all have direct river connection allowing depleted river waters to enter the lakes.

Lakes located in the mid-delta exhibit a lighter shading indicating moderately depleted isotopic compositions are present. The mid-delta is much wetter than the upper delta due to lower levee heights and has more wetland area than the upper delta as well.

Lakes located in the upper delta, due to levee heights that can reach approximately 1.5 to 3 meters during Great Slave Lake low summer water levels (Figure 8), have no river influence. These lakes receive their water from snowmelt and precipitation, except when directly connected to the Slave River. These much higher levees restrict seasonal flooding and river inputs, allowing for more enriched isotopic compositions of lake waters to develop, due to evaporative enrichment occurring with a minimal input of isotopically depleted water throughout the ice-off season. This is represented by the darker areas on the spatial plot (Figure 9).

7.2 2003 Temporal Sampling

7.2.1 Water Levels

Figure 10 shows continuous water levels recorded by automated data loggers installed in the lakes during the 2003 sampling season for five of the six study lakes. The level logger for SD 2 malfunctioned and the data was unusable.

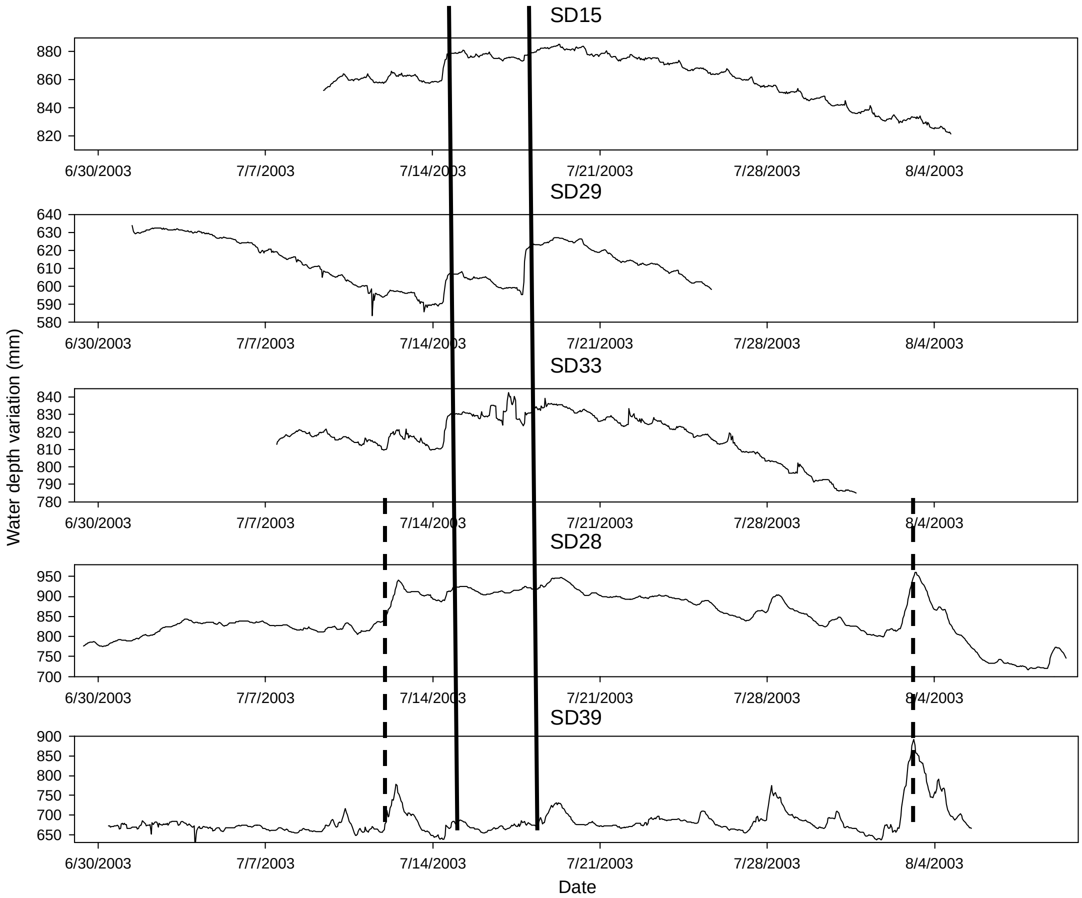


Figure 10 Water levels collected during 2003 for SD 39, SD 15, SD 28, and SD 33. Dashed lined represent seiche events, and solid lines represent summer precipitation events.

The continuous water levels recorded by the data loggers can help in identifying key hydrological processes that can drive the lake water balance changes. The hydrologic processes captured by the continuous recorders can possibly be attributed to fluctuations in water level due to evaporation, precipitation events, flood events, seiche events, and bank/shoreline water storage/recharge (Figure 10). The downwards trends are reductions in water levels due to evaporation.

Table 3 Water level records from continuous data loggers for the six study lakes during 2003.

Lake ID	2003 Sampling Period	Maximum Level Recorded (mm)	Minimum Level Recorded (mm)	Water Level Change (mm)
SD 39	04/07 – 05/08	892	637	255
SD 2	NA	NA	NA	NA
SD 15	09/07 – 04/08	885	822	63
SD 28	29/06 – 09/08	959	717	242
SD 29	01/07 – 25/07	634	588	46
SD 33	07/07 – 31/07	843	785	58

NA – data not available.

The greatest variation in water level observed over the 2003 field season was 255 mm and 242 mm for SD 39 and SD 28 respectively (Figure 10). In these lakes, water levels appear to be controlled by Great Slave Lake and the Slave River water levels as precipitation events are not occurring during the periods of greatest change and they are connected to GSL and the Slave River. Water level appears to change in SD 39 in response to GSL, then afterwards, SD 28 exhibits response from the Slave River.

Major water level variations in these two lakes are thought to be due to GSL seiche events that periodically occur in the delta increasing river level upstream. The water level data set exhibits four events that are possible seiche events occurring on July 13th, 20th and 28th, and August 3rd, 2003.

Lakes not connected to Great Slave Lake or the Slave River (closed basin lakes), and that are dependent on snowmelt, precipitation and evaporation to control their water balances show a much smaller water level variability experienced over the 2003 sampling season of 65 mm, 50 mm, and 58 mm for SD 15, SD 29, and SD 33 respectively.

The three closed basin lakes SD 15, SD 29, and SD 33 have approximately the same downward trend after July 17, 2003 due to evaporation occurring from the lakes. The slight recharge seen daily is possibly due to evaporation occurring throughout the day then water stored in the surrounding sediments around the lake replenishing water levels slightly overnight. Another possibility is due to uncompensated temperature effects affecting the data loggers.

Two precipitation events can be observed to affect all the lakes by increasing their water levels on July 14th, and July 17, 2003. SD 29 exhibits the greatest change in water level due to these two precipitation events. This is due to SD 29 being the smallest lake with the lowest water volume. Other factors that may play a significant role in water level variability and reactions to precipitation events are basin morphology and catchment area and lake volume.

7.2.2 Precipitation

Summer precipitation and winter snow samples were collected over the 2003 and 2004 field seasons (Figure 11). The isotopic compositions of the snow samples collected vary from -27.7‰ to -21.1‰ and -211.2‰ to -164.5‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively. They show a broad distribution below the calculated LMWL using Fort Smith CNIP data, indicating that there is a slight difference in what is experienced in the Slave River Delta, than that at Fort Smith, thereby having a slightly different LMWL. Another possible reason for the slight difference is that the Fort Smith data was collected during the 1960s.

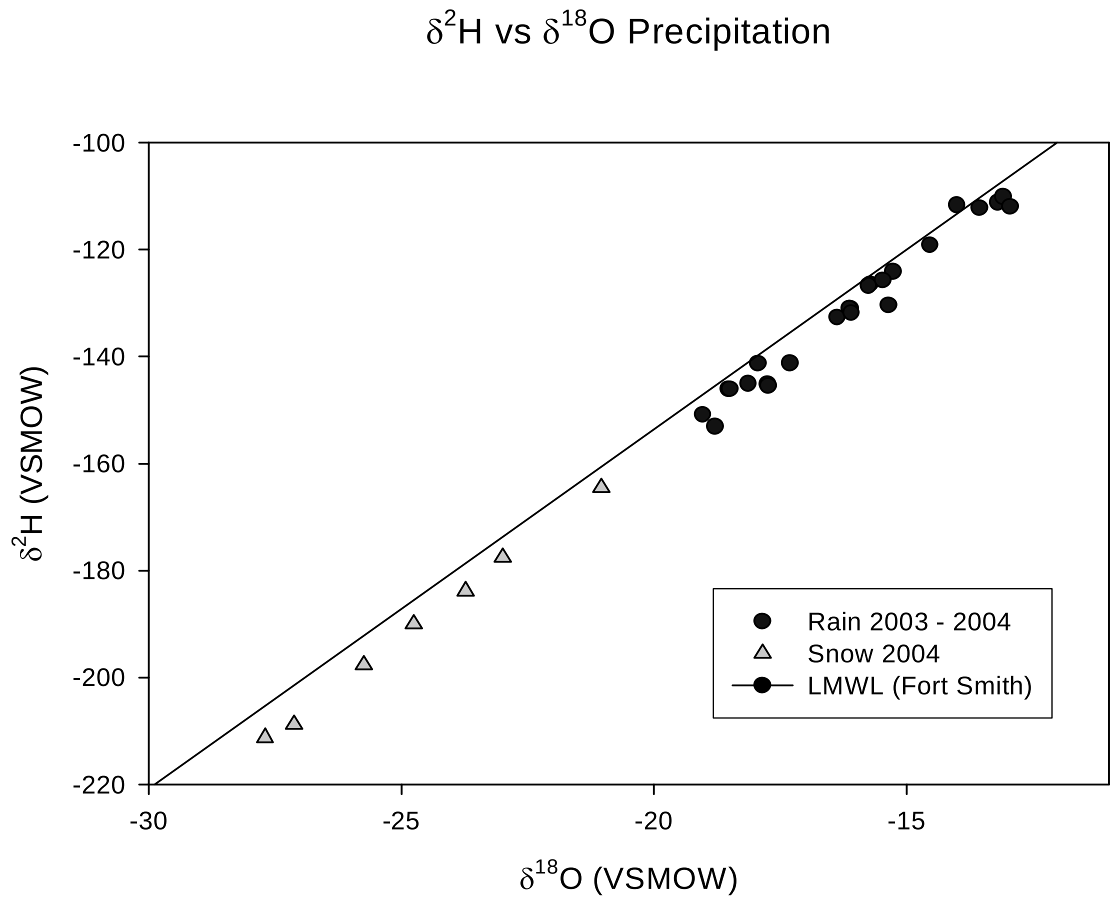


Figure 11 Summer and winter precipitation samples collected in the Slave River Delta during 2003.

The large variability observed in the precipitation samples can be attributed to seasonal variability and rain-out effects. The depleted snow isotopic compositions are a good indicator of the potential range of δ_I values that can be experienced throughout the delta.

7.2.3 Construction of the 2003 LEL

Parameters used in the construction of the predicted LEL for 2003 in the Slave River Delta were a δ_I, isotopic composition of input waters, of –21.5‰ and –163.5‰, for $\delta^{18}O$ and δ^2H respectively. These values were obtained by constructing a regression line through all closed basin lake data sets (SD 2, SD 15, SD 29, and SD 33) and taking an average of the data. Flux-weighted relative humidity during the ice-off season for the area was obtained from 2003 climate data for Hay River at 62.8%, and an average flux-weighted temperature of 13.4^{o}C was used. The limiting isotopic composition, δ^*, was determined to be –3.49‰ and –82.79‰, for $\delta^{18}O$ and δ^2H respectively using equation (3).

7.2.4 2003 Isotopic Results from the Temporal Sampling

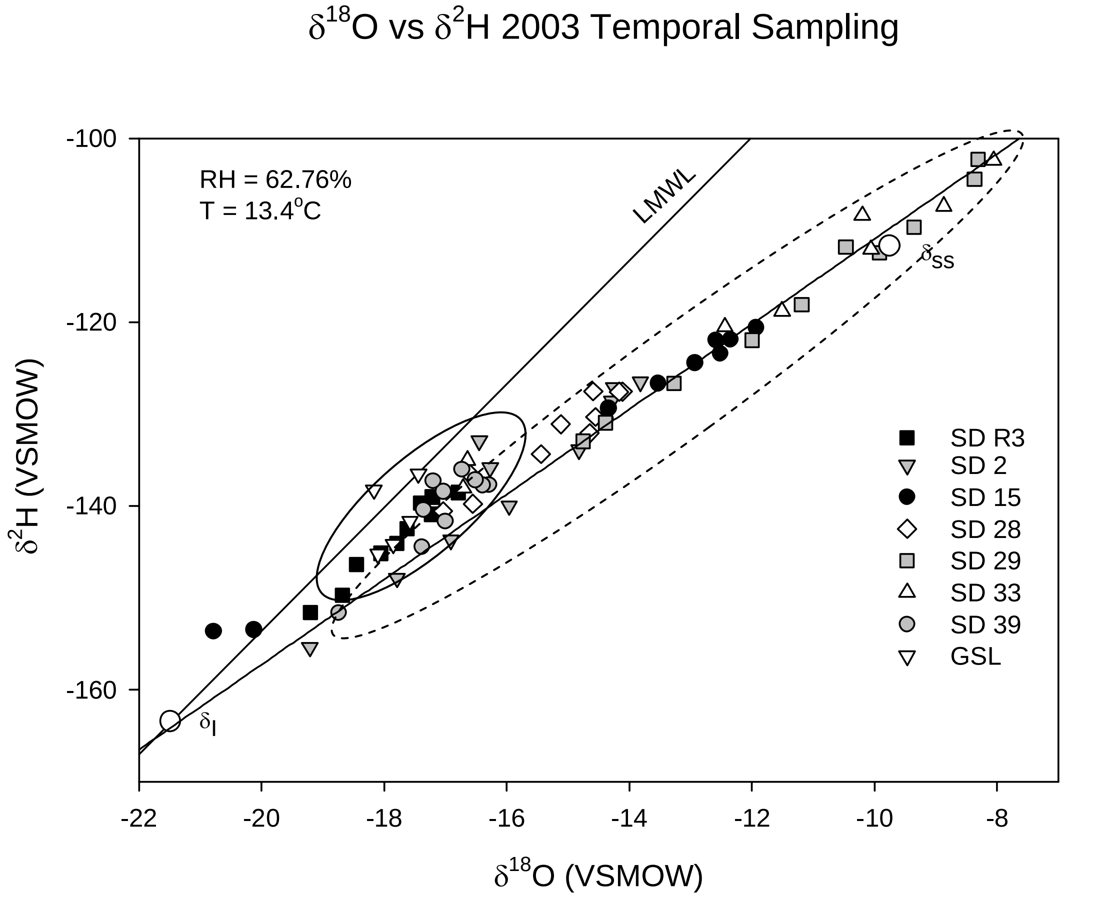
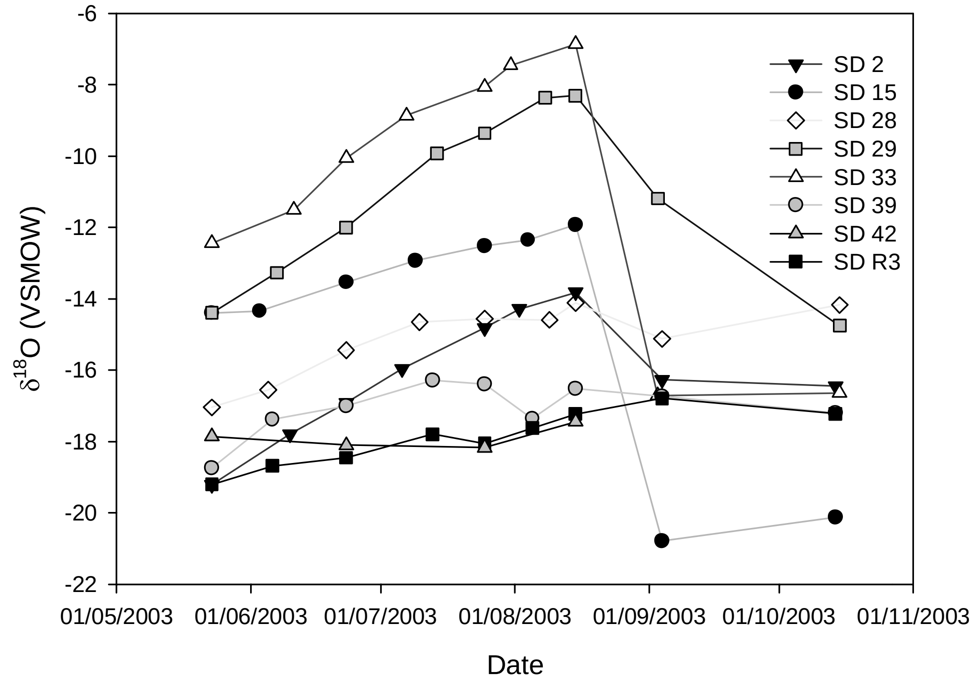


Figure 12 Temporal isotopic data obtained from the 2003 seasonal sampling exhibits a wide range of $\delta^{18}O$ and $\delta^{2}H$ compositions showing extensive seasonal lake water variability.

Results from the isotopic analysis of the 2003 detailed seasonal sampling of six lakes and three river locations in the Slave River Delta show a broad distribution along the predicted Local Evaporation Line (LEL) for the region, represented by $\delta^{2}H = 4.16\delta^{18}O - 69.03$ (Figure 12). δ_I was determined by constructing a regression line through the closed basin lakes only, which have less outside water inputs than open or restricted basin lakes. The δ_I value is representative of winter 2003 snow isotopic compositions exhibited in the Slave River Delta area.

The variability observed along the LEL in Figure 12 is attributed to varying water balances of the lakes. This is due to varying precipitation inputs, river water inputs, flood events, and seiche events and, as the ice-off season progressed, lakes exhibiting greater amounts of evaporative enrichment, leading to a progression upwards along the LEL. There appear to be two groupings of lake samples along the LEL in Figure 12. These two groupings are shown by the dashed and solid circles. The solid circle represents lakes with direct river connection, and an influence by GSL and Slave River water. Great Slave Lake and the Slave River plot on a separate evaporation line reflecting the influence of conditions upstream of the delta. Slave River water pools along the edge of the delta where GSL water samples were collected. As stated earlier, this pooling can be observed by the presence of river sediment along the outer fringe of the delta. The dashed circle groups represent closed basin lakes primarily undergoing evaporative enrichment.

δ[18]O Temporal Distribution



δ[2]H Temporal Distribution

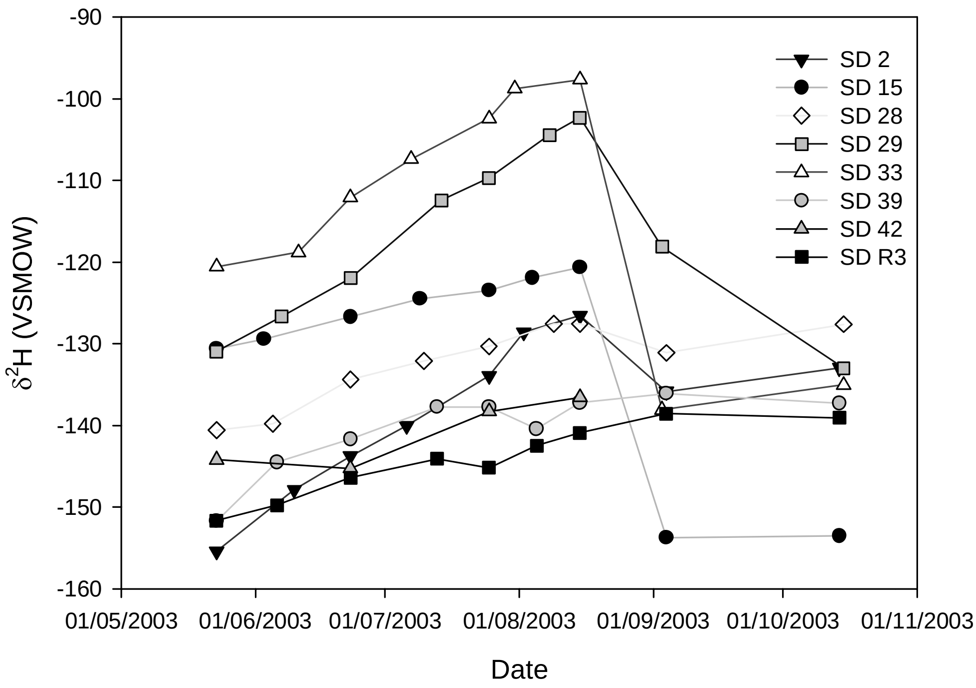


Figure 13 $\delta^{18}O$ and $\delta^{2}H$ temporal distribution of the six study lakes, the Slave River (R3), and Great Slave Lake (SD 42).

Lake water isotopic compositions for the six study lakes range from -18‰ to -9.5‰ and -142‰ to-106‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively (Figure 13). This range of isotopic composition mainly reflects varying degrees of evaporative enrichment occurring in the lakes, and is represented by the upward slopes in the temporal graph due to the lakes becoming enriched over time. The large depletion of lake water samples observed at the end of the data set represents a late season precipitation event. The excessively strong response of SD 15 may indicate that it was not well-mixed at the time of sampling.

Table 4 Lake Location, Hydrologic Influence, and Range of Isotopic Compositions for 2003.

Lake ID	Geomorphologic Zone	Hydrologic Influences	Range of $\delta^{18}O$ Values (‰)	Range of $\delta^{2}H$ Values (‰)
SD 39	Outer	F, R, S, SM, P, E	-18.7 to -16.3	-151.7 to -136.1
SD2	Mid	F, SM, P, E	-19.2 to -13.8	-155.4 to -126.5
SD 28	Upper (connected)	F, R, S, SM, P, E	-17.0 to -14.1	-140.6 to -127.5
SD 15	Upper	SM, P, E	-20.8 to -11.9	-153.7 to -120.6
SD 29	Upper	SM, P, E	-14.8 to -8.3	-133.0 to -102.3
SD 33	Upper	SM, P, E	-16.7 to -6.87	-138.1 to -97.7
R 2	Slave River	S, SM, P, E	-19.2 to -16.8	-295.9 to -254.2

F – Flooding, R – River Connected, S – Seiche Events, SM – Snow Melt,
P – Precipitation, E – Evaporation

The six study lakes show an evolution of isotopic conditions over the 2003 ice-off season. Table 4 shows the range of isotopic variability expressed in the lakes due to varying hydrologic influences. The difference between flooding (F) and the river connected (R) designation in the following table is flooding affects lakes due to high water events, and river connected is a lake with a direct connection to the Slave River.

7.2.4.1 Lakes Influenced by the Slave River and Seiche Events

7.2.4.1.1 SD 39

SD 39, located in the outer delta, adjacent to Great Slave Lake is the most isotopically depleted lake of the data set. Isotope values for SD 39 range from -18.7‰ to -16.3‰, and -151.7‰ to -137.7‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively. This isotopic depletion, when compared to other study lakes can be explained by SD 39 being influenced by GSL during early spring flooding, as well as seiche events that can occur throughout the summer and fall. Great Slave Lake exhibits an isotopic range of -18.2‰ to -17.4‰ and -145.2‰ to -136.5‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively.

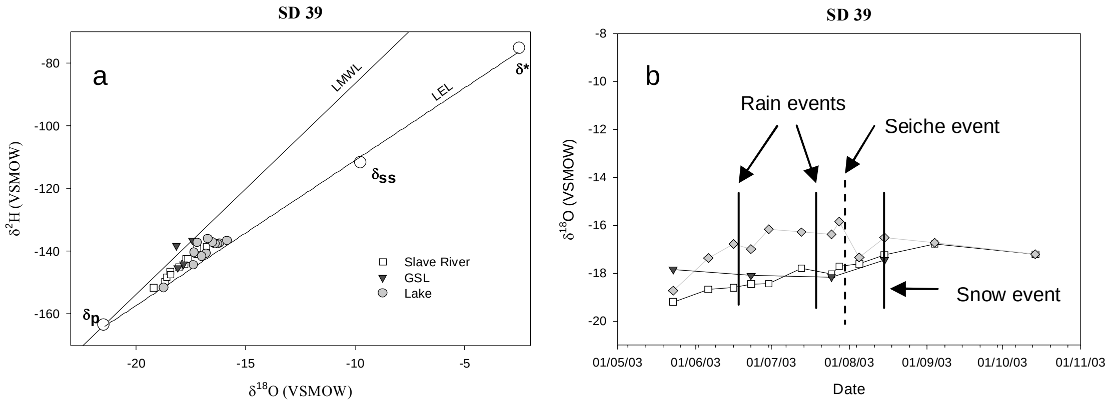


Figure 14 a) $\delta^{18}O$ and $\delta^{2}H$ plot and b) $\delta^{18}O$ temporal plot of SD 39, the Slave River and GSL for 2003 data.

There appears to be a strong correlation and clustering of SD 39, GSL, and Slave River water samples above the LEL, nears its base (Figure 14a). This is possibly due to evaporative enrichment of SD 39 being offset by input of GSL water, which corresponds with the Slave River water isotopic composition. The offset may also indicate a different δ_I from the closed basin lakes influencing the open basin lakes.

Figure 14b shows a strong correspondence between SD 39 isotopic composition to that of GSL. The slight offset can be attributed to evaporative enrichment of the smaller study lake. A seiche event can also be seen in August 2003, when SD 39 lake water becomes more depleted and closely reflects the isotopic signature exhibited by the isotopic composition of GSL along the outer edge of the delta. Other evidence that suggests a seiche event influencing the lakes water balance is the abrupt increase then decrease of water level experienced at the same time of the isotopic depletion.

Water along the outer edge of the delta where GSL water samples were collected exhibit river water isotopic compositions. This is due to river water entering Great Slave Lake from the many channels and pooling along the outer edge of the delta in

Great Slave Lake. This was also observed visually from the air with the presence of a sediment plume from river sediment.

7.2.4.1.2 SD 2

SD 2, located in the mid-delta, adjacent to the main channel of the Slave River is a closed basin lake. In 2003, the isotopic composition of SD 2 varied between -19.2‰ to -13.8‰ and -155.4‰ to -126.6 ‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively. Slave River water isotopic composition at the beginning of the thaw season was -19.2‰ and -151.5‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively.

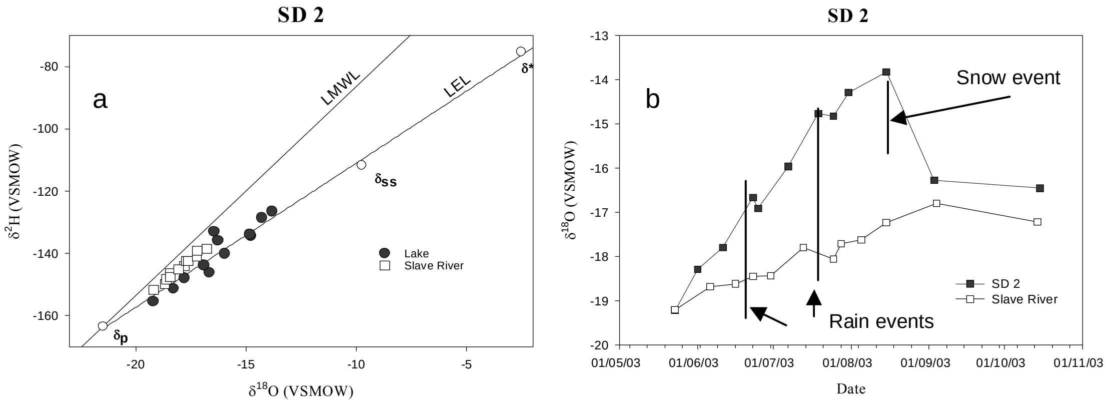


Figure 15 a) $\delta^{18}O$ and $\delta^{2}H$ plot and b) $\delta^{18}O$ temporal plot of SD 2 and the Slave River for 2003 data.

Flooding during spring thaw high water events can affect SD 2 water balance. Flooding was observed and visibly evident during the first sampling period, May 23, 2003, by turbid river floodwater entering the lake over the southern levee. Figure 15b shows the lake water of SD 2 having an isotopically depleted Slave River composition during the first sampling event. This exhibits the strong influence over-bank flooding can have on the initial 2003 lake water balance. The more depleted values (last 2 samples) observed in the $\delta^{18}O$ temporal plot (Figure 16b), can possibly be attributed to a minor snowmelt influence.

After flooding subsided, evaporative enrichment became the dominant control on the water balance of SD 2. Over the ice-off months, SD2 steadily progressed along the LEL becoming more isotopically enriched.

Three precipitation events are apparent in Figure 15b. These events are shown by a depletion of lake water isotopic composition after the precipitation event. At the end of the 2003 sampling season, a depletion of lake water isotopic composition of greater than -2‰ ($\delta^{18}O$) was observed over two sampling events. This depletion can be attributed to an unusual early fall snow storm that was observed by local residents of Fort Resolution. This can be observed by the last two samples becoming more depleted (Figure 15b), and two data points moving off the LEL towards the LMWL in Figure 15a.

7.2.4.1.3 SD 28

SD 28 is directly connected to the Slave River by a long narrow channel, and is situated in the upper delta. The isotopic composition of SD 28 during the 2003 thaw season sampling, varied between -17.0‰ to -14.1‰, and -140.6‰ to -127.5‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively. These samples plot above the LEL, indicating a river influence.

The channel connecting SD 28 to the Slave River can allow for the inflow of Slave River water into the lake. When Slave River water levels decrease over the summer months, the channel can become disconnected from the river, isolating the lake from river water inputs.

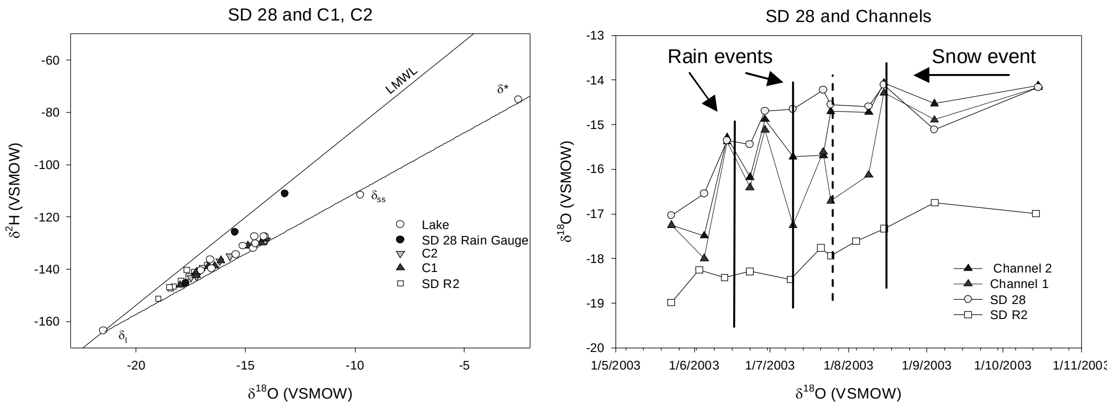


Figure 16 a) $\delta^{18}O$ and $\delta^{2}H$ plot and b) $\delta^{18}O$ temporal plot of SD 28 and SD 28C1 and SD 28 C2 and the Slave River for 2003 data.

Figure 16a and b shows that SD 28 did not undergo as much isotopic enrichment over the ice-off period as other study lakes in the upper delta. This is due to evaporative enrichment being offset by inputs of depleted water from the channel and surrounding catchment.

Samples were collected from opposite ends of the channel to determine the influence of the Slave River on SD 28. SD 28 C1 samples were collected approximately 100 m away from where the channel connected to the Slave River. SD 28 C2 samples were collected approximately 20 m away from the channel inlet to SD 28.

The channel samples show occasional offset from each other indicating the Slave River has a stronger influence on one end of the channel and the lake influences the other end (Figure 16b). Near the end of the 2003 sampling season (last three data points), the channel became disconnected from the Slave River due to low summer river water levels, and the lake water was flowing out of the lake into the channel.

Throughout the summer SD 28 exhibits periods when lake water became slightly depleted due to precipitation events and a possible seiche event (dashed line) (Figure 16b). The end of season depleting precipitation event did not affect SD 28 lake water as much as observed in other lakes in the upper delta showing only a small depletion of 1‰ and 4.2‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively, possibly due to its large size.

7.2.4.2 Lakes Influenced by Evaporation

7.2.4.2.1 SD 15

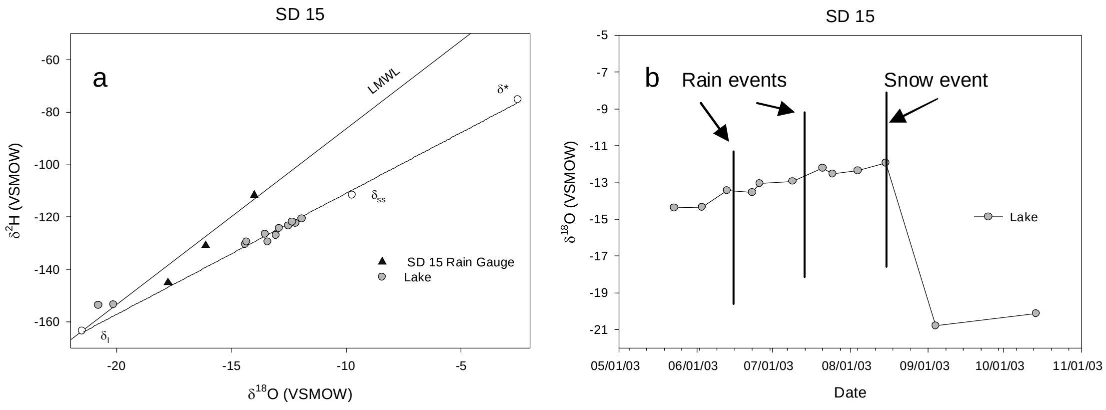


Figure 17 a) δ^{18}O and δ^2H plot and b) δ^{18}O temporal plot of SD 15 for 2003 data.

Isotopic composition of SD 15, a closed basin lake on the Jean River in the mid-delta, varied between -20.8‰ to -11.9‰ and -153.7‰ to -120.6‰, for δ^{18}O and δ^2H respectively, and plots along the calculated LEL (Figure 17a, b). Isotopic composition of SD 15 steadily becomes more enriched over the ice-off period due to evaporation. However, possibly due to its large size and/or input water from the surrounding catchment, the amount of enrichment observed when compared to the other closed basin lakes (SD 29, SD 33) of the data set was not as great. A late end-of-season precipitation event lowered the δ^{18}O and δ^2H signature by almost -9‰ and -33‰, for δ^{18}O and δ^2H respectively, as seen in Figure 17a by two data point plotting near the LMWL. As noted above, the extreme response may indicate that the lake was not well-mixed when sampled.

7.2.4.2.2 SD 29

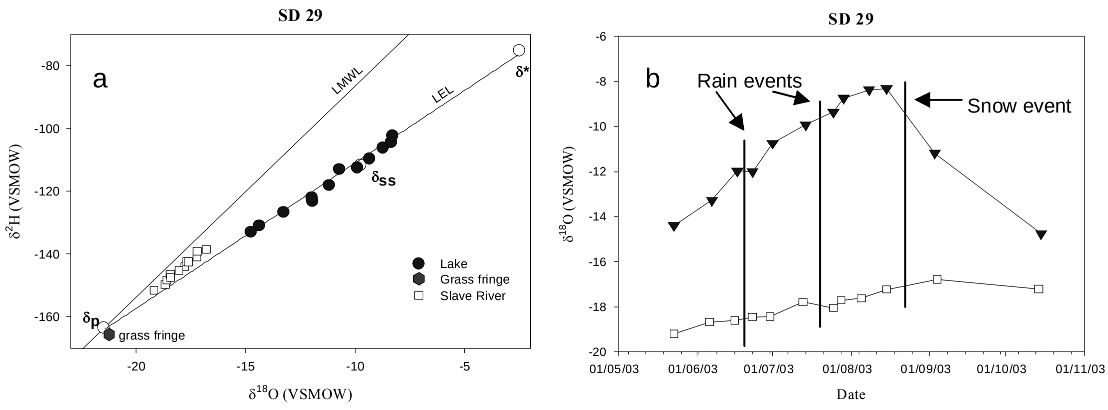


Figure 18 a) $\delta^{18}O$ and $\delta^{2}H$ plot and b) $\delta^{18}O$ temporal plot of SD 29 and the Slave River for 2003 data.

During the 2003 thaw season, SD 29, a closed basin lake in the upper delta exhibits the second most enriched isotopic signature of all the study lakes. The isotopic composition varied between -14.8 to -8.3 and -133 to -102.3‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively (Figure 18a and b).

Due to SD 29 being a closed basin lake, it is mainly dependent on snowmelt and precipitation to maintain its water balance. The data from the lake show a steady enrichment due to evaporation, plotting along the LEL with 3 samples plotting above δ_{SS}. This lake was observed to have undergone a lot of drying during the 2003 season. A water sample was collected from within the sedge fringe surrounding the lake, and is considered to represent snow melt in the area, and is thought to be a good approximation of δ_{I} for the lake (Figure 18a).

The end of season precipitation event observed in other lakes in the data set is also captured in SD 29. Lake water became depleted by -6.4 and -30.9‰, for $\delta^{18}O$ and δ^2H respectively (Figure 18b).

7.2.4.2.3 SD 33

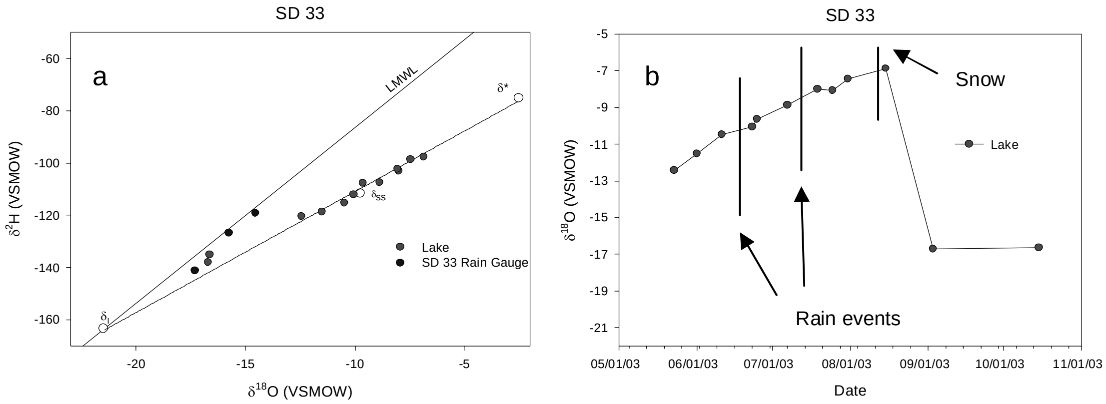


Figure 19 a) $\delta^{18}O$ and δ^2H plot and b) $\delta^{18}O$ temporal plot of SD 33 for 2003 data.

During the 2003 thaw season, SD 33, a closed basin lake in the upper delta exhibited the most enriched isotopic signature of all the study lakes. The water's edge was observed to recede by more than 15 m over the thaw season. The isotopic composition of SD 33 varied between -16.7 to -6.9 and -138.1 to -97.7‰, for $\delta^{18}O$ and δ^2H respectively (Figure 19a and b).

Due to SD 33 being a closed basin, and depending mainly on snowmelt and precipitation to maintain its water balance, the water samples collected plot along the LEL showing the strong control of evaporation on the system. Five samples plot above δ_{SS}, and observations made indicate that SD 33 underwent extensive drying during the summer of 2003. Two data points, plotting along the LMWL, can be attributed to the end of season precipitation event, and showed a depletion of -9.8 and -37.7‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively (Figure 19a and b).

7.3 2002 Isotope Mass Balance Modelling

Isotope mass balance equations were used to estimate individual lake water balances, as captured in lake water isotopic compositions measured in September 2002. Initial modelling used Hay River A station Climate Normals obtained from Environment Canada. Also incorporated in the equations listed in Section 6.2 of the theory section of this report, was a common value for input composition (δ_I) based on mean annual precipitation $\delta^{18}O$ and $\delta^{2}H$ values from Fort Smith, a station in the Canadian Network for Isotopes in Precipitation (CNIP), and vapour isotope composition based on equilibrium with Fort Smith thaw-season precipitation (δ_{ps}).

Using these model parameters, evaporation/inflow (E/I) ratio results show a good correlation to a 1:1 line below E/I <0.4, but poor correlation above E/I > 0.4 when calculated from sampled lake water $\delta^{18}O$ and $\delta^{2}H$ compositions (Figure 20). There seems to be a systematic offset from the 1:1 line giving E/I ($\delta^{2}H$) values greater than E/I ($\delta^{18}O$), which becomes increasingly magnified for lakes having undergone greater evaporative enrichment.

Discrepancies in $\delta^{18}O$- and $\delta^{2}H$-derived E/I ratios for evaporatively enriched lakes can effectively be reconciled by changing the input parameters to the mass balance model. This is done by incorporating mixing of local ambient moisture isotope composition with vapour isotope composition derived from Great Slave Lake, site-specific input compositions, and using locally obtained samples of precipitation to help constrain δ_{ps} and δ_I values to represent actual local conditions.

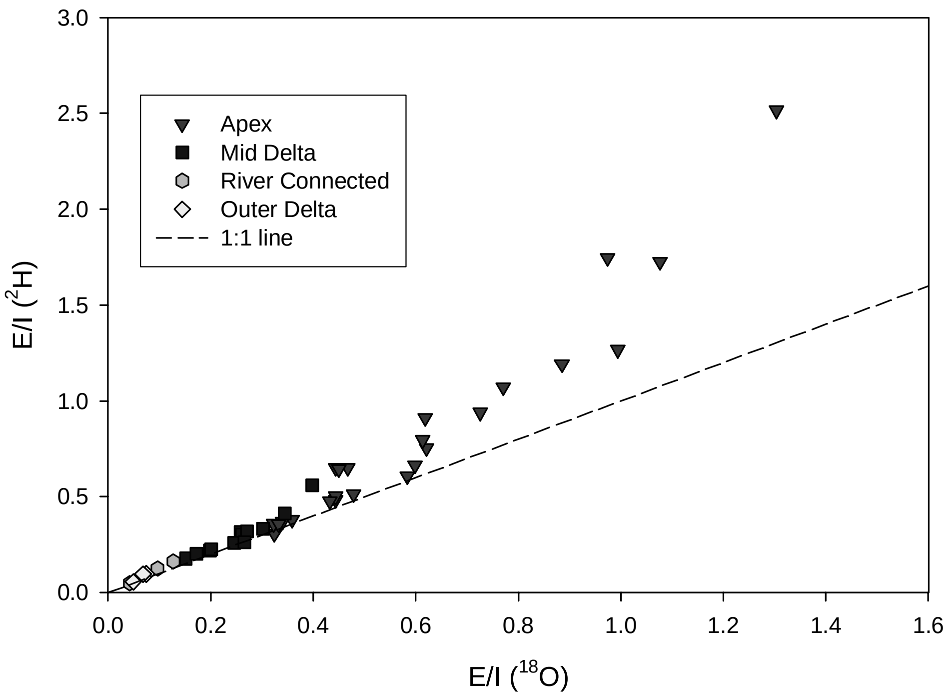


Figure 20 E/I ratios determined using δ^2H and $\delta^{18}O$ from water samples, assuming steady-state, obtained from 42 lakes in the SRD in September 2002 using a common input isotope composition and vapour isotope composition in equilibrium with thaw season precipitation isotope composition, as measured at the nearest CNIP station (Fort Smith).

The varying of input parameters has a strong physical basis as when field work was undertaken, it was noted that northwesterly winds coming off of Great Slave Lake were pronounced during the late summer and fall.

Varying input parameters was undertaken to achieve a better agreement between $\delta^{18}O$- and δ^2H-derived E/I ratios. For this mixing model, each lake E/I ratio is calculated from site specific data. This site specific characterization is important due to lakes having variable δ_I isotopic compositions entering the lake depending on its geomorphologic location in the delta and catchment variability surrounding the study lakes. For example, some of the study lakes' initial input water comes from the Slave River, while other lakes depend solely on snowmelt, while other lakes receive a mixture of different input waters. The size and characteristics of a lakes catchment can also influence δ_I. δ_A may also vary depending on its location in the delta with respect to Great Slave Lake which may provide a substantial source of vapour to the area.

To account for differences in δ_I and δ_A across the Slave River Delta, variable site specific δ_I were determined, and δ_A was allowed to fluctuate by incorporating a percentage of mixing with Great Slave Lake vapour δ_E. δ_E of Great Slave Lake was calculated using equation (10) in the theory section.

Site specific δ_I values were calculated by using a regression line parallel to the calculated LEL, from each individual lake water isotopic composition down to the LMWL. The intersection of the regression line and the LMWL determined δ_I for the sample lake. Site specific δ_I values ranged from -20.4‰ to -18.5‰ and -156.5‰ and -143.1‰, for $\delta^{18}O$ and $\delta^{2}H$ respectively. These are reasonable δ_I values as they fall within the range of snow and rain isotopic compositions collected during the 2003 field season.

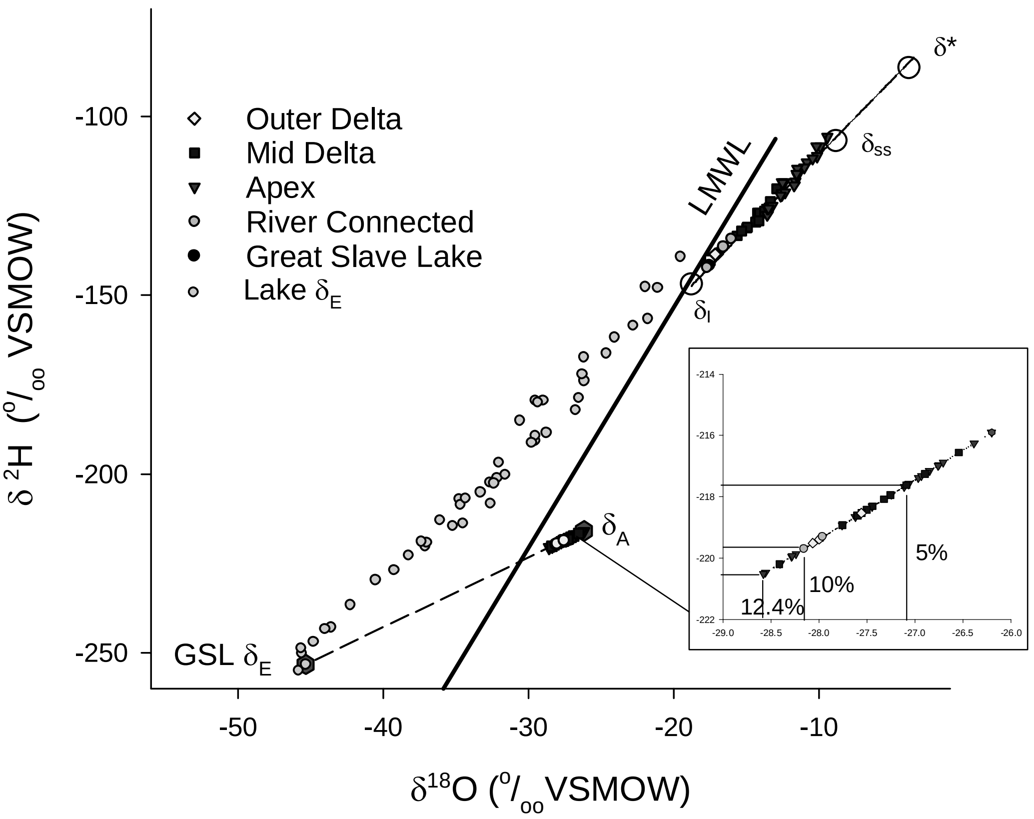


Figure 21 Varying percent mixing between δ_E and δ_A by forcing E/I ratios along a 1:1 line.

Site-specific δ_A values were determined by connecting a mixing line between the calculated δ_A (based on equilibrium with local thaw season precipitation) and vapour derived from the evaporation of Great Slave Lake δ_E (Figure 21). The percentage of mixing between δ_A and δ_E was determined by varying the percentage of mixing until all lake E/I ratios were forced along a 1:1 line in E/I (^2H) vs. E/I (^{18}O) space (Figure 21 insert).

Moisture from Great Slave Lake was found to contribute up to 12% to local ambient moisture with δ_A values ranging from -26.2‰ to -28.6‰ and -220.5‰ to -215.9‰, for $\delta^{18}O$ and δ^2H respectively.

By using site specific inputs, and allowing for mixing of 9% (best fit to 1:1 line) of atmospheric vapour from Great Slave Lake, the offset from the 1:1 line in Figure 21 is reduced (Figure 22).

Due to the large size of the delta, variable geomorphology and ecology, the variability observed in percent vapour mixing and input water isotope composition may be attributed to differences in catchment characteristics which will affect each lake differently. Catchment variability is related to the size of the catchment, surrounding vegetation, and variable input waters (spring melt waters or continuous seasonal input from multiple sources).

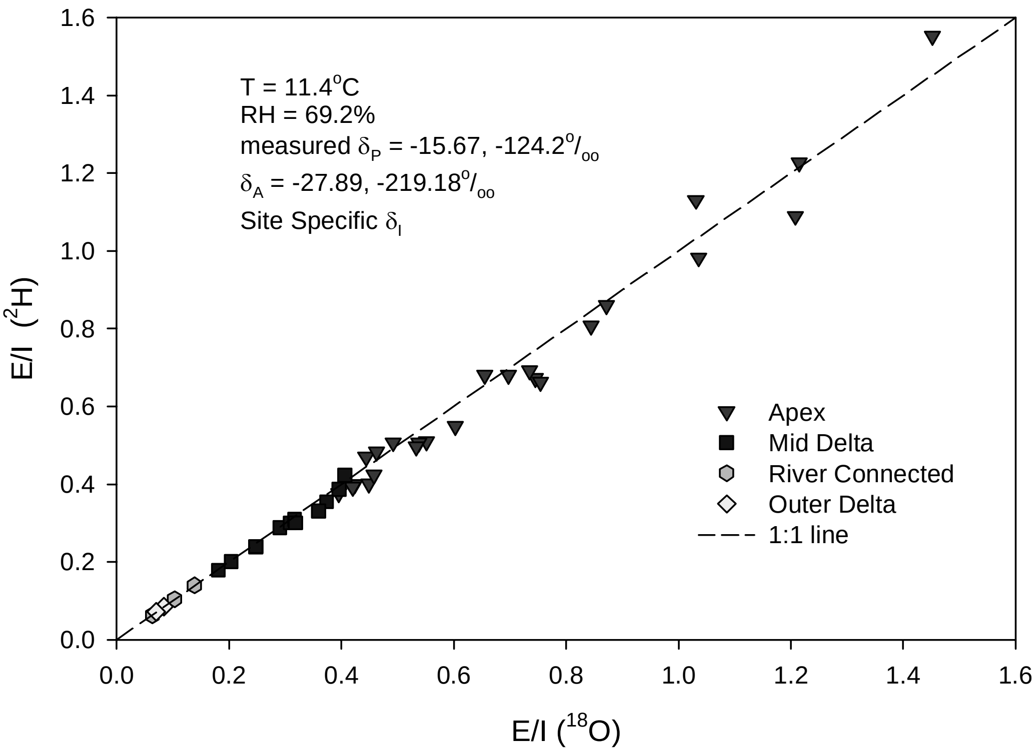


Figure 22 E/I ratios derived using site-specific input information and a common mixed δ_A derived from mixing δ_{EGSL} and δ_A .

The E/I ratios derived for the 2002 data set indicate that 37 lakes have an E/I ratio of <1 indicating that these lakes were receiving more input than water loss due to evaporation. Five lakes in the upper delta (SD 12, SD 27, SD 29, SD 33, and SD 35) are exhibiting E/I ratios of >1, indicating that these lakes were desiccating at the time of sampling.

7.4 2003 Isotope Mass Balance Modelling

The 2002 vapour mixing model was applied to the six lakes studied in the 2003 temporal data set. Isotope mass balance equations explained in the Theory section, were used to estimate individual lake water balances. As discussed in the previous section, E/I values obtained using a common δ_I value for the mass balance equations obtained from the CNIP Fort Smith station, results in poor agreement between evaporation/inflow (E/I) ratios calculated from lake water $\delta^{18}O$ and δ^2H values.

The use of locally derived parameters that vary over the ice-off season is essential for an accurate depiction of local conditions. The data used in the equations were determined using a time sensitive average. The sampling season was divided into 4 month long periods of time. For example, climate data for May was used for that month, but an average number was used to calculate data used for May and June and so forth. This was done to depict the variability of these parameters over the sampling season. For example δ_A was calculated five different times with climate data representing cumulative seasonal ranges, to represent the δ_A for month-long time periods. Calculations using this variability were undertaken to depict conditions in May, June, July, August, and the end of the sampling season (Table 5). Variable cumulative climate data (RH and temperature) were used to incorporate the change in weather experienced in the delta over the sampling period. Monthly mean relative humidity values ranged from 55% at the beginning of the season representing the RH in May to 63% at the end of the sampling season representing the cumulative RH experienced in the delta from May to the end of the sampling season. Monthly mean temperature ranged from 9.2°C in May to 13.4°C for the entire sampling season (Table 5) (Environment Canada, 2002). Precipitation samples were also collected from the individual lake locations allowing for seasonal variability in δ_{ps} to be incorporated in the mass balance equations. An average delta-wide initial input composition (δ_I) of -21.5‰ and -163.5‰, for $\delta^{18}O$ and δ^2H respectively was determined for the area by constructing regression lines through the closed basin lakes, as they have the least variability in input waters, and averaging the values of the intersection with LMWL. This average δ_I value is representative of the isotopic composition of snow samples collected in the region which composes the snowmelt input to lakes at the beginning of the season.

Table 5 Variable monthly input parameters used in the 2003 vapour mixing model.

Date Range	RH	T (°C)	Sampled Variable δ_{ps} (‰)	δ_I (‰)	Monthly δ_A (‰)	$\delta_{E\ GSL}$ (‰)	δ^* (‰)
May	0.55	9.2	-17.5, -143.4	-21.5, -163.5	-28.2, -237.8	-42.8, -247.4	2.98, -68.4
June	0.75	11.1	-17.0, -133.1	-21.5, -163.5	-27.6, -225.2	-43.3, -246.4	1.38, -67.0
July	0.58	14.6	-15.6, -127.3	-21.5, -163.5	-25.8, -215.1	-43.1, -225.9	2.15, -65.3
August	0.59	14.9	-15.3, -124.1	-21.5, -163.5	-25.5, -211.6	-41.5, -220.5	1.48, -65.9
End of Season	0.63	13.4	-17.0, -133.1	-21.5, -163.5	-27.3, -222.4	-42.8, -213.0	-2.50, -85.5

This model has a strong physical basis as weather is extremely variable over the ice-off season and observed northwesterly winds off of Great Slave Lake are pronounced during the summer and fall. E/I values for the lake water samples were calculated using the variable input parameters in Table 5, representing the time period the samples were collected.

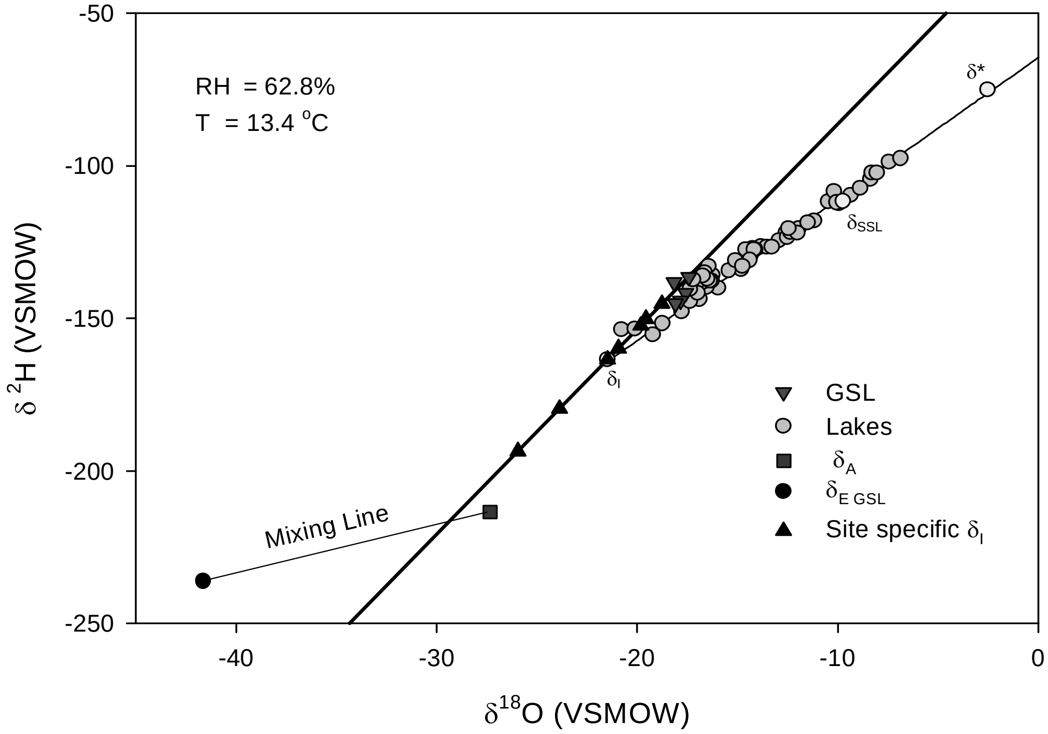


Figure 23 All 2003 lake water samples, site specific δ_I that were averaged to determine the regional δ_I, and the vapour mixing line between $\delta_{E\ GSL}$ and δ_A.

Site specific δ_A values were determined by connecting a mixing line between the calculated regional δ_A, ($\delta_A = (\delta_p - \varepsilon^*)/\alpha^*$), and $\delta_{E\ GSL}$, vapour derived from the evaporation of Great Slave Lake water (Figure 23). The percentage of mixing between δ_A and δ_E was determined by varying the percentage of mixing until all lake E/I ratios plotted along a 1:1 line in E/I (^2H) vs. E/I (^{18}O) space (Figure 24).

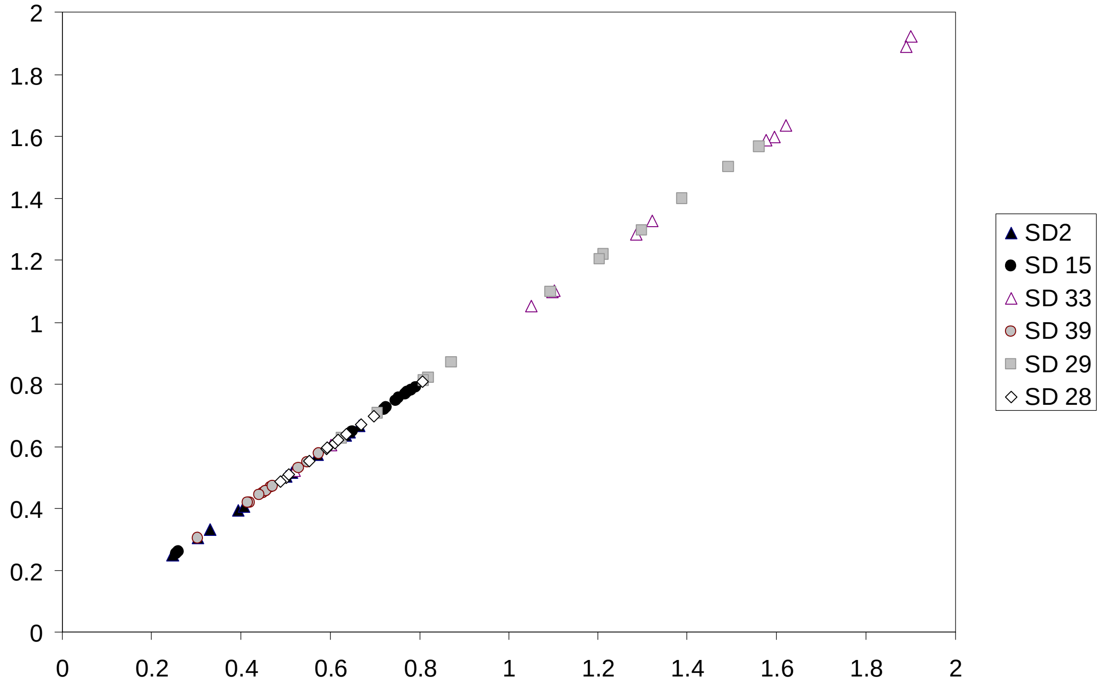


Figure 24 Forced E/I ratios along a 1:1 line using the vapour mixing model.

E/I values over the sampling season ranged from 0.25 to 1.93 for the six study lakes (Table 6). SD 29 and SD 33 are exhibiting E/I values of >1, indicating that these lakes were undergoing drying. This interpretation corresponds with visual records of the lakes shoreline receding. The other study lakes in the dataset have E/I ratios of <1 indicating that the lakes received more water than was lost due to evaporation.

Table 6 Range of Calculated Mixing Ratios and E/I Ratios.

Lake	SD 39	SD 2	SD 28	SD 15	SD 29	SD 33
Mixing Ratio	0.30 - 0.50	0.09 - 0.45	0.22 - 0.57	0.16 - 0.69	0.14 - 0.41	0.12 - 0.43
E/I Range	0.31 - 0.59	0.25 - 0.67	0.50 - 0.82	0.26 - 0.80	0.63 - 1.58	0.61 - 1.93

As observed in Figure 25, moisture from GSL over the thaw season was found to contribute up to 69% to local ambient moisture (Table 6). The variability observed over the thaw season shows greater mixing of moisture sources at the beginning and end of the ice-off season when more moisture is present in the environment due to evaporation of snowmelt and late precipitation events. The increase in mixing ratios observed at the beginning of October 2003 can be attributed to samples being compromised by the late season depleted precipitation event deriving from Great Slave Lake vapour, thereby increasing the mixing ratio.

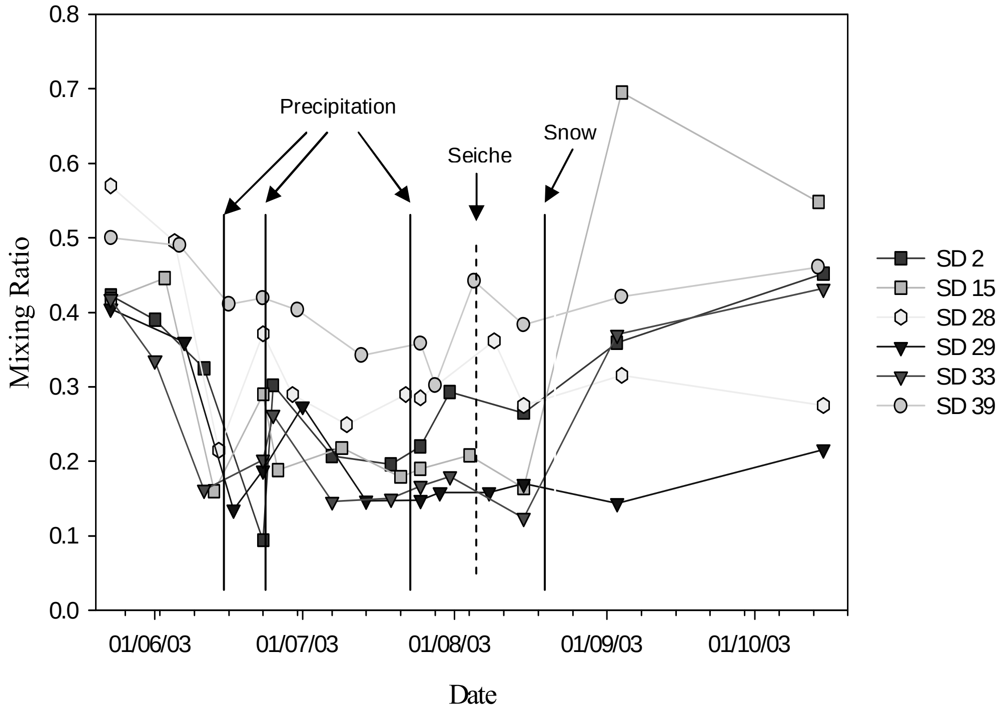


Figure 25 Mixing model ratios showing seasonal variability.

Lakes without continuous river water or GSL water influence (SD 2, SD 15, SD 29, and SD 33) tend to have similar relatively stable mixing ratios. Mixing values for these lakes range from 9% to 45% over the thaw season.

SD 39 and SD 28, which exhibit open and restricted basins with Slave River and GSL water inputs throughout the thaw season, exhibit the highest amount of mixing over most of the ice-off season. Vapour mixing values range from 30% to 50%.

There is greater variability at the beginning and end of the thaw season when there is a large variability of input compositions and volumes of water entering the lakes. Time periods when precipitation events occurred in the area also show an increase in mixing ratios, as well as greater inter-lake variability. There appears to be good correlation between mixing ratios when the lakes are only undergoing periods of evaporative enrichment. Gat et al (1994) estimated that evaporation from the Upper Laurentian Great Lakes can influence atmospheric moisture by as much as 4.6% to 15.7%.

8 CONCLUSIONS AND RECOMMENDATIONS

There are many sources of water that affect and control Slave River Delta lakes modern water balances and isotopic compositions. These influences include spring thaw snowmelt, flood events from the Slave River, seiche events from Great Slave Lake and thaw season precipitation events. An important component of Slave River Delta hydrology is evaporation, which is the key factor in lake variability, both physically and isotopically, experienced throughout the entire delta during the ice-off season.

Isotopic snowmelt signatures have been captured in the study lakes during the 2003 ice-off season, exhibiting very depleted isotopic lake water compositions. These samples were collected just after lake ice break-up, so very little evaporative enrichment is expected to have occurred on the lakes prior to sampling. For many lakes in the delta, predominantly in the upper delta, snowmelt is the primary hydrological input to the lake water balances. Upstream snowmelt runoff also affects river isotopic signatures and levels, which potentially leads to flooding of the delta with depleted waters.

Flood events from Great Slave Lake and the Slave River play a key role in controlling modern water balances and isotopic compositions of lakes in the outer and mid-delta, as well as lakes with a direct connection to the Slave River. Outer delta and mid-delta lakes experience the greatest amount of flooding during the spring. Lakes that are affected by spring flood events have a different overall isotopic signature than those lakes in the upper delta.

All lakes have a broad distribution along the LEL. Lakes plotting above the LEL have a river or GSL influence (SD 39 and SD 28) which may reflect a different LEL, while lakes plotting along the LEL have their isotope signatures strongly controlled by evaporation.

Lakes that have a continued river connection, or experience seiche events throughout the summer from Great Slave Lake show a more depleted signature than non-connected lakes. This is due to depleted river water entering and mixing with lake water, suppressing most of the evaporative enrichment signal.

Levee height throughout the delta seems to strongly affect local hydrology, with areas with the greatest levee heights having the most enriched lake water compositions, and areas with the lowest levee heights, having the most depleted isotopic signatures.

Thaw season precipitation effects on Slave River Delta lakes varies depending on the amount of precipitation received, surface area and volume of the lake, and catchment size. The isotopic signal of precipitation was also shown to vary during the ice-off season. Lakes where no flooding occurs, or have no direct river connection depend solely on snowmelt runoff and precipitation to maintain their water balances.

During the ice-off season, evaporation exerts a strong control on the variability, both physically and isotopically, on Slave River Delta lakes. The main controlling factor on water balances during the summer months is evaporation.

The late-season precipitation event observed to isotopically deplete the six study lakes prior to October 1, 2003 may be attributed to precipitation deriving from local Great Slave Lake vapour, due to the isotopic composition of the lakes being reset to compositions that plot along the LMWL. Lakes throughout the delta show varying degrees of response to this event. This can be in part due to lake size, patchiness of precipitation, where some lakes will receive greater amounts of input, and the influences of Slave River and Great Slave Lake water inputs.

E/I ratios derived for the 2002 data set indicates that five lakes have surpassed steady-state conditions, with E/I ratios >1. During 2003, SD 29 and SD 33 also exhibited drying conditions having E/I ratios >1, which was also observed by field personnel conducting the sampling.

The mixing model, when applied to the September 2002 data set has allowed for discrepancies between $\delta^{18}O$- and $\delta^{2}H$-derived E/I ratios to be effectively reconciled. This was done by incorporating site specific information into the mass balance equations, and allowing mixing between Great Slave Lake vapour δ_E, and local atmospheric vapour δ_A. The use of measured locally derived parameters ensures a more accurate depiction of local conditions.

A good correlation can be observed during July 2003 between mixing of GSL vapour and atmospheric moisture. The mixing ratios obtained from SD 33 and SD 29 correspond well to values that were estimated by Gat *et al*., (1994) for the contribution of 4.6% to 15.7% of vapour derived from large water bodies to local atmospheric moisture. Using the approach of mixing atmospheric vapour with a neighbouring large water body's vapour, along with using site-specific input parameters in mass balance modelling, allows for apparent isotopic discrepancies in E/I ratios to be reconciled.

From the observations made in this thesis it can be surmised that the area of the delta with the greatest susceptibility to hydrologic change if climate were to become drier would be the upper delta. Lakes in this area are subject to high degrees of drying, and as stated earlier, are dependent on snow melt and summer precipitation to maintain their water balances. This could mean that the lakes in this area could dry. This study has shown that snowmelt is a key input to mid and upper delta lakes. Reduction in local snowpack would result in less initial thaw water input, which could drastically affect lake water balances.

Areas in the outer delta could also be prone to drastic water level changes if Slave River and Great Slave Lake water levels were to decline. These lakes in the low levee outer delta would not receive as much thaw flooding and high water event fluctuations like seiche events.

Results from the 2002 and 2003 isotope study give an initial understanding of the modern water balances of lakes in the different geomorphologic zones of the Slave River Delta. From this research, more exact isotopic constraints have been placed on input parameters to give a better understanding of actual conditions of the delta.

Future research conducted at the University of Waterloo and Wilfrid Laurier University by the multi-disciplinary research group will further enhance the understanding of the large variability of water balances experienced in a deltaic environment. Using the input parameters determined from this research, paleohydrological reconstructions of lakes within the delta can be performed with more accuracy.

One area of research that would be useful in understanding the modern water balances of Slave River Delta lakes and constraining inputs parameters further, would be to determine the role of groundwater on a deltaic lake. Groundwater could play a significant role in maintaining a lakes water balance. This could be done by installing drive point monitoring wells around the study lake's, as well as within the lake, to determine whether there are upward or downward hydraulic gradients in the area.

A climate monitoring station located within the delta itself would also significantly reduce uncertainty deriving from the use of climate data obtained from Hay River, 150 km west of the Slave River Delta. This would allow for local values of relative humidity and temperature to be determined and used in the mass balance equations to give more accurate local isotopic modelling.

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APPENDIX A

Slave River Delta (SRD) Lake & River UTM Coordinates

Lake	Northing	Easting	Name
SD 1	6796450	360900	
SD 2	6796800	361650	
SD 3	6797350	363250	
SD 4	6796760	362150	
SD 5	6795888	365177	
SD 6	6798670	363650	
SD 7	6802929	363807	
SD 8	6792549	358400	
SD 9	6797369	359764	
SD R1	6798437	358872	East Channel
SD 10	6800325	363078	
SD 11	6798140	369545	
SD 12	6796301	371053	
SD 13	6798099	371918	
SD 14	6799258	373304	
SD R2	6803358	373749	Jean River
SD 15	6802209	372375	
SD 16	6801021	372195	
SD 17	6791348	368063	
SD 18	6795593	370045	
SD 19	6796500	375250	
SD 20	6800033	375441	
SD 21	6797868	378831	
SD 22	6798855	380493	
SD 23	6795825	381409	
SD 24	6795230	377971	
SD 25	6793846	378186	
SD 26	6786563	370914	
SD 27	6789184	372615	
SD 28	6791339	372046	
SD 28 C1	6791432	372492	Channel 1
SD 28 C2	6791348	372342	Channel 2
SD 29	6790800	381718	
SD 30	6787657	387222	
SD 31	6786252	385316	
SD 32	6783643	385619	
SD 33	6779992	381208	
SD 34	6787134	362162	
SD 35	6779578	380385	
SD 36	6771359	380103	
SD 37	6770753	381762	
SD R3	6800111	360483	Resdelta Channel
SD 38	6800416	359957	
SD 39	6800378	357341	
SD 40	6795784	356331	
SD 41	6798317	355966	

2002 Sampling Event

2002 Initial Sampling	Lab #	18O	Repeat	Average	2H	Repeat	Average
SD1	52261	-14.99		**-14.99**	-130.95	-131.61	**-131.28**
SD2	52262	-14.22	-14.28	**-14.25**	-126.69	-127.57	**-127.13**
SD3	52263	-14.22		**-14.22**	-127.78	-127.51	**-127.65**
SD4	52264	-14.11		**-14.11**	-126.89	-127.23	**-127.06**
SD5	52265	-13.38	-13.39	**-13.385**	-123.89		**-123.89**
SD6	52266	-14.39		**-14.39**	-129.45	-129.52	**-129.49**
SD7	52267	-12.93		**-12.93**	-119.99	-120.43	**-120.21**
SD8	52268	-13.78		**-13.78**	-126.41	-126.63	**-126.52**
SD9	52269	-14.95		**-14.95**	-130.80	-131.14	**-130.97**
SD10	52270	-15.66		**-15.66**	-133.45	-133.34	**-133.40**
SD11	52271	-13.67	-13.46	**-13.565**	-127.83	-127.18	**-127.51**
SD12	52272	-9.93		**-9.93**	-108.35	-108.63	**-108.49**
SD13	52273	-12.42		**-12.42**	-118.22	-118.61	**-118.42**
SD14	52274	-10.87		**-10.87**	-112.75	-112.98	**-112.87**
SD15	52275	-12.59		**-12.59**	-122.08	-121.90	**-121.99**
SD16	52276	-13.42		**-13.42**	-125.15	-125.37	**-125.26**
SD17	52277	-16.06		**-16.06**	-133.91	-134.63	**-134.27**
SD18	52278	-13.54	-13.63	**-13.585**	-125.36	-125.94	**-125.65**
SD19	52279	-11.05		**-11.05**	-114.95	-113.58	**-114.27**
SD20	52280	-11.54		**-11.54**	-114.67	-114.54	**-114.61**
SD21	52281	-11.57	-11.72	**-11.645**	-118.13	-118.28	**-118.21**
SD22	52282	-11.53		**-11.53**	-116.29	-117.11	**-116.70**
SD23	52283	-11.72		**-11.72**	-119.22	-119.33	**-119.28**
SD24	52284	-12.59		**-12.59**	-121.76	-121.33	**-121.55**
SD25	52285	-13.25		**-13.25**	-124.83	-125.10	**-124.97**
SD26	52286	-13.49		**-13.49**	-125.85	-125.62	**-125.74**
SD27	52287	-10.14	-10.15	**-10.145**	-111.40	-111.04	**-111.22**
SD28	52288	-16.61		**-16.61**	-136.14	-136.77	**-136.46**
SD29	52291	-10.47		**-10.47**	-112.37	-111.27	**-111.82**
SD30	52292	-17.74		**-17.74**	-142.01	-142.52	**-142.27**
SD31	52293	-12.35		**-12.35**	-121.47	-121.08	**-121.28**
SD32	52294	-12.67		**-12.67**	-122.15	-122.16	**-122.16**
SD33	52295	-10.27	-10.13	**-10.2**	-108.03	-108.76	**-108.40**
SD34	52296	-12.59		**-12.59**	-118.40	-118.46	**-118.43**
SD35	52297	-9.44		**-9.44**	-105.67	-105.84	**-105.76**
SD36	52298	-12.54		**-12.54**	-118.09	-119.07	**-118.58**
SD37	52299	-11.56	-11.58	**-11.57**	-115.95	-116.25	**-116.10**
SD38	52300	-15.35		**-15.35**	-131.85	-132.36	**-132.11**
SD39	52301	-17.03		**-17.03**	-138.43	-138.45	**-138.44**
SD40	52302	-14.05	-14.27	**-14.16**	-129.40	-129.10	**-129.25**
SD41	52303	-17.16		**-17.16**	-138.48	-138.69	**-138.59**
SD42	52307	-17.58		**-17.58**	-142.48	-140.92	**-141.70**
SD28 CHANNEL	52289	-15.07		**-15.07**	-130.82	-130.95	**-130.89**
SD28 CHANNEL 2	52290	-14.67		**-14.67**	-128.89	-129.12	**-129.01**
Slave Snow	52306	-24.94		**-24.94**	-178.70	-178.51	**-178.61**

SD R1	52309	-17.67		**-17.67**	-140.57	-140.88	**-140.73**
SD R2	52310	-17.68		**-17.68**		-140.27	-140.27
SD R3	52311	-17.41		**-17.41**	-139.79	-139.59	**-139.69**

2003 Sampling Event

2003 Sampling	Lab#	Result	Repeat	Result	Repeat	18O Avg	2H Avg.
LAKE WATER							
SD 2 2003-05-23	71089	-19.21		-155.58	-155.24	**-19.21**	**-155.41**
SD 2 2003-06-10	71090	-17.79		-147.92	-147.81	**-17.79**	**-147.865**
SD 2 2003-06-23	71091	-16.91		-144.47	-143.01	**-16.91**	**-143.74**
SD 2 2003-07-06	71092	-15.96		-139.71	-140.3	**-15.96**	**-140.005**
SD 2 2003-07-25	71093	-14.82		-134.51	-133.3	**-14.82**	**-133.905**
SD 2 2003-08-02	71094	-14.26	-14.31	-128.2	-128.95	**-14.285**	**-128.575**
SD 2 2003-08-15	71095	-13.82		-125.93	-127.12	**-13.82**	**-126.525**
SD 2 2003-09-04	71096	-16.27		-135.56	-136.14	**-16.27**	**-135.85**
SD 2 10/14/03	71097	-16.45		-132.95	-132.96	**-16.45**	**-132.955**
SD 15 2003-05-23	71098	-14.39		-130.45	-130.71	**-14.39**	**-130.58**
SD 15 2003-06-03	71099	-14.34		-130.23	-128.6	**-14.34**	**-129.415**
SD 15 2003-06-23	71100	-13.53		-126.32	-127.04	**-13.53**	**-126.68**
SD 15 2003-07-09	71101	-12.93		-124.16	-124.76	**-12.93**	**-124.46**
SD 15 2003-07-25	71102	-12.68	-12.35	-123.13	-123.77	**-12.515**	**-123.45**
SD 15 2003-08-04	71103	-12.35		-122.17	-121.63	**-12.35**	**-121.9**
SD 15 2003-08-15	71104	-11.93		-120.35	-120.86	**-11.93**	**-120.605**
SD 15 2003-09-04	71105	-20.78		-153.84	-153.56	**-20.78**	**-153.7**
SD 15 10/14/03	71106	-20.12		-154.17	-152.83	**-20.12**	**-153.5**
SD 20 2003-05-23	71107	-13.67	-13.68	-127.61	-126.34	**-13.675**	**-126.975**
SD 20 2003-06-23	71108	-12.77		-122.57	-121.41	**-12.77**	**-121.99**
SD 20 2003-07-25	71109	-11.71		-118.48	-117.79	**-11.71**	**-118.135**
SD 20 2003-08-15	71110	-10.91		-113.71		**-10.91**	**-113.71**
SD 28 2003-05-23	71111	-17.04		-140.28	-140.87	**-17.04**	**-140.575**
SD 28 2003-06-05	71112	-16.55		-139.66	-139.93	**-16.55**	**-139.795**
SD 28 2003-06-23	71113	-15.44		-133.97	-134.77	**-15.44**	**-134.37**
SD 28 2003-07-10	71114	-14.65		-132.83	-131.36	**-14.65**	**-132.095**
SD 28 2003-07-25	71115	-14.66	-14.45	-130.82	-129.83	**-14.555**	**-130.325**
SD 28 2003-08-09	71116	-14.59		-127.75	-127.33	**-14.59**	**-127.54**
SD 28 2003-08-15	71117	-14.11		-128.15	-126.98	**-14.11**	**-127.565**
SD 28 2003-09-04	71118	-15.12		-131.03	-131.19	**-15.12**	**-131.11**
SD 28 10/15/03	71119	-14.12	-14.22	-127.38	-127.8	**-14.17**	**-127.59**
SD 29 2003-05-23	71120	-14.39		-130.94	-130.95	**-14.39**	**-130.945**
SD 29 2003-06-07	71121	-13.27		-127.23	-126.07	**-13.27**	**-126.65**
SD 29 2003-06-23	71122	-11.93	-12.07	-121.78	-122.16	**-12**	**-121.97**
SD 29 2003-07-14	71123	-9.92		-112.4	-112.5	**-9.92**	**-112.45**
SD 29 2003-07-25	71124	-9.36		-109.93	-109.43	**-9.36**	**-109.68**
SD 29 2003-08-08	71125	-8.37		-103.98	-104.88	**-8.37**	**-104.43**
SD 29 2003-08-15	71126	-8.31		-102.15	-102.48	**-8.31**	**-102.315**
SD 29 2003-09-03	71127	-11.19		-118.89	-117.34	**-11.19**	**-118.115**
SD 29 10/15/03	71128	-14.75	-14.76	-132.58	-133.38	**-14.755**	**-132.98**
SD 33 2003-05-23	71129	-12.44		-120.63	-120.41	**-12.44**	**-120.52**
SD 33 2011-06-01	71130	-11.51		-119.69	-117.9	**-11.51**	**-118.795**
SD 33 2003-06-23	71131	-10.06		-112.5	-111.69	**-10.06**	**-112.095**
SD 33 2003-07-07	71132	-8.87		-106.84	-107.95	**-8.87**	**-107.395**
SD 33 2003-07-25	71133	-8.06		-102.55	-102.28	**-8.06**	**-102.415**
SD 33 2003-07-31	71135	-7.46		-98.45	-99.05	**-7.46**	**-98.75**
SD 33 2003-08-15	71136	-6.87		-98.41	-96.9	**-6.87**	**-97.655**

SD 33 2003-09-03	71137	-16.76	-16.66	-137.21	-138.93	**-16.71**	**-138.07**
SD 33 10/15/03	71138	-16.64		-135.48	-134.58	**-16.64**	**-135.03**
SD 39 2003-05-23	71139	-18.74		-150.9	-152.42	**-18.74**	**-151.66**
SD 39 2003-06-06	71140	-17.38		-144.34	-144.63	**-17.38**	**-144.485**
SD 39 2003-06-23	71141	-16.99	-17.01	-141.27	-142.1	**-17**	**-141.685**
SD 39 2003-07-13	71142	-16.29		-138.17	-137.24	**-16.29**	**-137.705**
SD 39 2003-07-25	71143	-16.39		-138.15	-137.38	**-16.39**	**-137.765**
SD 39 2003-08-05	71144	-17.17	-17.54	-140.18	-140.68	**-17.355**	**-140.43**
SD 39 2003-08-15	71145	-16.51		-137.23	-137.15	**-16.51**	**-137.19**
SD 39 2003-09-04	71146	-16.73		-136.88	-135.25	**-16.73**	**-136.065**
SD 39 10/14/03	71147	-17.2		-136.88	-137.7	**-17.2**	**-137.29**
SD 28 C (1) 2003-05-23	71148	-17.25		-141.98	-142.94	**-17.25**	**-142.46**
SD 28 C (1) 2003-06-05	71149	-18		-145.63	-146.48	**-18**	**-146.055**
SD 28 C (1) 2003-06-23	71150	-16.45	-16.36	-138.64	-138.73	**-16.405**	**-138.685**
SD 28 C (1) 2003-07-10	71151	-17.25		-141.32	-140.62	**-17.25**	**-140.97**
SD 28 C (1) 2003-07-25	71152	-16.71		-139.51	-138.22	**-16.71**	**-138.865**
SD 28 C (1) 2003-08-09	71153	-16.13		-136.71	-136.69	**-16.13**	**-136.7**
SD 28 C (1) 2003-08-15	71154	-14.29		-130.52	-129.12	**-14.29**	**-129.82**
SD 28 C (1) 2003-09-04	71155	-14.89		-130.96	-131.12	**-14.89**	**-131.04**
SD 28 C (1) 10/15/03	71156	-14.16		-128.05	-128.64	**-14.16**	**-128.345**
SD 28 C (2) 2003-05-23	71157	-17.25		-142.44	-143.03	**-17.25**	**-142.735**
SD 28 C (2) 2003-06-05	71158	-17.34	-17.64	-143.77	-142.69	**-17.49**	**-143.23**
SD 28 C (2) 2003-06-23	71159	-16.18		-136.41	-137.3	**-16.18**	**-136.855**
SD 28 C (2) 2003-07-10	71160	-15.72		-135.06	-135.08	**-15.72**	**-135.07**
SD 28 C (2) 2003-07-25	71161	-14.7		-131.23	-130.22	**-14.7**	**-130.725**
SD 28 C (2) 2003-08-09	71162	-14.74	-14.7	-130.98	-131.73	**-14.72**	**-131.355**
SD 28 C (2) 2003-08-15	71163	-14.06		-129.09	-128.74	**-14.06**	**-128.915**
SD 28 C (2) 2003-09-04	71164	-14.53		-129.85	-130.8	**-14.53**	**-130.325**
SD 28 C (2) 10/15/03	71165	-14.07	-14.17	-129.52	-128.51	**-14.12**	**-129.015**
SD 42						**-17.58**	**-141.7**
SD42 05/23/03		-17.85		-143.92	-144.45	**-17.85**	**-144.185**
SD42 06/23/03		-18.1		-144.94	-145.55	**-18.1**	**-145.245**
SD42 07/25/03		-18.04	-18.29	-138.26		**-18.165**	**-138.26**
SD42 08/15/03		-17.44		-136.99	-136.05	**-17.44**	**-136.52**
SD R2 2003-05-23	71166	-18.99		-151.01	-151.66	**-18.99**	**-151.335**
SD R2 2003-06-13	71167	-18.42		-146.98	-147.51	**-18.42**	**-147.245**
SD R2 2003-06-23	71168	-18.29		-147.02	-146.34	**-18.29**	**-146.68**
SD R2 2003-07-09	71169	-18.47		-146.58	-147.13	**-18.47**	**-146.855**

SD R2 2003-07-25	71170	-17.94		-144.23	-144.85	**-17.94**	**-144.54**
SD R2 2003-08-04	71171	-17.66	-17.55	-143.62	-142.05	**-17.605**	**-142.835**
SD R2 2003-08-15	71172	-17.33		-140.99	-141.28	**-17.33**	**-141.135**
SD R2 2003-09-04	71173	-16.75		-138.43	-138.48	**-16.75**	**-138.455**
SD R2 10/14/03	71174	-16.99		-140.09	-138.85	**-16.99**	**-139.47**
SD R3						**-17.41**	**-139.69**
SDR3 05/23/03		-19.2		-151.01	-152.27	**-19.2**	**-151.64**
SDR3 06/06/03		-18.68		-149.86	-149.65	**-18.68**	**-149.755**
SDR3 06/23/03		-18.45		-146.53	-146.3	**-18.45**	**-146.415**
SDR3 07/13/03		-17.79		-144.53	-143.64	**-17.79**	**-144.085**
SDR3 07/25/03		-18.1	-18	-145.16	-145.18	**-18.05**	**-145.17**
SDR3 05/08/03		-17.62		-142.22	-142.71	**-17.62**	**-142.465**
SDR3 08/15/03		-17.23		-140.87	-140.95	**-17.23**	**-140.91**
SDR3 09/04/03		-116.79		-138.53	-138.55	**-16.79**	**-138.54**
SDR3 10/14/03		-17.19	-17.24	-139.04		**-17.215**	**-139.04**
PRECIPITATION							
SD2RG 2003-06-10	71176	-15.36		-130.56	-130.2	**-15.36**	**-130.38**
SD2RG 06/21/03		-15.72		-126.22	-126.71	**-15.72**	**-126.465**
SD2RG 07/18/03		-16.38		-132.66		**-16.38**	**-132.66**
SD2RG 02/08/03		-15.46	-15.08	-124.51	-123.71	**-15.27**	**-124.11**
SD15RG 2003-06-13	71177	-17.75		-144.65	-145.68	**-17.75**	**-145.165**
SD15RG 06/26/03		-14.01		-111.7	-111.62	**-14.01**	**-111.66**
SD15RG 07/21/03		-16.12		-130.33	-131.63	**-16.12**	**-130.98**
SD28RG 2003-06-14	71178	-17.74		-145.71	-145.29	**-17.74**	**-145.5**
SD28RG 06/29/03		-13.2		-111.18	-111.2	**-13.2**	**-111.19**
SD28RG 10/07/03		-15.51	-15.44	-125.77		**-15.475**	**-125.77**
SD29RG 2003-06-17	71179	-18.69	-18.89	-152.66	-153.46	**-18.79**	**-153.06**
SD29RG 06/01/03		-13.09		-109.8	-110.43	**-13.09**	**-110.115**
SD29RG 07/29/03		-12.95		-111.68	-112.26	**-12.95**	**-111.97**
SD33RG 2003-06-11	71180	-17.31		-141.89	-140.6	**-17.31**	**-141.245**
SD33RG 06/25/03		-14.39	-14.7	-119.53	-118.79	**-14.545**	**-119.16**
SD33RG 07/19/03		-15.76		-126.32	-127.22	**-15.76**	**-126.77**
SD39RG 2003-06-16	71181	-18.14		-145.8	-144.31	**-18.14**	**-145.055**
SD39RG 06/30/03		-13.56		-112.87	-111.6	**-13.56**	**-112.235**
SD39RG(1) 07/28/03		-16.14		-130.49	-131.46	**-16.14**	**-130.975**
SD39RG(2) 07/28/03		-16.1		-132.33	-131.4	**-16.1**	**-131.865**